

# **Architectural Integration of Photovoltaic and Solar Thermal Collector Systems into buildings**

Master's Thesis in Sustainable Architecture

June 2012, Trondheim

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## **ABSTRACT**

In the time when the world is debating on climate change issues which is basically due to use of fossil fuel, the use of solar energy in various form is relevant. The existing buildings are responsible for use of large amount of energy for lighting, heating, cooling and use of various energy run equipments mostly powered by fossil energy. Today's intention should be to replace this fossil fuel by solar energy which is free and available in abundance.

At the moment, solar technologies in the form of photovoltaics and thermal collectors are available in competitive prices. However, their use has not been to the expectation specially in building sector to replace the use of fossil fuels. The main reason for these technologies not being popular in building integration is the lack of good architectural quality rendered not meeting desired design considerations. Innovative approaches have to be explored in terms of design and implementation in order to match the modern technological components to the scale, proportion, material, colour scheme and balance of buildings. So, the objective of this thesis is to pave possible ways of integrating these technologies into buildings, both on existing and new constructions to add emphasis on the overall architectural expression in addition to producing energy. The intention here is to highlight design possibilities regarding the use of solar technologies into buildings with innovative approaches. Basic focus is on the appearance or aesthetics part of integration as this makes the major impact on the people. PVs and thermal collectors can deliberately be used as architectural design elements in a distinctive way.

The development towards passive house, zero energy and zero emission buildings will cause a more frequent use of building integrated solar energy systems as a source of renewable energy. Due to the limitations in the integrability of such systems in relation to the design, colour and scale of the building envelope, their integration may ruin the final architectural quality of the building. Many solar systems do exist on the market, and with better and better energy performance. But, if they are not designed to be integrated into buildings to enhance the quality of architecture, probably no one will opt using

these systems as a source of renewable energy generators. In this case, even though there will be more and more efficient PV or STC systems in the market, they won't be of use if aesthetic ways of integrating them is not sought. It looks like PV integration have brought about some improvements in the architectural quality of building integration, but the solar thermal collectors lacks on this part to some extent.

While the technical development and energy performance improvements are always in progress, the actual use of these systems in buildings is not increasing as it could and should do. Existing buildings account for over 40% of the world's total primary energy use and 24% of greenhouse gas emissions (Wall, 2009). A combination of making buildings more energy-efficient and using a larger fraction of renewable energy is therefore a key issue to reduce the non-renewable energy use and greenhouse gas emissions. With this aim, integration of PV and solar thermal collector systems into buildings becomes very important.

Integrating these PV and solar thermal collectors systems into buildings is not only for clean energy but also to use them as multifunctional elements where they replace the conventional building elements. With this, the economical viability of integration is met and most importantly, they become architectural components.

So the possible ways of architectural integration of PV and solar thermal collector systems have been explored and analysed in the thesis with special focus made on the aesthetic part of integration. 'Integrability' of both the systems in terms of different integration requirements have been compared. In doing so, integration advantages of both the systems have been explored.

## **ACKNOWLEDGEMENTS**

This thesis is the result of support from the Faculty of Architecture and Fine Arts, Professors, Teachers, Family and Friends.

My sincere thanks goes to Nicola Lolli for supervising and guiding me in due course of producing this work. I would also like to acknowledge Professor Anne Grete Hestnes for her precious time with the guidance, comments and support. Her ever welcoming gesture made me feel at ease while discussing issues related to the study. Associate Professor Annemie Wyckmans, the co-ordinator of our program, needs special acknowledgment for her valued suggestions.

My colleagues Alise, Chenchen, Elisabeth, Elisabetta, Ivan, Kristof, Lin, Maria, Michael, Mila, Nigar, Noora and Vegard need mentioning for their companion for the two years of study.

Last but not the least; I would also like to extend love and gratitude to my parents, my wife and my beautiful daughter for their support, understanding and love.





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## **ABBREVIATIONS**

BIPV: Building Integrated Photovoltaic

EAESL: The Encyclopedia of Alternative Energy and Sustainable Living

EERE: Energy Efficiency and Renewable Energy

EST: Energy Saving Trust

PV: Photovoltaic

STC: Solar Thermal Collector

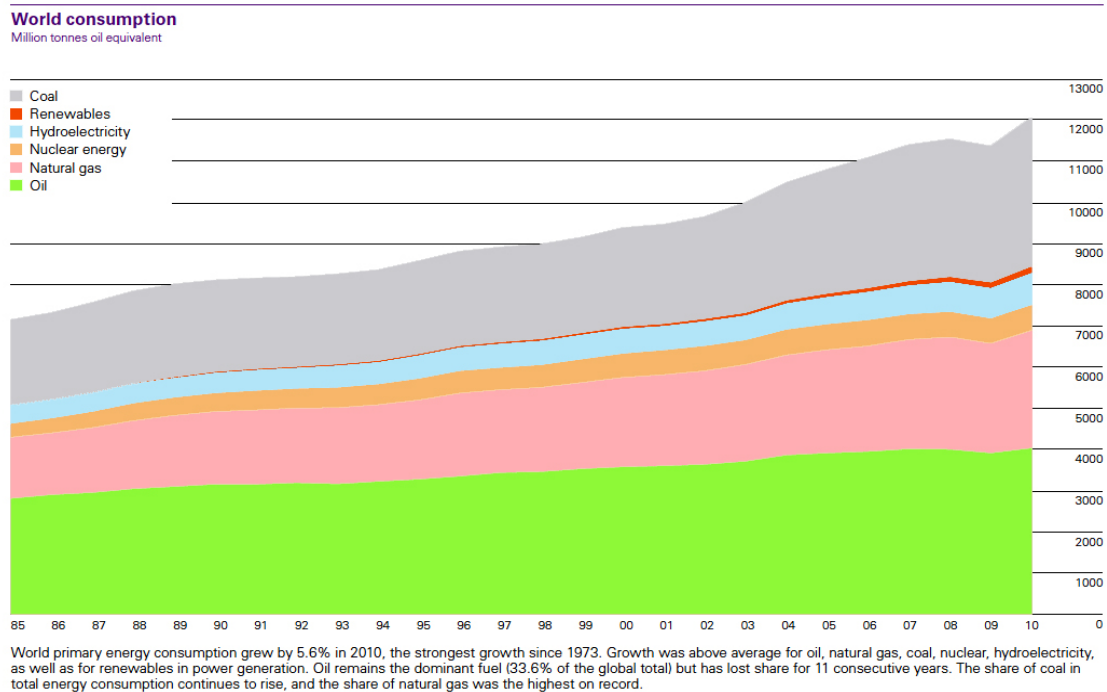




## 1 INTRODUCTION

### 1.1 Need for renewable energy

The 19<sup>th</sup> century was the age of coal, 20<sup>th</sup> was that of use of fossil oil while the 21<sup>st</sup> century that we are, is the age of use of solar energy (Thomas et al., 2001). The reason for emphasizing the use of solar energy is due to number of facts, firstly fossil fuel reserve is depleting due to their excessive use and secondly the emissions of CO<sub>2</sub> from the consumption of these fuels are the main cause of climate change. Hence, the use of renewable energy, and most importantly the energy from the sun which is abundantly available and that too for free is encouraged to reduce CO<sub>2</sub> emissions. All renewable energy sources provide 3078 times the current global energy needs and the solar energy is of the highest fraction(Horvat et al.). Hence, the solar energy must be the main consideration for architects, engineers, regulatory authorities and clients/investors when creating the built environment.

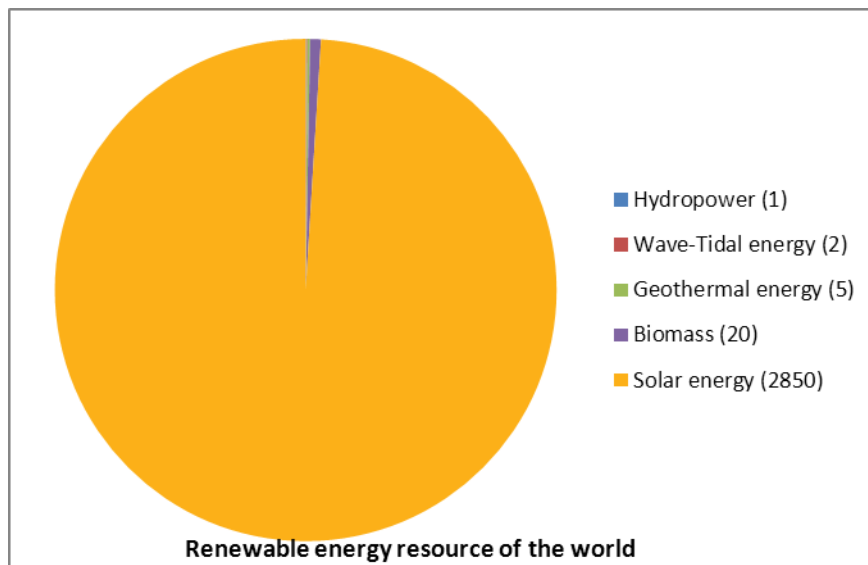


**FIG 1.1: World primary energy consumption from 1985 to 2010 in million tonnes oil equivalent,**

Credit: BP statistical report

Buildings should always be designed and built in an energy efficient way. Energy used for construction and operating the building should be minimised. In the case of new construction this can be done through appropriate

orientation, passive use of solar energy and selection of appropriate materials. As per Hermannsdorfer and Rub (2005), appropriate materials means they are produced or extracted by very little use of energy as far as possible. In old buildings energy consumption can be reduced significantly by insulating the building shell, use of windows with better U-values for thermal performance, exchange of heating systems etc. The remaining energy demand should be covered by active systems that use energy from a renewable source.



**FIG 1.2: Abundance of the availability of solar energy**

Credit: IEA Task 41

## 1.2 Solar energy

Solar energy can be divided into two passive and active. In a passive system, solar energy is directly used as a source of natural light and radiated heat through the windows and building envelopes. In case of active systems, solar energy is transferred from a photovoltaic module and thermal collectors in the form of electricity and heat respectively

The use of renewable energy should not be considered a substitute, but rather a modern complement that is aimed at energy saving. However, the use of renewable energies is currently viewed mainly as a goal within the scope of new buildings. This also includes solar architecture, since solar thermal and photovoltaic facilities can be particularly well integrated if they are planned along with the building as a whole from very early in the design. Solar

technologies imply vast opportunities for aesthetics and interesting solutions and solar heating technology is amongst the least expensive in the area of renewable energy (Hermannsdorfer and Rub, 2005; Kjellerup et al., 2010).

### **1.3 Solar technologies in building**

The importance of planning and design concepts that contribute to an increase in public acceptance of the solar building through convincing visualization and realization has to be emphasized. The installation of a solar facility during the renovation of an existing building produces both synergies and savings. If, for eg; a roof has to be completely recovered and a solar facility is installed, cost on tiling is saved in addition to energy generation. Solar facilities can also be easily integrated into planned extensions such as conservatories (Hermannsdorfer and Rub, 2005).

Use of solar energy for electricity and heating is a silent and non-polluting way that requires minimum maintenance. However, their integration into buildings represents a real architectural challenge, as to a great degree, the development of solar systems for energy has been characterized by the wish for energy effectiveness and low cost, while the architectural aspects have been neglected. In fact, these systems can be integrated into buildings as a multifunctional element that increases the architectural quality besides providing free energy(Kjellerup et al., 2010).

It is important that we do not regard solar facilities as technological systems that only serve the purpose of producing heat or electricity; instead, they must be regarded and treated as elements that make an important contribution to the architectural design. Thus seen, they can enhance the architecture, accentuate it and distinguish it from the mass. They can express adaptation and transformation or modernity while at the same time are able to preserve traditional features. With this, both the building and the owner will have a positive image on architectural integration (Hermannsdorfer and Rub, 2005).

Integration on existing buildings unavoidably tend to be more fragmented than on new buildings, since they have to comply with an existing context. As standardized products are often not applicable, the situation calls for innovative

approaches. Existing buildings, monuments and landscapes mainly call for a slight integration of the technological components such as PV and STC systems into the given context (Hermannsdorfer and Rub, 2005). In case of new buildings, integration becomes much easier and renders quality if it is thought of right from the conceptual stage

#### 1.4 Research Question

With a brief explanation of PV and STC integration into the buildings above, I have formulated a research question in order to focus the study basically on the aesthetics or formal aspect of integration. The question is:

*How can the Photovoltaic and solar thermal collector systems be integrated into buildings to serve the dual purpose of generating solar energy and enhancing architectural quality?*

I have tried to answer the above question in a structured form by studying, analyzing and explaining all aspects related to the architectural integration of these PV and STC systems. The following supporting questions will further help find answer to architectural integration in a more simple way. The whole thesis is the answer to these questions.

- *What is the difference between architectural integration and building integration? What is architectural integration of Photovoltaic and solar thermal collector systems?*
- *What are the challenges between integration into existing and new building?*
- *Does integration of these systems really boost the architectural quality of the buildings?*
- *To what extent can energy generation be compromised over architectural aesthetics and vice versa?*

## **1.5 Scope of Research**

The research is basically confined to the architectural integration of PV and STC systems into buildings, both new construction and existing. I have not considered integration into urban spaces and landscapes rather focused on integrating into buildings on individual basis. Different aspects of integration have been explained with relevant examples to make the study illustrative and easy to understand.

## **1.6 Structure of thesis**

The main objective of this study is to find out different possible and relevant ways of architectural integration of PV and STC systems into buildings mainly in order to enhance the overall architectural expression of the building in addition to using them as building elements. It is done with an aim that if these systems help enhance the quality of architecture and will appeal both the building owners and designers; they will definitely develop as regular and normal building components in the days to come.

The study begins with a brief theoretical study of the systems in the 2<sup>nd</sup> chapter highlighting some technical aspects that is important in the integration process. The 3<sup>rd</sup> chapter is an attempt to understand architectural integration by answering to some aspects in the research question. Then the integration of PV and STC systems are discussed separately in the 4<sup>th</sup> and 5<sup>th</sup> chapter. Chapter 6 basically talks about the quality of architectural integration on the basis of functional, construction and formal issues. The formal issues related to architectural integration is the main focus of the thesis. Guidelines have been drawn in chapter-7 underlying various aspects that will elaborately address and influence the visual expression of the buildings. With these guidelines as the point of departure, an attempt has been made to compare the two solar technologies in terms of their architectural integration abilities in chapter-8. Before concluding, architectural integration evaluation of some selected projects have been made based on the type of systems integrated in chapter-9.

## **2 LITERATURE**

### **2.1 Photovoltaic**

It has been long until electricity was actually generated from photovoltaic since the discovery of photovoltaic effect in 1839 (EERE). These systems are usually based on silicon and are used to convert solar radiation into electricity. Direct current (DC) is generated when the devices are exposed to sunlight. The electricity generated is either used directly into DC appliances or converted using inverters to run AC appliances. The DC current can also be stored in batteries for use during the night when the PV systems don't produce electricity. PVs respond to both direct and diffused radiation and the output increases with increasing sunshine which is called irradiance while decrease with the module's rise in temperature. Common PVs available are mono-crystalline silicon, polycrystalline silicon and thin film silicon called amorphous silicon (A-Si) (Thomas et al., 2001).

#### **2.1.1 Photovoltaic Cells**

Photovoltaic systems are sustainable, environmental friendly, quiet, light and require minimal maintenance as they have no moving parts. In a PV system, cells combine to form modules, which give the system the flexibility to be expanded or reduced to suit any given application. The versatility of PV panels gives numerous possibilities for their integration into new and existing structures. Although the most commonly used cell types come from the same base material silicon, different technologies offer cells with different technical and aesthetic characteristics.

##### **2.1.1.1 Mono-crystalline cells**

Mono-crystalline cells are cut into thin wafers from a singular continuous crystal that has been grown for this purpose, hence are also called single crystal cells. To minimize waste, the cells may be fully round or they may be trimmed into other shapes, retaining more or less of the original circle. As each cell is cut from a single crystal, it has a uniform color (Solar, 2011). Mono-crystalline silicon modules normally appear as a solid colour, ranging from blue to black. A wide variety of colours is available but these are of lower efficiency. Eg:

magenta or gold results in a loss of 20% efficiency (Reijenga and Kaan, 2011; Thomas et al., 2001). These cells are around 10 x 10 cm<sup>2</sup> and 350 micron in thickness with an efficiency of up to 14-17%. They produce, on average in European weather, 900-1000 kWh per each kW installed (Fuentes, 2007; Thomas et al., 2001).

### 2.1.1.2 Poly-crystalline cells

Polycrystalline cells are made from similar silicon material to that of the mono-crystalline except that instead of being grown into a single crystal, they are melted and poured into a mold. This forms a square block that can be cut into square wafers with less waste of space or material than round single-crystal wafers. As the material cools, it crystallizes in an imperfect manner, forming random crystal boundaries (Solar, 2011). Polycrystalline cells with equal dimensions reach a performance of up to 12% and would produce on average 750-850 kWh per each kW installed in European weather (Fuentes, 2007; Thomas et al., 2001).

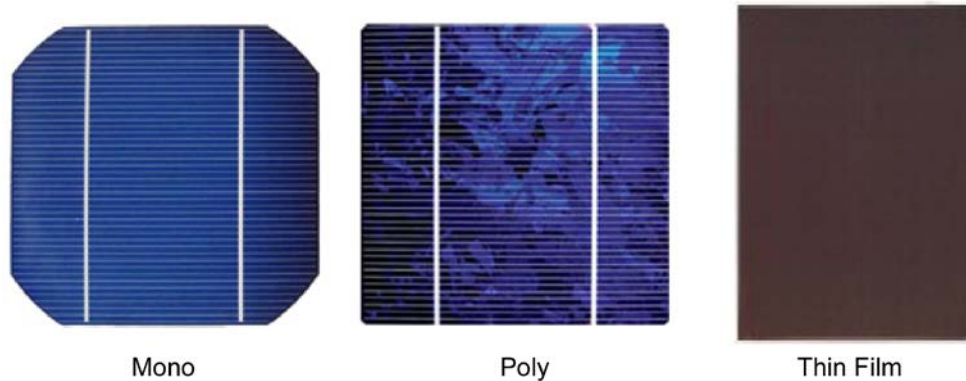
### 2.1.1.3 Thin-film cells

This latest technology of thin film is either from silicon or produced from a new base materials, such as Gallium- Arsenide (GaAs), Cadmium-Telluride (CdTe) or Copper-Indium-Diselenide (CIS). These cells also called amorphous (Solar, 2011) protected by means of encapsulation with front glass and back protection, resulting in PV modules. Thin-film cells have efficiencies up to 5-8% and produce in average 600-800 kWh per each kW installed and are available in range of colours (Fuentes, 2007; Thomas et al., 2001).

Table 2.1: Efficiencies of different types of cells

	Type	Appx. Cell Efficiency	Appx.modular Efficiency	Area Requirement
1	High performance hybrid silicon		17-18%	6-7m <sup>2</sup> /kW <sub>p</sub>
2	Mono-crystalline silicon	13-17%	12-15%	7-9m <sup>2</sup> /kW <sub>p</sub>
3	Polycrystalline silicon	12-15%	11-14%	7-10m <sup>2</sup> /kW <sub>p</sub>
4	Thin-film CIS		9-99%	9-11m <sup>2</sup> /kW <sub>p</sub>
5	Thin-film CdTe		6-8%	12-17m <sup>2</sup> /kW <sub>p</sub>
6	Thin-film amorphous silicon		5-7%	14-20m <sup>2</sup> /kW <sub>p</sub>

Source:(Roberts and Guariento; Thomas et al., 2001)



**FIG 2.1: Types of photovoltaic cells**

credit: <http://www.pvsolarchina.com/>

Besides the above mentioned, there are a wide range of new PV technologies being researched and developed in the pursuit of higher performance. HIT (heterojunction with intrinsic thin-layer) is a hybrid construction of a crystalline and thin-film silicon cell. Amorphous silicon is coated onto both front and rear faces of a monocrystalline silicon wafer. These cells are more efficient compared to monocrystalline silicon and have less degradation of efficiency with increase in operating temperature. This technology is used in Vauxhall transport interchange (fig 2.2), London UK which is excellent showcase for PV integration (Roberts and Guariento).



**FIG 2.2: Vauxhall transport interchange**

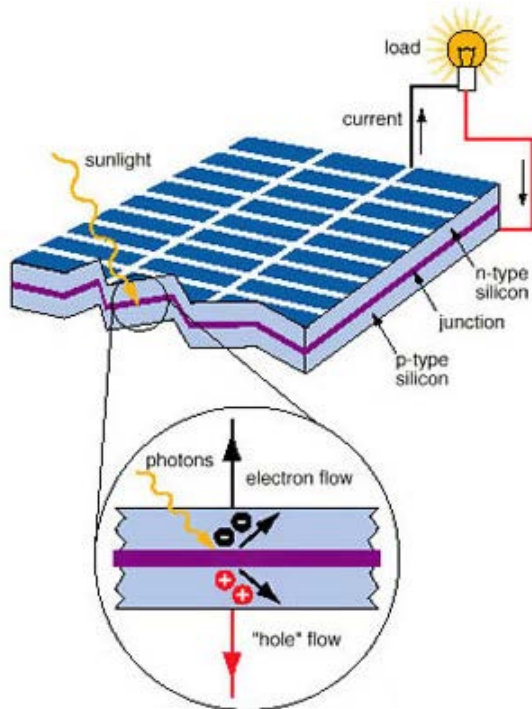
Credit: (Roberts and Guariento)

*Vauxhall transport interchange is a good example of the integration of HIT P. The PV modules are incorporated in the sloping sections (forks) of the canopy at an angle of 20° to the horizontal and 25° west of south-facing. The canopy which takes the form of a sculptural ribbon running the length of the bus station provides shelter from rain and wind. Each fork*

*carries 4 sub-arrays of 21 modules, which are connected back to the PV distribution board. The PV units replace the stainless steel cladding panels of the top portion of the canopy. The wireways, trunking and junction boxes are located underneath the*



waterproof membrane, in the void of the canopy structure. Each fork is provided with a walkway for further maintenance and replacement of the solar arrays (Sohie, 2003; EST, 2006).



**FIG 2.4: The photovoltaic principle,**  
Credit: [http:// clengreenenergyzone.com/](http://clengreenenergyzone.com/)

Crystalline silicon cells consist of p-type and n-type silicon. The cells, which are of low voltage, are joined in series to form a module of higher, more useful voltage. The modules are constructed like a sandwich and have a backing sheet and a cover of low-iron glass which protects the front surface of the material while maintaining high transmissivity (Thomas et al., 2001). The backing sheet does not necessarily have to be opaque. It could be glass as in Doxford Solar Office, the PV cells are encapsulated between two

layers of glass with transparent spacing between cells; thus light passes through the transparent areas (fig 2.3). Crystalline silicon modules come in a



**FIG 2.3: Doxford Solar Office**  
Credit: <http://www.studioe.co.uk/>

variety of sizes and shapes. With larger modules cost reductions are possible through lower wiring costs and simple framing arrangements.

Polycrystalline modules are normally blue although other colours are also available. The

appearance of thin-film cells is uniform with a dark matt surface with colours ranging from grey, brown and black (Reijenga and Kaan, 2011; Thomas et al., 2001).

PVs (Thomas et al., 2001; Fthenakis et al., 2008) have longer life span of more than 20 yrs with rated output of at least 80% and energy payback period for the production is 5 yrs. They have the significant advantages of reducing emissions which is very important from environmental perspective. In general for the manufacturing processes for crystalline silicon and amorphous silicon there are no environmental issues which raise concern. Some reservations have been expressed about the environmental impact of new materials, particularly cadmium telluride. However, the production process can be designed so that cadmium is not emitted and manufacturers are actively developing recycling techniques to avoid disposal problems (Thomas et al., 2001). Overall, all PV technologies generate far less life-cycle air emissions per GWh than conventional fossil-fuel based electricity generation technologies and at least 89% of air emissions associated with electricity generation could be prevented if electricity from photovoltaic system displaces electricity from the grid (Fthenakis et al., 2008).

The output from the PV array will depend on (Thomas et al., 2001):

- The daily variation due to the rotation of the earth and the seasonal one due to the orientation of the earth's axis and the movement of the earth about the sun
- Location, (the solar radiation available at the site)
- Tilt.
- Azimuth, (orientation with respect to due south)
- Shadowing
- Temperature, (The drop in performance is more marked for crystalline silicon than amorphous silicon. Designs for building-integrated PVs need to consider this from the very beginning in order to allow air to flow over the backs of the modules to maintain high performance.)

### **2.1.2 PV modules**

PV cells are arranged together to form modules. The modules are designed for outdoor conditions, so they are able to be part of the building skin. However, different encapsulation technologies result in a range of PV panels having different performances as a constructive element like glass-plastic or glass-glass back sheet. Standard modules have an aluminium frame. Modules without a frame, also called "laminates", are more commonly used for building integration (Fuentes, 2007).

## **2.2 Solar Thermal Collectors**

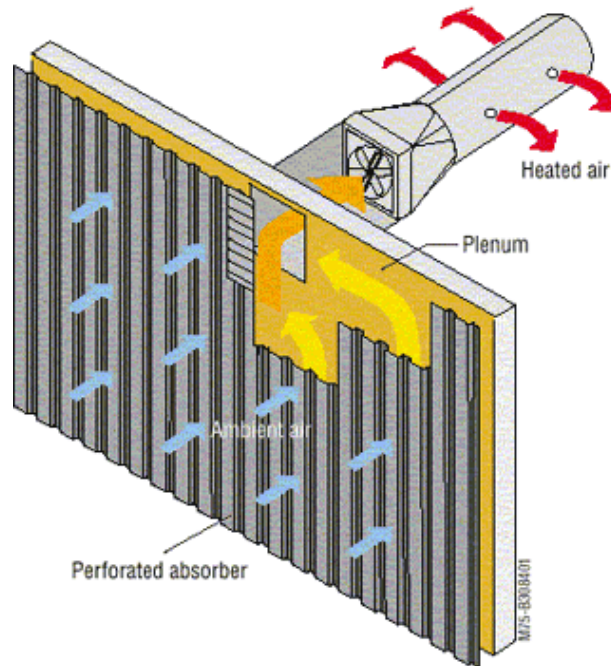
Solar thermal collector is a device which absorbs the incoming solar radiation, converts it into heat, and transfers this heat to a fluid (usually air, water, or oil) flowing through the collector. The solar energy thus collected is carried from the circulating fluid either directly to the water or space conditioning equipment or to a insulated storage tank from which hot water can be drawn for use even during nights and in cloudy days (Kalogirou, 2004; Probst, 2009).

Maria Probest (2009) in here Ph.D thesis have described this STC system as active. Energy when collected on surfaces optimized for heat collection called absorbers which are placed on the outside of the building envelop and transported by a medium either directly to the place of use, or to a storage to be used when needed is commonly known as active system. According to the medium used, active systems are mainly of two types: air collectors and water collectors.

### **2.2.1 Air-based collector systems**

These are primarily designed for preheating ventilation air or for space heating. When used for preheating ventilation air, the collectors are often placed on the façade close to where the fresh air enters the building. This results in short ducts, as well as higher efficiency during the space-heating period (favourable inclination at low solar angles). An air-based collector system is usually designed to make use of the building structure for heat storage, although separate storage elements are sometimes used. The use of a central air-handling system or a double-envelop façade also makes it suitable to use air-

based collectors on the roof (EAESL, *Transpired air collector*). In a report by International Energy Agency task 20 (Haller et al., 1999), it is stated that most air-based collector systems used in renovation projects have so far been more or less special designs.



**FIG 2.5: Air based collector system**

Credit: <http://www.daviddarling.info/>

### 2.2.2 Water-based collector systems

These cost effective systems are also called hydraulic collectors. These allow easy storage of solar gains and are suitable both for domestic hot water production and space heating. Their medium consists mainly of water charged with glycol in variable percentages to avoid freezing according to the specific climate. Since water has a good thermal capacity, it is capable of good quality of heat exchange both with the absorber and the storage. The solar energy gained can easily be stored in insulated water tanks and used for domestic hot water or for space heating. According to the technology, hydraulic systems can be divided into four types as: evacuated tubes, glazed flat plate collectors, unglazed flat plate collectors and unglazed plastic collectors (Probst, 2009; Probst and Roecker, 2011).

### 2.2.2.1 Evacuated tubes collectors

Evacuated-tubes collectors are composed of several individual glass tubes, each containing an absorber plate bonded to a heat pipe and suspended in a vacuum. The great insulation power of vacuum allows working at very high temperatures even in cold climates mainly due to low heat loss. These systems are suitable for domestic purpose for heating water and spaces and also for industrial applications where high working temperature is required. Their flexibility to orient the inner absorbers independently from the module mounting angle as in (fig 2.6) is an advantageous feature of this type of collector (Probst and Roecker, 2011).



**FIG 2.6: (Left) evacuated tubes**

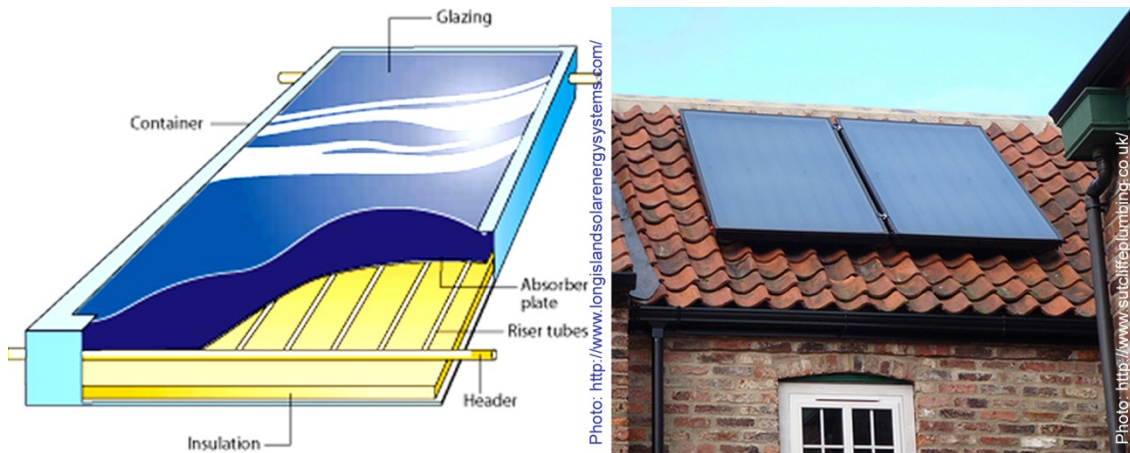
credit: Maria Cristina

**(Right) evacuated tube collector set**

credit: <http://greenbrotherservices.blogspot.com/>

### 2.2.2.2 Glazed flat plate collectors

These are most common collectors used for domestic hot water and space heating. A flat-plate collector consists basically of an insulated metal box with a glass or plastic cover (the glazing) and a dark-coloured absorber plate. Solar radiation is absorbed by the absorber plate and transferred to a fluid that circulates through the collector in tubes (fig 2.7). These collectors heat the circulating fluid to a temperature less than that of the boiling point of water and are best suited to applications where the demand temperature is 30-70°C and/or for applications that require heat during the winter months (Foster et al., 2009; Probst, 2009).



**FIG 2.7: (Left) Parts of flat plate solar thermal collector**

**(Right) Collectors on to the roof**

Credit: <http://www.longislandsolarenergysystems.com/>

Credit: <http://www.sutcliffeplumbing.co.uk/>

### 2.2.2.3 Unglazed flat plate collectors

Unglazed flat plate collectors are technically less complex than glazed or evacuated collectors. They are made of fewer layers and can be assembled without the need for different jointing. These are composed of a selective metal plate which is the absorber, an hydraulic circuit heated up by the absorber and by a back insulation. As opposed to the glazed collectors, the absorber is not insulated by a covering glazing and working temperatures are also comparatively lower. These collectors can easily reach temperatures of 60-65°C, and can be used for swimming pools, for low temperature space heating systems, and for DHW pre-heating (Probst, 2009). A special type of unglazed collector called a perforated plate collector is used to preheat ventilation air for commercial buildings (Foster et al., 2009).

Unglazed flat plate collectors of several commercial types are not as widely used as typical solar collectors with glazing. The absence of the protective transparent cover contributes to the reduction of optical losses, but the direct exposure of the absorber to the ambient air increases the thermal losses by radiation and convection, with a significant sensitivity of the absorber to wind speed, making the unglazed collectors suitable for efficient operation only in low temperatures. On the other hand, the low cost of unglazed collectors is an advantage for cost effective solar thermal energy applications in this temperature range, e.g. water preheating for domestic or industrial use, water

heating of swimming pools, space heating, air heating for industrial or agricultural procedures, etc.(Tripanagnostopoulos et al., 2000).



**FIG 2.8 (Left) Unglazed flat plate collectors integrated on the façade, (Right top, bottom) Unglazed flat plate collectors integrated on the roof**

Credit: Energie Solaire

#### **2.2.2.4 Unglazed plastic collectors**

Collectors of this type are usually made of black plastic or rubber that has been stabilized to withstand ultraviolet rays, and are not insulated (fig 2.9). However, because they are not insulated a large portion of the heat absorbed is lost, particularly when it is windy and not warm outside. They transfer heat so well to air and from air that they can actually capture heat during the night when it is hot and windy outside. Due to their very low working temperatures they are only useful for swimming pool water heating (Probst, 2009; EAESL, *Solar thermal systems*).



**FIG 2.9: Unglazed plastic collectors**

credit: <http://www.solarexpert.com/>, <http://www.daviddarling.info/encyclopedia/>

### 2.3 PV and STC Integration

The usual practice has been the installation of PV and STC panels on flat and tilted roofs in buildings. This is more common in areas near the equatorial region where the sun's position is usually high all round the year. The integration of these technologies into facades also offers tremendous potential, especially in countries in the northern latitudes like Norway with low sun. Integrating PV and STC into new and existing architecture offers great possibilities for the design of energy efficient and ecologically sound buildings, without compromising comfort or aesthetics. These systems not only offer design benefits but also cost benefits. Integrated PV panels, in addition to generating electricity also acts as part of the building fabric. This combined function can result in cost savings where the cost of traditional building fabric is comparable to that of the PV panels. Also, no additional land or separate support structure is required, giving further cost advantages (Fuentes, 2007; Voss et al.). Same advantage is achieved with the integration of STC systems as well.

Although the production cost of electricity is much higher compared to that from a conventional source, the cost of producing electricity from PV has fallen marginally in the last ten years as a result of constant improvements in PV technology, integration techniques and increased production volumes (Fuentes, 2007; Voss et al.). With this fall in the price set to continue against a background of prices of fossil fuel rising, the economic benefits of PV will continue to rise. Building Integration of these systems help designers to meet



goals of sustainability and reduced emissions while maintaining or improving comfort. The synergy between integrated PV or STC's main functions of on-site energy generation and forming part of the building fabric, along with increasing cost competitiveness makes integration an especially attractive option. (Fuentes, 2007).

### **3 ARCHITECTURAL INTEGRATION AND BUILDING INTEGRATION**

#### **3.1 Building Integration**

The PV and solar thermal collector systems when integrated in a building, become part of the general building design and also often become general building elements (Hestnes, 1999). From economical point of view, it is necessary that the systems are integrated into the building envelop so that no extra investments on the support structure is needed. These systems must replace the conventional building elements in addition to their ability to produce energy and serve dual function to reduce the total cost. Hence, the energy systems in a building must be designed as an integral part of the whole; ie, a 'holistic' approach to building design should be approached. These systems must be taken very early in the design phase and should not be treated as separate elements that are added after the design or building is completed.

Example of the largest solar thermal project integration is seen in the "Solar City", housing development in the suburb Plan-les-Quates, Switzerland (fig 3.1). Integrating the systems on the roof was thought of right from the conceptual design phase. These collectors cover the entire south facing part of the roof replacing the traditional roofing materials, thereby reducing the total cost of the project. In addition to energy production for space and water heating, the aesthetics of the building is enhanced by the elegant curvature of the roofs. In summer the excess energy production is sold to neighbouring buildings (Hestnes, 1999).

The terms component integrated and building integrated photovoltaics (BIPV) refers to the concept of integrating photovoltaic elements into the building envelope, establishing a symbiotic relationship between the architectural design, functional properties and economic regenerative energy conversion (Odersun, 2011). The photovoltaic modules thus replace conventional construction materials, taking over the function that these would otherwise perform. Although this idea is not new, it is not widely harnessed due to the extensive planning and architectural challenges currently involved.



**FIG 3.1: Elegant use of solar thermal collectors on the curved roof of 'Solar City', housing development in the suburb Plan-les-Quates, Switzerland**

credit: (Hestnes, 1999)

In principle, BIPV can be used in all parts of the building envelope. Although roof surfaces are the preferred area for installing PV elements due to their advantageous irradiation values, façades also offer enormous potential specially in Nordic region where the angle of the sun is low all throughout the year. The ratio of façade surface area to roof surface area increases along with the building height. In addition, the available roof area is often reduced due to the installation of facilities and superstructures, which means that BIPV façades are of particular value in high-density urban centers. Besides, with the availability of thin-film PV, integration into the facades has become even more relevant (Odersun, 2011).

In building or architectural integration, besides producing energy; the active solar elements have to play the same role as the traditional wall, windows or roof cladding elements they replace. Roberts and Guariento in their handbook of BIPV have said that the requirements that must be addressed by building integrated active solar systems are colour, image, size, weather-tightness, wind loading, durability and maintenance, safety during construction and in use (fire, electrical, stability) and cost.

Building integration concerns the physical integration of a PV or STC system into a building, with the emphasis of overall impression they give to the building. For the architect, the aesthetic aspect, rather than the physical integration, is the main reason for talking about building integration. The optimal situation is a physically and aesthetically well-integrated system. In fact, many examples of physical integration show a lack of aesthetic integration. Visual analysis of solar systems in buildings shows that the look of a poorly designed building does not improve, simply by adding a well-designed system. On the other hand, a well-designed building with a nicely integrated solar system will be accepted by everybody (Reijenga and Kaan, 2011).

### **3.2 Difference between architectural integration and building integration**

The answer to this is to look for different types of integration. It is usually possible to do architectural integration, ie, integrate the systems in an architecturally good way so that the aesthetics of the building is enhanced. However, it may always not be that easy to do building integration.

Most of the times, the PV or collector systems on the buildings are either architecturally integrated or building integrated or both. These systems doesn't have to be building integrated to achieve architectural integration. It can be further said that building integration is architectural integration but all architectural integration is not building integration. When the process of integration enhances the architectural quality of the building, it is called architectural integration. So, in a building integrated PV roof, the roof may be specially manufactured with PV already fixed as the external part of the roof. In case of architecturally integrated PV roof; PV modules can be laid as normal roofing element with normal construction techniques. In both the cases, the integration may add on to the aesthetics of the roof and the whole building and hence called architectural integration. Integration also doesn't mean that the PV and STC systems are used in such a way that they are not recognizable. It isn't necessarily wonderful or important that the integrated PV and collector system is 'hidden' and not shown.

In practice, energy output of PV and STC systems may have to be compromised over architectural integration. Which means, in an approach to use these systems in such a way that the building's architectural expression is enhanced; they may not be located in the best position, direction and orientation. It is necessary to compromise but the best thing would be not to compromise. Due to practical reasons, there are compromises. We must be more innovative and creative enough to tackle this (Hestnes, 2012).

### 3.3 Does architectural integration really boost aesthetics of a building?

When the PV and STC systems are part of the architectural composition, they are architecturally integrated. Architectural integration is an important topic in an old building compared to a new one if the integration adds value to the aesthetics of the building as is done in one of the buildings at NTNU. A glass facade with PVs is added on the south facing wall of the building. The solar wall made the building look 'nicer' than it used to be (fig 3.2). Architectural integration has enhanced the architecture of a boring looking old building on the left giving it a better look on the right. While working with an old building, it would be wise to make a note/list of elements that we want to keep and some others that we want to enhance (Hestnes, 2012).



**FIG 3.2: (Left) Office building at NTNU before PV integration, (Right) Same building after PV integration on the glass façade**

credit: www.sintef.no/

credit: Author

The same principle of integration may not look elegant incase of a recessed balcony for example. A balcony which is into the building may be made warmer by glazing it on the outside. Of course, the thin film PV systems could also be

integrated into the glass. However, the consequence is that the façade becomes two dimensional, plain and boring.

If a new building integrating PV and solar thermal collector systems is to be designed, the concept is usually driven by these systems and so, the final result may turn out high-tech. However, in case of an old building, the design, layout and use of these active systems is actually driven by the architecture and colour of the building.

### **3.4 What are the challenges between integration into existing and new building?**

Existing or historic buildings, like new buildings, offer a broad range of possibilities for PV and STC system integration. However, installations on existing buildings unavoidably tend to be more fragmented than on new buildings, since they have to comply with an existing situation. As standardised products are often not applicable, the situation calls for innovative approaches with custom made products (Hermannsdorfer and Rub, 2005). It is always not an easy task to make integration in an existing building due to various practicalities. Integration task will have to be planned according to the situation observed on site which varies from building to building.

In case of historically important building, sometimes the PV and thermal collector systems might have to be integrated somewhere else other than the building itself, if there are regulations not to make interventions. In some cases little intervention is allowed like the church in Carlow, Germany (fig 7.1). The church was equipped with PV in the course of roof repairs. The polycrystalline module was produced to match the existing roof tiles in shape and colour; one photovoltaic module replaced six roof tiles. The PVs are integrated into only a small part of the roof replacing the normal roofing material. Thus the historical appearance of the church was maintained as stipulated by the monument protection authority (Hermannsdorfer and Rub, 2005).

In case of new buildings, integration of PV or STC systems is conceived from very early stage of the design. As such, these systems will be an integral part of the design concept; forms may be derived accordingly and material use

determined as well. The solar cells are interesting as a material when integrated in the architectural concept. The possibilities of working with PVs or STC as a part of the concept have varied. This depends much on when these systems are introduced in the project (Lundgren and Torstensson, 2004). In this way, integration in new buildings looks comparatively easier than the existing ones as these solar systems will be used accordingly after appropriate design have been developed.

### **3.5 Good Integration**

PV and STC systems that are architecturally pleasing within the context of the building, good material and colour composition, that adapt well to overall modularity, the visual aspect of the grid which is in harmony with the building and creates a satisfactory composition will result in good integration and renders high architectural quality (Roberts and Guariento). Further, these systems that are appropriate to the context of the building and the integration of which is well designed and their use has generated an innovative concept will often make the architectural integration rich and successful.

### **3.6 Integration of PV and STC modules in buildings**

For architects, the application of PV and STC systems in buildings must be part of a holistic approach. A high-quality of these solar systems can provide a substantial part of the building's energy needs if the building has been designed in the right way. By holistic approach, integrating these systems does not only mean replacing a conventional building material, but also aesthetically integrating it into the design which is called architectural integration. The integration also takes over other functions of the building's skin. Mounted on a sloped roof for instance, profile systems mean that PV or STC modules can be part of the watertight skin. A distinction can be made between literal integration of these systems in the building skin as cladding elements or integrated into the roof or as building components like awnings, shading devices etc. (Reijenga and Kaan, 2011).

The aim of architectural and building integration of these systems into buildings is to reduce the requirement for land and the costs, in addition to aesthetics

that is generated by the process. This could be the cost of support construction and the cost of building elements, such as tiles and cladding elements. It is evident that PV and STC systems integrated into buildings give a more elegant look and is more efficient to integrate these systems when constructing the building, rather than mounting it afterwards. Usually there are three locations for integrating these systems into buildings. They are the roofs, facades and building components like balcony railings, sunshades and sunscreens(Reijenga and Kaan, 2011).

### **3.7 Integration Method**

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

#### **3.7.1 Superimposed**

This is a simple method well suited in case of existing buildings. The solar modules are mounted on a structure; for eg: roof, on the building envelope and in parallel with them. There is no savings in substituting elements as the materials underneath the solar modules are not replaced (Fuentes, 2007). With superimposition, architectural integration can still be achieved as the buildings can be made elegant. If this is the case, it may also be called architectural integration but is certainly not building integration. However, the scope of the thesis is to emphasize more on architectural integration that is also building integration.

#### **3.7.2 Integrated**

The PV and STC systems are used both as an architectural element as well as a means of energy generation. This method is most likely to be suitable for new buildings. The traditional constructive elements are substituted for PV and STC materials. Savings are possible where the cost of the substituted elements is below that of the traditional elements. It offers a pleasant and clean appearance (Fuentes, 2007). The most common integration types and techniques are discussed in the following two chapters.



## 4 INTEGRATION OF PHOTOVOLTAICS

With the discovery of photovoltaics, the building's skin is found to have the capacity to produce energy as well. Photovoltaic modules are in most cases still considered to be technical devices that need to be adjusted to the building skin, despite the fact that a variety of products that convert them into building components have been developed lately. However, in case the solar module becomes part of the building skin, it gains multiple functions and requires aesthetical integration into the overall design concept (Farkas, Facade Integration Typologies of Photovoltaics). Both roofs and facades can be explored for the architectural potential of integration. Inclined and pitched roofs are equally visible as facades are, and hence can provide architects with both opportunities and challenges for architectural integration. Any part of the roof or external walls that is well-exposed to sunlight e.g. skylights, claddings, windows, external shading devices and railings can be used for PV integration. On non-exposed or other surfaces where PVs are not considered integrating or are not suitable, the use of dummy<sup>1</sup> elements could be the possible option. With this uniformity can be achieved.

Integration of PV into buildings have the following advantages (Reijenga and Kaan, 2011; Voss et al.):

- Part of building is used for PV installation and so additional land is not required. This is particularly significant in the densely populated areas in the cities.
- The cost of the PV wall or roof can be offset against the cost of the building element it replaces.
- Power is generated on site and replaces electricity that would otherwise be purchased at commercial rates and avoids distribution losses.

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<sup>1</sup> Dummy: non-active elements with a similar appearance, fulfilling only the construction function

- PV, if grid connected ensures security of supply and high cost of storage is avoided.
- Architecturally elegant, well-integrated systems will increase market acceptance.

#### **4.1 Roof Integration of PV**

A PV system can be integrated into the roof in several ways. One choice is for the integrated system to be part of the external skin and therefore part of an impermeable layer in the construction. The other type is that the PV is glued onto insulation material. This type of warm roof construction system is very well suited to renovating large flat roofs. Using PV modules as roof covering reduces the amount of building materials needed, which is very favourable for a sustainable building and can help to reduce costs. There are also many products for small-scale use to suit the scale of the roof covering, for eg., PV shingles and tiles. The small scale of these products makes them very convenient for use in existing buildings. Transparent PV modules used as roofing materials serve as water and sun barriers and also transmit daylight. In glass-covered areas, such as sunrooms and atriums, sun protection on the roof is necessary in order to avoid overheating in summer. The PV cells absorb 70-80% of the sun radiation. The space between the cells transmits enough diffused daylight to achieve a pleasant lighting level in the area as through the double glazed roof of Café Ambiente in Germany ( fig 4.1) (Reijenga and Kaan, 2011).



**FIG 4.1: PV integrated double glazed roof of Café Ambiente, Germany**  
credit: <http://www.pvdatabase.org/>

PV cells convert sunlight into electricity (typical efficiencies of 6-18%) with the remainder of the solar energy being converted into heat. At the project 'Haus de Zukunft' in Linz (Austria), this residual heat is also used to warm the home. An air cavity has been created underneath the PV modules, through which warm air heated by the PVs above, is exhausted. The hybrid collector provides warm air to the heating system in the home, which in this case, makes it a cost-effective use of the collector.

A relatively new application of PV combined with a thermal system is PVT: a PV module mounted on a solar thermal module. The residual heat is used to heat the liquid in the thermal system (Reijenga and Kaan, 2011). The facade of Fiat Research Center (fig 4.2) has dual functions of electrical and thermal energy generation. The photovoltaic elements, that has a total power of 19.5 kWp, produces electric energy, while the forced air circulation beneath the modules recovers the thermal fraction of captured solar radiation and cools the cells as well. The electricity generated by the photovoltaic panels is used to feed a heat pump and internal electrical requirements. The produced heat is used by the air conditioning plant of the kitchen: in winter for pre-heating of the renewal air and in summer to feed the system of dehumidification (Solar plaza, 2009).



**FIG 4.2: PV combined with a thermal system (PVT) façade of Fiat Research Center**

Credit: <http://www.solarplaza.com/>

#### **4.1.1 PVs on flat roof**

PVs laid horizontally on the flat roofs are normally not visible from the ground and hence the significance of aesthetic part of integration can be less. However, from efficiency view point, mono and poly-crystalline PV systems produce the most energy when their angle is optimised to that of the sun. So, usually it may not be a good idea to lay these cells horizontally on the flat roofs both from aesthetic point of integration and energy yield. Unlike to this, thin films work equally well even when laid horizontally on flat surfaces proving to be the best options for integrating into flat roofs. However, installing the PV systems in an angled position on the flat roof may not play a positive role in adding to the aesthetics of the building and hence may not be termed as architectural integration.

#### **4.1.2 PVs on Inclined/ Pitched roof**

Photovoltaic facilities on inclined or pitched roofs when facing in the right direction is suitable for good energy yield. Architectural aesthetics should be taken into consideration while integrating as these are visible parts of the building unlike the flat roofs. PVs can be integrated as a combined roof elements or they can be added to the roof structural system and has been termed as 'retrofits' (Solstice energy, 2012). In retrofits, PV modules are laid

onto the existing roof above the roofing material. The modules are held on to the rails which are clamped by roof hooks from under the tiles. In this case the PV module is not a multifunctional element and usually the aesthetics is lost if the colour of the roofing material is different from that of the PV (fig 4.3, left).



**FIG 4.3: (Left) PV modules added on to the roof as pure technical element, (Right) Semi-integrated PV modules on the Roof**

Credit: <http://www.solarplaza.com/>, <http://www.energyenv.co.uk/>

Semi-integrated mounting keeps the modules much closer to the existing roof-line than retro-fitting to give a more integrated appearance. This method avoids wasting slate or tiles in the case of a re-roof or new build, and also keeps the roof weight to a minimum. There will be no future problems of loose or damaged tiles underneath the modules, and any future re-roofing can be done around the PV array without needing to dismantle it (Solstice energy, 2012). This method can be called building integration and the appearance may be a little better than the retrofit option. However, this may not always be called an architectural integration unless the overall expression is enhanced by the integration of the PV modules. In the figure 4.3 (right), the PV is integrated in the same method but has not been able to enhance the architectural quality of the building satisfactorily.

On new buildings or where a house is being re-roofed, roof integration can be done in a way that the overall expression is enhanced. The integrated PV system usually works as a multifunctional element. In this case whole roof may have the PV modules laid in clean line and finish replacing the conventional roofing materials as in the the vacation house Bartholomä-Park in Germany (fig 4.4, left). It is a small building with a special inclined roof design (alignment

east/west), whereby the roof is completely designed with an integrated photovoltaic system. The system is installed with a drainage canal over the roofing battens and the modules are designed with double glass (PV Database). In the Schlierberg Solar Settlement in Freiburg, the houses are covered with PV integrated roofs (fig 4.4, right)



**FIG 4.4: (Left) Integrated PV on the pitched roof of vacation house Bartholomä-Park in Germany  
(Right) Integrated PV roofs in Schlierberg Solar Settlement in Freiburg**  
Credit: <http://www.pvdatabase.org/>, <http://www.rolfdisch.de/>

### 4.1.3 Roof with integrated PV tiles

It has been a normal practice to lay or integrated larger standard modules of PV on the roof for energy yield. However, when the integration is to be done on traditional tiled roofs, it may always not be possible to use large modules and the character of the roof may also be ruined. To overcome this, photovoltaic roof tile was developed which would of course resemble the standard tiles. They can be produced with similar colours and dimensions to that of the normal tiles. The advantage of PV tiles or shingles over panels is that they look similar to roofing tiles, are available in different colours and are aesthetically more pleasing, having features of a good architectural integration.

Photovoltaic tiles are attached to standard timber roofing lathe which is fixed to the rafters. The PV tiles function as traditional tiles, protecting the building from the elements and they integrate with a wide range of commonly available roof tiles as in figure 4.5 below (Horizon Renewables, 2010).



FIG 4.5: Integrated PV roof tiles on the roof

#### 4.1.4 PV in saw-toothed north light roof/ sky light

Saw-tooth roofs can be implemented as (semi-)transparent or opaque. Glass saw-tooth roofs make optimum use of daylight, protect against direct sunlight, and thus minimise a building's cooling loads. The world's largest Integration of thin-film PV systems on the saw-toothed glass roof of Paul Lobe Haus, Berlin optimizes interior light conditions in addition to producing clean energy (fig 4.6, left) (CBD Energy).



FIG 4.6 (Left) Integrated PV on the saw-toothed glass roof of Paul Lobe Haus, Berlin (Right) Sawtooth roof with PV integration, DIY store, Hamburg

Credit: Credit: <http://www.cbdenery.com.au/>, <http://www.solarfassade.info/>

#### 4.1.5 PVs on Curved roof/wall

The flexibility with the integration of PV is further emphasized by the fact that PV modules can also be mounted on curved load-bearing surfaces. Arched surfaces and roofs are equally suited for use with PV systems. This allows added freedom of design involving PV integration. The BP solar Showcase in Birmingham, UK is a good example of PV integration on curved roof (fig 4.7).

It was designed as a prototype building, showing the integration of PV cells into the energy efficient domestic and commercial buildings. The use of PVs was the driving force behind the construction of this pavilion, and the embracing architectural concept and expression of the solar paths. The solar units are inherently part of the south-facing solar wall/roof cladding system. The wall is curved and angled to optimise absorption of the solar energy and maintain a nearly constant electrical output, whilst also shading the east and west vertical walls to protect against excessive solar gain. The mono-crystalline PV installation with a peak power generation of 15kW is used to operate ventilation, lighting and electrical equipment. The excess power is fed to the national grid and imported during the night(Sohie).



**FIG 4.7: PV integration on the curved roof of BP solar Showcase in Birmingham**  
Credit: <http://www.solartechnologies.co.uk/>



#### 4.1.6 PVs in Atrium/skylights

PVs can equally be integrated as multifunctional elements in transparent roof structures or atriums that allow controlled light into the interior. As semitransparent roof units, they can protect the building from heat, sunlight, glare and the weather. One way of integration would be to place small sized PV cells on the atrium glass creating transparent gaps between them to allow controlled daylight into the interior of the building. Well designed PV integrated atriums may also be a strong feature of the building when viewed from the interior.

These glazing systems, though best suited for small capacity PV systems, can be very visually appealing and provide great visibility. Because skylight, atrium and greenhouse glass is often heavily tinted to minimize glare, semitransparent PV glazing can make a good substitute. The glazing panels consist of PV material attached to the glass. Many off-the-shelf PV modules are suitable for this application. Open-air PV atriums (Wolter, 2003) are especially economical because the PV modules do not require extra ventilation (fig 4.8, left). In the Bejar Market retrofits (fig 4.8. right), PVs have been integrated into Skylights that combines three types of glasses with different colours and transparency degrees to create an aesthetical mosaic inspired by Piet Mondrian neoplasticism (Onyx Solar, 2012).



**FIG 4.8: (Left) Atrium with PV modules, Ludesch/Vlbg., Austria; (Right) PV on coloured skylights at Bejar Market, Salamnca, Spain**

Credit: <http://www.solarfassade.info/>, <http://www.onyxsolar.com/>

## 4.2 Facade integration of PV

It is a normal building practice that external walls of buildings are covered with insulation and protective cladding. This cladding can be wood, metal sheets, panels, glass or PV modules. For luxury office buildings, where the cladding is often expensive, Integrating PV modules as cladding on opaque parts of the building is not more expensive than other commonly used materials like natural stones, granite or aluminium cladding. In the Solar XXI building (SHC, 2012), Portugal, vertical bands of photovoltaic panels are integrated into the south facade, with an alternative rhythm with the glazing, resulting in an elevation based on the concept of modularity and repetition (fig 4.9).

PV can equally be integrated into the glazing of the façade. Structural glazing or structural facades are constructed using highly developed profile systems, which can be filled with all types of sheeting, such as glass or frameless PV modules (Reijenga and Kaan, 2011). Transparent and semi-transparent modules of PV have been developed that are used in curtain walls for controlling daylight in addition to producing energy. The arrangement of solar cells on the glass cladding with gaps in between functions both in shading as well as contribute to the passage of controlled light into the interior space as seen in the Tobias Grau Production Building in Germany (fig 4.10). Besides generating electricity and shading the building's southern front, the solar cells also insulate the building quite successfully. The semitransparent glazing prevents direct sunlight from entering the building, which reduces cooling loads and glare (SHC, 2012).



**FIG 4.9: PV integrated into the opaque parts of the façade of Solar XXI building, Portugal**

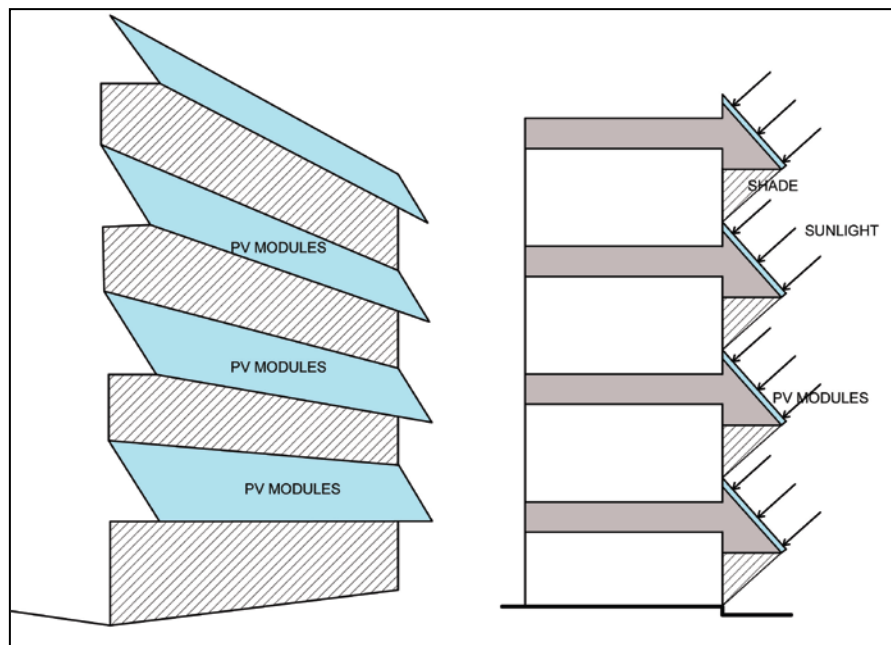
Credit: <http://csc.esbensen.dk/>

Facades offer a large area for integration PV modules. Besides generating electricity PV facades must look appealing and protect the building from weather. They can be integrated with windows, daylighting, and shading schemes to provide multiple benefits. The typical BIPV facade is vertical and faces southward. However, vertically oriented PV panels have much reduced electricity output compared to panels sloped toward the sun. The reduction is greatest in the summer when the sun is high in the sky; this is also when electricity is most valuable. To overcome this problem, facades can be sloped using a saw tooth design (fig 4.11). Saw-tooth PV facade may consist of overhanging PV shade screens on the façade where there are no windows. The overhang reduces direct sunlight in the summer but allows solar heating in the winter (Wolter, 2003).



**FIG 4.10: Tobias Grau Production Building in Germany has PV integrated into its south glazed facade**

Credit: <http://csc.esbensen.dk/>



**FIG 4.11: Saw-tooth PV facade consisting of overhanging PV shade screens**

Drawing based on (Wolter, 2003)

#### 4.2.1 Vertical integration of PV

Opaque PV module can be used as cladding elements in opaque parts of the facade while a transparent PV facade can be planned in almost the same way as a standard glazed facade. With slightly more work compared with standard solutions, it is thus possible to create eco-friendly, architecturally attractive facades which gives buildings high-tech and more elegant look.

#### 4.2.1.1 PV on inclined walls

It is quite interesting to incline the façade where PV is integrated basically for two reasons; first because it would then be easy to optimized the PV modules' position for the maximum energy yield and secondly because this would further add to the elegance of the façade. The west side of the Vocational College in Tirol, Austria is treated in similar fashion (M9 Architects, 2009). The PV integrated façade is curved and inclined which is one of the main features of the architectural expression of the building (fig 4.12).



**FIG 4.12: Inclined PV integrated glazed façade of Vocational College in Tirol, Austria**

Credit: <http://www.m9-architekten.at/>

In the Solar-Fabrik building, Freiburg, Germany, PV modules cover the entire glazed facade. This zero-emissions factory is integrated with around 575 m<sup>2</sup> of solar power modules that generates one-fifth of its electricity need. PV modules are also fixed in front of the south-facing wall positioned such at an angle to shade the glass building when the summer sun is at its highest. However In winter, the low-lying sun can easily penetrate into the building and helps in passive heating (SolarFabrik).



**FIG 4.13: Inclined PV integrated façade of Solar-Fabrik building, Freiburg, Germany**

Credit: <http://www.solar-fabrik.de/>

Similarly, in Daxford Solar Office the 15metre tall PV façade is designed to slope back at an angle of  $60^\circ$  mainly for two reasons. First is to maximize the solar radiation exposure whilst the second is to ensure that there is no disturbing glare reflected from the wall. Since daylight enters from the south side between the PV bands, on normal days no artificial lighting is need (Phillips, 2000).



**FIG 4.14: PV integrated inclined wall of Daxford Solar Office**

Credit: [superstock.com/](https://www.superstock.com/)

#### 4.2.1.2 PVs as sunshades

In energy efficient buildings, south facing glazings act as energy absorbers and hence the building can be designed to enable all the solar heat energy to be distributed from the south facade. However, problems can arise in the summer when the building overheats and becomes uncomfortable. High solar heat gain will increase the demand for air conditioning which will in turn increase the building's energy requirement. To avoid the energy need for air conditioning, external sunshades could be a good option to prevent the heat from

transmitting into the interior of the building. Typically, sun shades can take the form of a fixed or controlled glass louver system and can be installed either vertically or horizontally on the facade of a building. Solar PV cells can equally be integrated into the glass louvers as multifunctional elements both in order to generate electricity as well as providing shading to the building. These shades can both be fixed or movable. Besides, opaque PV modules can equally be used in similar way as a conventional shading device (Quality Domains Ltd, 2012).

The south glazed PV facade of the Solar-Fabrik building in Freiburg also has integrated PV shades to prevent overheating inside (fig 4.13). The Energy Research Centre in Netherlands has PV system integrated into the sun protection system (fig 4.15). This was done after the renovation as previously there were problems of overheating due to lack of sunshades. It was a nice idea to use PV as a multifunctional element. With this, the conventional PV mounting system is avoided. Similarly, the facade in the Editing office, Albstadt-Ebingen in Germany has also been renovated with active sun shade in the form of glass slats containing PV cells (fig 4.16) (Hermannsdorfer and Rub, 2005).



**FIG 4.15: PV used as shading in the Energy Research Centre, Netherlands**

Credit: Solar Design



**FIG 4.16: PV integrated into the glass louvered sun-shades in the Editing office, Albstadt-Ebingen, Germany**  
Credit: Solar Design



## **5 INTEGRATION OF SOLAR THERMAL COLLECTOR**

Integration of solar thermal collector systems in buildings can equally add on to the aesthetics similar to that posed by the photovoltaic systems. The need to produce and store thermal energy as close as possible near the consumption site, i.e., in the building itself; makes the integration of this system even more relevant. Since the existing solar collectors were normally manufactured as pure technical elements, they have posed a challenge for architectural integration(Probst and Roecker, 2011). Most solar thermal integrations seen are of course with the use of specially manufactured modules.

With the popularity of use STC systems for hot water and even space heating, their integration into the buildings become even more relevant. Integrating these systems into building means that they should not only answer to the technical constraints of their specific solar thermal technology, but also become architectural elements, conceived to be integrated into the building skin, similar as PV integration. There must exist some level of flexibility in all the system characteristics affecting the building appearance. These include collector material and surface texture, absorber colour, shape and size of the modules and type of jointing. The other equally important aspect of integration is that they should become multifunctional construction elements, facade cladding being the most relevant added function for glazed and unglazed flat plate collectors. With this the need for conventional cladding materials are replaced and cost can be economized. The use of dummy elements also becomes relevant on the non-exposed surface of the façade or roof according to the design (Munari Probst et al., 2007). Overall, the integration must result in public acceptance, thermal performance, aesthetics and cost effectiveness (Archibald).

### **5.1 Roof Integration of STC systems**

Besides producing energy for heating water and warming up the spaces inside the house, the objective of roof integration of STC systems is also to enhance the overall architectural expression of the building without actually affecting the normal function of the roof. A roof keeps precipitation out of the building, resist

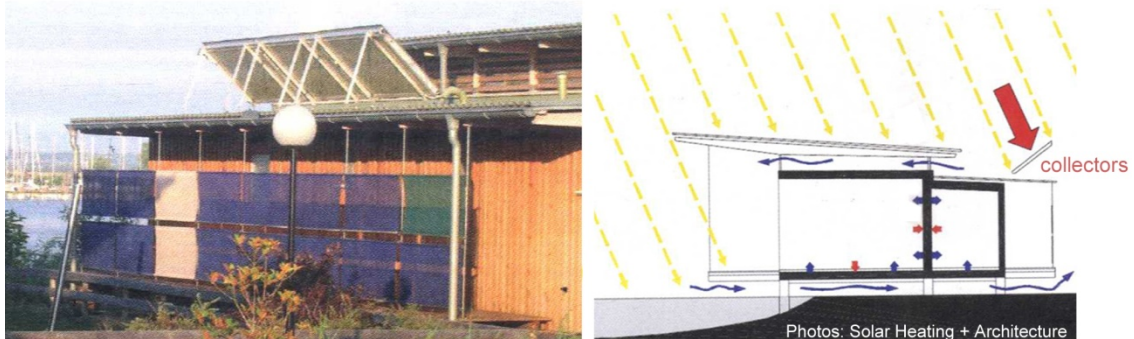
wind and in northern climates also withstand the weight of snow, sleet and ice. It also forms a layer of insulation or a vapour boundary to keep the building beneath it warm or cold, humid or dry. The visible roof in fact creates an impression of the building it covers. The roofs give identity to the building. The shape, color and surface texture and the type and quality of the materials used to cover the roof all create an impression on those who see the building(Archibald). Hence, all these features of the roof should be maintained or even improved with the process of integration.

A building's roof is usually not visible as the other four facades but its significance as an architectural expression is just as important as the rest of the building mass. As a result, integration especially in the case of steep roof slopes, solar collectors will affect the visual expression. On saddle roofs and shed roofs it is possible to integrate solar collectors in the actual roof construction and in this way replace part of the roof covering. In consideration for the architectural unity and to avoid shadows, solar collectors should not compete with other building elements on the roof surface such as dormers, skylights, chimneys and ventilation hoods. Vacuum solar collectors are ideal to place on the roof of buildings such as green house additions, as the light can pass between the tubes and thereby provide a certain degree of shade without completely blocking daylight access. It can also be more effective to place the solar collectors under the glass roof. Flat-plate collectors available in various sizes offer the possibility of optimal integration. Products already exist on the market, which combine skylights with solar collectors, and if the demand arises, dormers and other building elements with integrated solar collectors could be produced as standard products(Kjellerup et al., 2010).

### **5.1.1 Integration on Flat roof**

Usually, STC systems are laid in an angle on the flat roof in order to gain maximum output from the available solar energy. So, integrating STC systems on flat roofs may be a challenge to many architects as they could be visible when laid sloped and may ruin the building expression to some degree. However, Architect George W. Reinberg from Austria claims that mounting the STC system on a frame on to the flat roofs of his design, Holiday housing Jois

has actually enhanced the overall look of the units. He says the placement of the solar collectors harmonizes with the buildings' design and offers a fine interplay with the structure of the wood facades (fig 5.1) (Kjellerup et al., 2010).



**FIG 5.1: Solar thermal collector laid on flat roof of Holiday housing Jois, Austria**

Credit: Solar Heating + Architecture

### 5.1.2 Integration on Pitched roof

In a single-family house in Aarhus, Denmark; flat solar thermal collectors are well integrated into the lower part of the roof (fig 5.2). The clean finish and beautifully integrated PV and STC systems is in perfect harmony with the overall expression of the roof. The integration adds on to the beauty of the house which claims to be one of the first active houses in the world. The solar collectors cover 50-60% of the yearly hot water heating demand and to supplement for room heating (SHC).



**FIG 5.2: Integration of STC on the pitched roof of single-family house**

Credit: <http://www.iea-shc.org/>

Similarly, in the Hamburg Bramfeld multi-family house, the large continuous roof area is integrated beautifully with 3000m<sup>2</sup> of glazed flat-plate solar

collectors (fig 5.3). This integration has a positive architectural effect and thereby an influence on the building's architecture. The solar thermal collector system is a combined system, contributing to both domestic hot water preparation and space heating (SHC).



**FIG 5.3: Integrated STC systems in Hamburg Bramfeld multi-family house, Germany**

Credit: <http://www.oekosiedlungen.de/> & <http://www.iea-shc.org/>

## 5.2 Façade Integration of STC systems

Façade integrated collectors are becoming more and more popular mainly due to the fact that they are visible and in turn enhance the overall look of the building. The other advantage of façade-integrated collectors is the uniform irradiation of sunlight over the year, which is due to their vertical installation. This is very beneficial as a lot of irradiation can be used even in winter, when the highest heat demand occurs for space heating. Further, arguments for installing solar thermal collectors on the façade are that there is often not enough space on the roof or no suitable oriented roof area is available. This is typically the case for multi-family buildings and apartments with a relative high number of floors. In comparison to PV systems (Behling and Hieber), these collectors may well suited to façades mainly because of the fact that they are considerably more tolerant to shading with regards to their capacity and reduce, instead of increasing, the cooling requirements of the building.

Façade-integrated collectors fulfill several functions: first of all, they function as energy generators for heating water, they improve the building's thermal insulation, and they act as a weather skin for the façade through the glazing and are at the same time a structural element of the façade. Besides, they

contribute to lowering heat losses since the absorbers warm up even at low levels of sunlight in winter, thereby reducing the temperature difference between the internal space and the outer wall of the building. This multi-purpose use of building components may result in a considerable cost reduction (New4old).

### **5.2.1 Direct facade integration**

A collector element directly integrated in the facade acts as solid barrier for heat insulation which is a component both of the building as well as of the collector. There is no thermal separation between both of these in the form of rear ventilation. Advantages of this type of integration are (Stadler):

- Improvement in heat insulation of the building
- Protection against atmospheric conditions
- A structural design element for the facade
- Cost savings as a result of joint use of building components
- Replacement of the conventional façade

Consequence of the architectural integration:

- Appropriate collector sizes are not or rarely available in the market
- The architect determines the surface grid of the facade
- In the most cases the surface grid does not correspond to the size of the absorber
- Co-operation is necessary between the architect and the designer at a very early stage
- The collector is often 'only' part of the facade

Solar collectors can be advantageously integrated in parts of the facade or serve as the entire facade. In this way the actual facade siding can be replaced and in return reduce building costs. In new buildings, solar wall collectors are usually completely integrated in the facade as part of the total construction and design principle. When solar collector elements are built into the facade, they must satisfy the same building codes as the building does. This is very well seen in the integration of STC in the office building of AKS DOMA Solartechnik

(fig 5.4). 80 m<sup>2</sup> of glazed flat-plate solar collectors, each with 3000mm x 95 mm in dimension are integrated into the south facade of the building. The colour of the absorbers matches to that of the cladding adding to the overall aesthetics of the building (SHC).



**FIG 5.4: Integrated STC systems on the façade of office building of AKS DOMA Solartedhnik**

Credit: <http://www.iea-shc.org/>

Similarly, for another good integration of STC system to mention is the south facade of the Centre d' exploitation des Routes Nationales (CeRN) in Switzerland. The south facing facade integrated with non-glazed Energie Solaire metal collectors covering 40% of the building's heating demand and hot water (Probst, 2009). The vertical position of the collectors provides a good compromise between solar gains and architectural integration. Although dummy elements are rare in case of STC integration, they have been used here in the non-exposed areas with the same black colour and texture. The collectors produce maximum energy in the winter season which is used to heat the floor of the building. During summer the system still produces enough energy for the hot water needs of the building. The collectors act as multifunctional elements as it is an excellent corrosion-resistant building element. They also withstand the impact of aggressive climates without sustaining any damage and they are fully recyclable (Hullmann et al.).



**FIG 5.5: Façade integration of unglazed flat-plate collector, CeRN, Switzerland**

Credit: Maria Cristina Munari Probst. <http://www.nivo.ch/>

Due to the low flexibility of available products and their formal characteristics, integration of STC has number of hurdles. There are no variations in colours and those available are black and dark. The irregular appearance of their absorbers, the visibility of piping, their low dimensional flexibility and large size at the façade scale, and finally the lack of dummy elements are other challenges that has to be dealt with. However, colour collectors can be achieved using novel colours on the glazing covering the absorbers. These resulting glazing not only hide the black colour of the absorber and its imperfections, but can also be used as facade cladding on the non-exposed areas of the building envelope, opening the way to the concept of active solar facades and offering a new level of freedom to architects (Munari Probst et al., 2010; Roecker et al., 2007).

### 5.2.2 Solar thermal collectors as balcony railings

It is also possible to integrate solar collector elements as sun screening or on balcony surfaces as the balconies usually are oriented toward south and west. Besides the use of STC as cladding multifunctional elements in the facade, they can equally be used as balcony railings as is done in the Sunny Woods

multi-family housing in Zurich, Switzerland (fig 5.6). The tubular vacuum collectors as balcony railings, which makes the conventional railing unnecessary; have a nice degree of transparency giving interesting shadings on the floors. Most important is that these tubes make solar energy visible. (IEA task 41)



**FIG 5.6: Use of evacuated tube collectors as balcony railings, Sunny Woods multi-family housing in Zurich, Switzerland**

Credit: Solar Heating + Architecture



## 6 QUALITY OF ARCHITECTURAL INTEGRATION

Integration of PV and STC is influenced and guided by certain criteria to achieve quality in the process. There exists number of architectural issues that needs to be taken into consideration while integrating these systems into buildings. These issues play very important roles to achieve quality architectural integration. In order to achieve quality in architectural integration; the fundamental aspects of building such as functional, constructive and formal aspects needs to be fulfilled (Probst and Roecker, 2011).

Architectural integration quality of PVs and solar collectors can hence be defined as the result of their controlled and coherent integration simultaneously under functional, constructive and formal (aesthetic) points of view (Probst and Roecker, 2011). Among the functional, constructive and formal issues, it the latter that is to be given more attention as not much has been explored compared to the former two.

### 6.1 Functional Aspect of Architectural integration

A very important feature of architectural integration is multi-functionality. PVs and solar thermal collectors must be integrated into buildings such that they perform as multifunctional elements; i.e., in addition to collecting solar energy they must replace conventional building envelop materials. The solar element must be able to perform as a typical building envelop with all the necessary functions that a traditional building element fulfills. Some are listed as (Probst and Roecker, 2011):

- i. The interior must be protected from various external intrusions such as rain, wind, noise and other impacts;
- ii. Enough insulation must be ensured both for cold winters and hot summers;
- iii. The integrated solar element should be able to regulate the visual relations inside/outside and vice-versa, the supply of fresh air, daylight and passive solar gains;

- iv. They should be able to maintain user's comfort even when a reduction of the use of non-renewable energy for heating, cooling and lighting is made;

The opaque parts of the envelop in a building like walls and roofs, protect the interior from intrusions, rain, wind, noise, heat, cold and other impacts (Huan, 2011; Probst and Roecker, 2011). These opaque parts are structural/non-structural multilayer systems which may also include insulation. Insulation are usually used in buildings' outer layer in very cold or very hot places to minimise loss or gain in temperature in the interior of the building. The transparent or translucent parts like windows, atrium, glass cladding allow daylight, natural ventilation and passive solar gains into the building. They also visually link the interior with the exterior in addition to ensuring the whole set of protection functions similar to that of the opaque parts. These transparent parts may also be composed of mobile components and systems such as shading devices for regulating views, day lighting, passive solar gains and even natural ventilation(Probst and Roecker, 2011).

As per Probst and Roecker (2011), Integrating PVs and collectors into the building envelop requires to understand where opaque parts, transparent parts and fixed mobile elements are located and their compatibility in terms of material and function. For eg: standard opaque PV modules and thermal collectors are most likely to be integrated into the roof or even on the opaque parts of facades while thin film PVs on the atrium or windows. Normally, solar thermal collectors have less compatibility with the transparent parts of the building mainly due to the fact that their absorbers are opaque. In case of PV systems, they can be well integrated into these transparent parts with the possibility to laminate PVs in glass modules (fig 6.1, left).

Probst (2009) has said that the multilayer composition of flat plate collectors is suitable for the integration in the multilayer composition of the opaque envelop parts like walls and roofs. The insulation behind the absorber plate and the insulation of the building envelop can potentially become one single element or complement each other; the absorber for unglazed collectors and the glazing for glazed ones can take, under a purely functional point of view, replacing the

façade cladding layer. This is very interesting aspect of integration basically to reduce the use of materials and bring down cost. Evacuated tubes have been used as balcony railings (fig 6.1, right). Similarly, The PV modules (Fuentes, 2007) can be well integrated as opaque roof or facade elements as similar to the integration of STC elements. They offer even better freedom in terms of using them as multifunctional element.



**FIG 6.1: (Left) Integration of PV as shading and daylight control; (Right) Evacuated Tube collector used as balcony railing**

Credit: <http://www.esru.strath.ac.uk/>, <http://csc.esbensen.dk/>

## 6.2 Constructive aspect of Architectural Integration

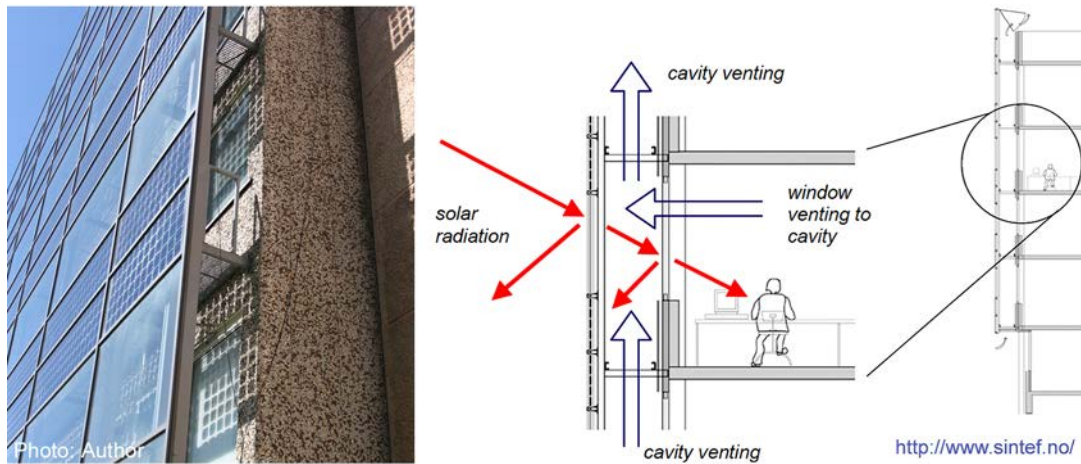
PV and STC systems (Fuentes, 2007) can be incorporated into buildings either by superimposition where the system is attached over the existing building envelop or by integration where the system forms a part of building envelop. In either case, if they enhance the appearance of the building, they are collectively called architectural integration. While integrating PVs and solar thermal collectors into the façade and roof, it is important to consider the construction characteristics of the specific technology to be integrated together with the specificities of the constructive system hosting them. This is to ensure that the new multifunctional façade elements meet all the safety façade constructive requirements as(Probst and Roecker, 2011):

- i. The load of the PV and collector systems must be correctly transferred to the load-bearing structure through appropriate fixing making sure that the fixing avoid thermal bridges;

- ii. These solar technologies must be able to withstand fire and harshness of the weather;
- iii. They should resist wind load and other impacts and should be safe in case of damages;
- iv. The resulting problems due to the temperature rise behind the systems must be rectified;
- v. Fixing details and jointing should make the PV and collector system's material expansions compatible with those of the other envelop materials.
- vi. Vapour transfer through the wall should avoid condensation layers, and allow the wall to dry correctly.

Point vi) is very important to consider while integrating flat plate collectors or cladding PV systems without an air gap. In normal cases, vapour transfer takes place from the higher temperature (inside) to the lower temperature (outside). So, the vapour barriers are placed on the inner warm part of the wall to avoid condensation layers. In doing so, special attention must be taken to protect insulation materials and wood if they are used. Mounting solar collectors directly to the wall without an air gap causes a fundamental modification of the vapour transfer; i.e., it flows out when the cladded PV or STC systems are cold and it is the other way round when they are heated up (Probst and Roecker, 2011). These facts must be carefully considered during integration.

To explain the construction aspect on integration, temperature of solar module could be one factor. The output in case of PVs start degrading as the module temperature start rising. In BP solar building at NTNU, Trondheim, 80cm cavity created between the glass façade and the adjacent building's wall assists in venting the cells thereby increasing efficiency (fig 6.2) (Aschehoug et al., 2003). Similarly, In Albstadt-Ebingen editing office in Germany, the solar slats used also as shading are hung 50 cm in front of the existing facade (fig 4.16) (Hermannsdorfer and Rub, 2005).



**FIG 6.2: Venting cavity behind the PV modules in BP Solar skin building, NTNU, Trondheim**

Credit: Author, <http://www.sintef.no/>

### 6.3 Formal (aesthetic) aspect

This is the main part of the thesis which is explored in detail. Aesthetics is what people see and admire. So, If PV and STC integration will be popular today and in the days to come will be for one important reason; which is their ability to enhance the architectural expression of the buildings. For this to take shape, a coherent and controlled formal composition of the different architectural elements necessary to satisfy the constructive and functional requirements is crucial for the design of the parts that is visible like facade and sloped roof. However, this aspect is rather subjective and the opinions of people regarding this vary. This is shown in the survey taken by Probst (2009) for her PhD thesis; architects, engineers and façade manufacturers, all had varied opinions about the integration of solar collectors on different buildings. The architects consistently agreed on the value of the integration quality of the objects, be it good or bad, with only minor differences in the intensity. Engineers and façade manufactures are generally less demanding regarding integration quality. These differences in appreciation highlight that judging architectural quality rely on architects' professional competences, showing the importance of using architects' skills to deal with formal issues.

When we have to compare the 'integrability' of PV and STC, there is more flexibility integrating PV systems as multifunctional elements in opaque and transparent parts of a building enhancing its overall expression. This is

basically due to the fact that PV systems are available in varied shapes and sizes from a small cell to a large module which makes it appropriate to be used in buildings of any scale. The range of colours they are available in is another advantage of using PV systems as architectural elements to enhance architectural expression. Unlike the first generation PVs, availability of thin film and amorphous systems has eased the task for the architects as these systems can be used in any external part of the building irrespective of the direction and angle of the sun. As a result, these thin film system can be used in place of any traditional cladding elements. The comparative integration abilities of PV and STC system are elaborated in chapter- 8.



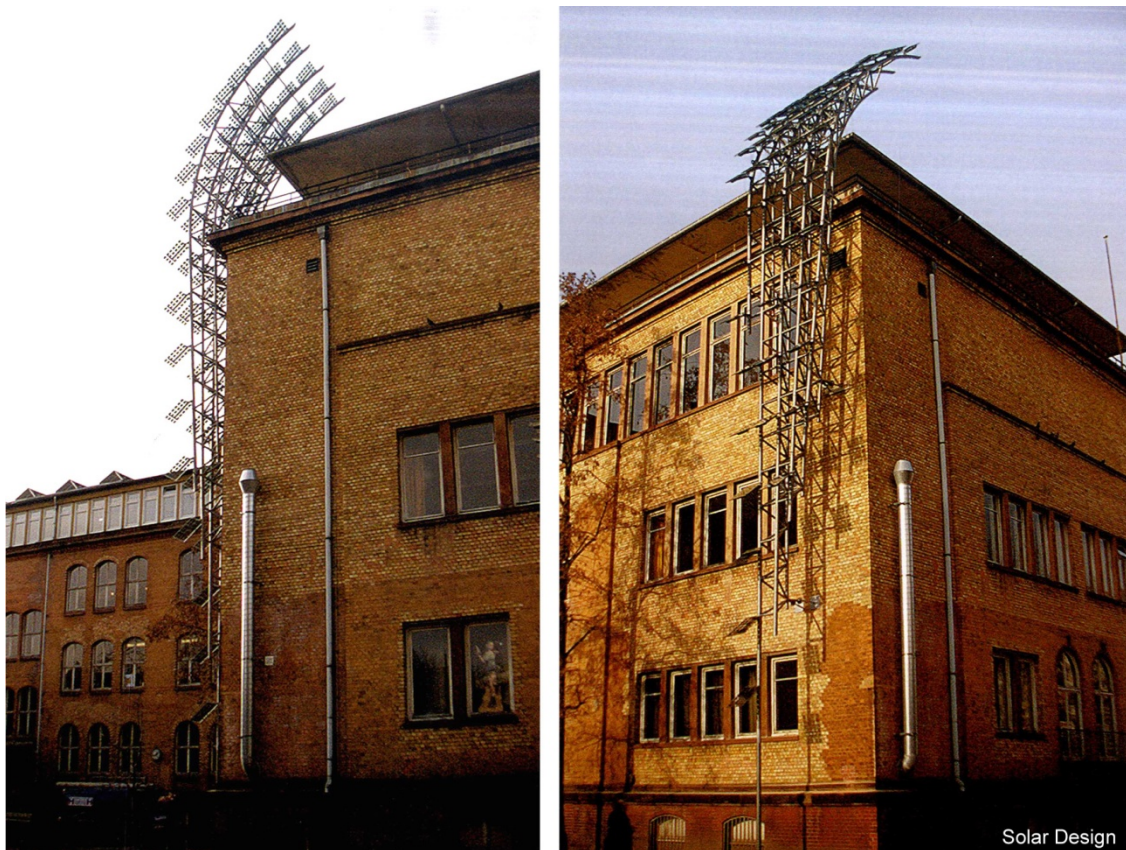
**FIG 6.3: Integration of PV, considering the formal aspect. (Left) Monte Rosa Hut, (Right) Novartis Building, Switzerland**

Credit: Klaudia Frakas

PV also offers wide range of flexibility in integration considering the formal aspect of architecture. In Monte Rosa Hut (Farkas, Facade Integration Typologies of Photovoltaics), Monte Rosa-Zermatt, Switzerland, the form of the building has been such as to optimize the sun's angle on the PV façade (fig 6.3 left). While in case of Novartis Building, Basal, Switzerland, PV modules have been laminated onto the transparent curved glass roof for reducing direct solar heat maintaining the architect's formal concept of the design (fig 6.3, right).

A different approach to PV integration is seen in the College of Fine Arts, Hamburg Germany. The conventional type of PV systems that is installed on the flat roof is more or less not visible and so does not draw any public attention. So, in order to draw attention, it was decided to give rather powerful,

yet inconspicuous PV system a more noticeable and visible look which helped portray the art school to the public as a place of art and technical experiment (fig 6.4) (Hermannsdorfer and Rub, 2005). With the emphasis give to multi-functionality, this may not be termed as architectural integration, but the installation has some formal/aesthetic aspect in the way of using PVs in architecture. It is indeed an element which adds on to the aesthetics of the building and highlights it.



**FIG 6.4: PV integration as a show element, College of Fine Arts, Hamburg Germany**  
Credit: Solar Design

## **7 ARCHITECTURAL INTEGRATION REQUIREMENTS**

To achieve quality in the architectural integration of PV and STC systems certain requirements need to be fulfilled. The global integration quality depends not just on module shape, size and colour but also on all formal characteristics as (Probst and Roecker, 2011):

- i. Field size and position of PV or collector systems
- ii. Materials and surface texture
- iii. Colour of the cells for PV systems and absorbers for solar collectors
- iv. Shape and size of the modules
- v. Type of jointing
- vi. Multifunctional elements

For successful integration, above mentioned characteristics must all be coherent with the overall building design logic. The characteristics with the relevant examples of the use of PV and Collectors are described below.

### **7.1 Field Size and Position**

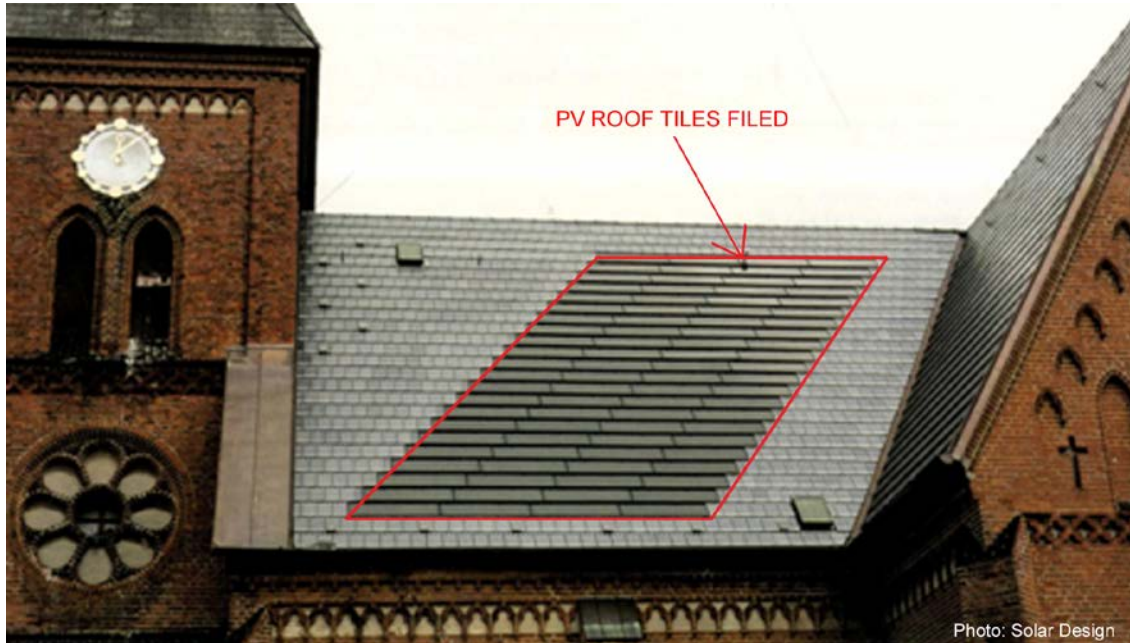
It is very important that the size and position of the PV and collector systems be coherent with the overall architectural composition of the whole building and not just with in the façade or part of the building where they are being installed (fig 7.1 & 7.2). However, it may always not be easy to achieve this and in order to achieve; certain parameters have to be followed. The parameters that influence the location, shape and size of the PV and collector systems are (Probst, 2009; Probst and Roecker, 2011):

- Position and dimension of the available exposed surface of the roof or façade
- Orientation of the surface available
- Energy requirements desired
- Solar technology
- Architectural needs of the building



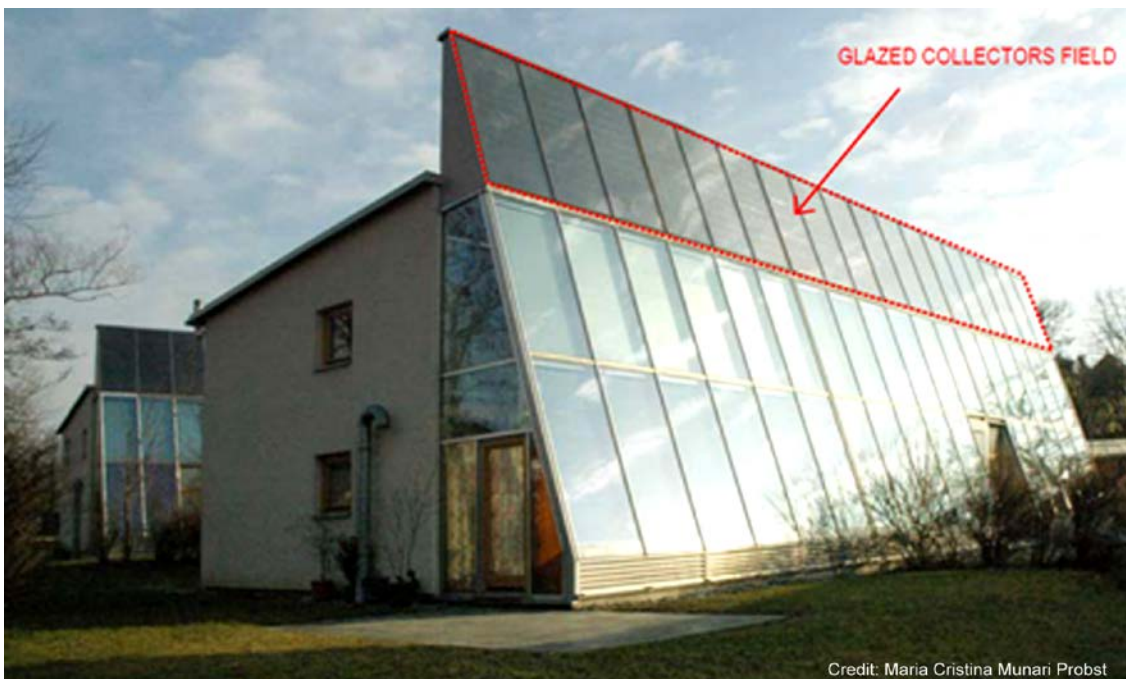
The surface or part of the building that is available for integration directly influences the energy production of the solar systems. In case of new construction, available exposed surface can be created according to the energy requirement aimed for. However, for retrofit projects the energy production has to be adjusted according to the available exposed surfaces. In addition, the choice of solar technology also influences production and exposed surface requirements. In case of PV systems, crystalline cells produce much more electricity than amorphous solar cells. So, for the yield of same amount of power, amorphous solar cells have to be installed on a larger surface than for crystalline cells. Same applies for solar collectors. Evacuated tube collectors are more efficient than flat plate collectors. So, the choice of a specific solar thermal technology affects the exposed surface requirements.

An effective approach to the positioning and dimensioning issue is to use the PV and thermal collectors as multifunctional elements serving both as energy generators and roof/façade elements. With this, the architect has to design in such a way that he uses fewer elements as possible as each fulfils several functions. Use of PV or solar collectors all over the surface may often be unnecessary and difficult due to practicalities. So, the use of dummy elements will help to decouple the geometric dimensioning of the system and bring uniformity in the appearance of the system. However, the down side of this is that in most occasions, such applications require the development of a tailored product specific to just one project, and are therefore very expensive (Probst, 2009; Probst and Roecker, 2011).



**FIG 7.1: Architectural integration of PV on the roof of a Church, Carlow, Germany. The formal characteristics of the PV system have an impact on the integration quality.**

Credit: Solar Design



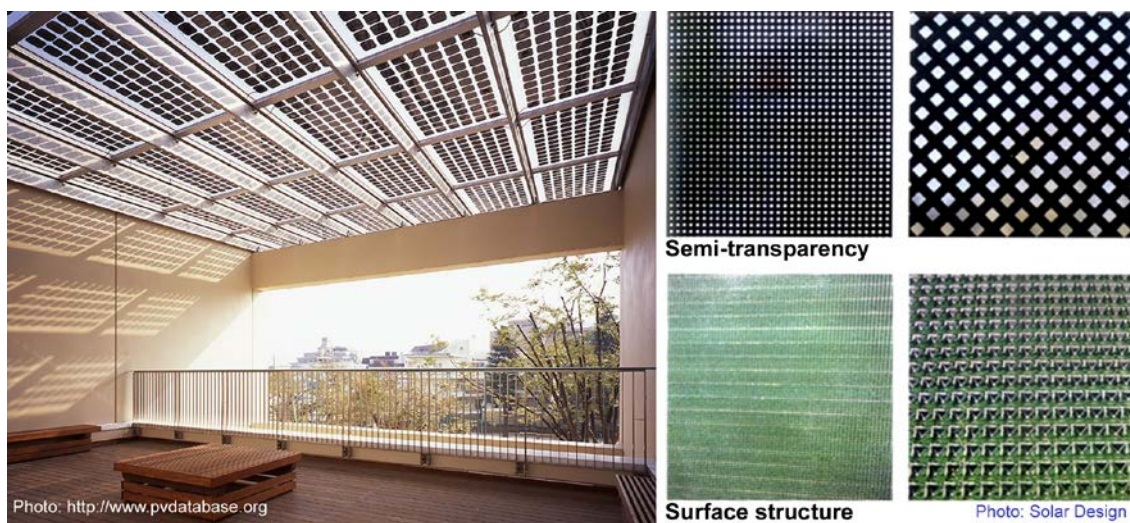
**FIG 7.2: Architectural integration of STC systems on the inclined façade of multifamily dwelling, Gleisdorf, Germany. The formal characteristics of the STC system have an impact on the integration quality.**

Credit: Maria Cristina Munari Probst

## 7.2 Materials and surface texture

The characteristic of the material and their surface texture used in PV and thermal collector systems must be in harmony with the same characteristics of other elements of the building envelop.

In the case of PVs, both opaque and semitransparent modules can be used in the building fabric as desired. Semi-transparency of PV cells and modules is an important design feature, offering new application possibilities and providing good potential for architectural integration. Glass as a shiny material that is commonly used as module cover, strongly contrasts with the matt and respectively uneven finish of traditional building material like brick, render or roof tiles and the reflections on its surface make the modules highly visible at a distance and occasionally cause undesirable glare. To overcome this, matt surfaces have been created by sandblasting producing all kinds of regular and irregular patterns. Various types of structured glass can also be used as a glass cover to create a matt finish (Hermannsdorfer and Rub, 2005).



**FIG 7.3: Illustrations of some possible variations in the surface texture of PV**

Credit: <http://www.pvdatabase.org>, Solar Design

In the case of glazed thermal collectors, it is again glass that is visible. This glass is normally extra white to optimize solar energy transmission. Its surface can be lightly textured, to become slightly diffusing, or it can be perfectly smooth and transparent with anti-reflection coating sometimes available to increase the energy transmission. The absorber is usually black metal sheet

mainly made of copper, aluminium or steel and can either be in one piece or made of a row of metal strips. The geometry and surface texture of absorbers can be quite diverse depending on the manufacturer, but usually no flexibility is offered within one specific product. For unglazed collectors, the absorber metal sheet is the only visible layer. The glass tubes, the absorber metal strip inside and in most cases also the back module sheets are visible in the case of evacuated tubes(Probst, 2009; Probst and Roecker, 2011).

### 7.3 Colour

The colours of the crystalline and amorphous silicon cells are normally blue. By modifying the anti-reflection layer it is possible to create other colours. Thin film solar cells consisting of amorphous silicon or CIS are black in colour while CdTe-cells have a greenish look. The range of colours gives the possibility to produce any kind of pattern that is desired in a building fabric(Hermannsdorfer and Rub, 2005).

The absorbers used in solar thermal collectors are usually black or dark blue to assist their heat collection function. The absorber colour results most of the time from selective coatings used to optimize absorption and to reduce emission losses. The colour of these coatings can change according to the angle of vision, so that a black absorber may look violet or blue or red depending on the incidence angle of the sun on the surface. Dark brown and dark green shades have also appeared in the market but very little (Probst and Roecker, 2011).

Within the chosen technology, the different products available in the market should be explored to find the colour and surface texture most suitable for the given application. PV products provide more freedom compared to the collectors in this regards. However, it would be a clever approach to define the materials of the other envelope elements so as to be compatible with the materials, textures and colours of the chosen collectors which is possible in new construction.



**FIG 7.4: (Left) Range of colours in PV; (Right) visible colours due to the sunlight striking onto the extra white glass above the absorber of STC system,**

credit: credit: Klaudia Farkas; Maria Cristina Munari Probst

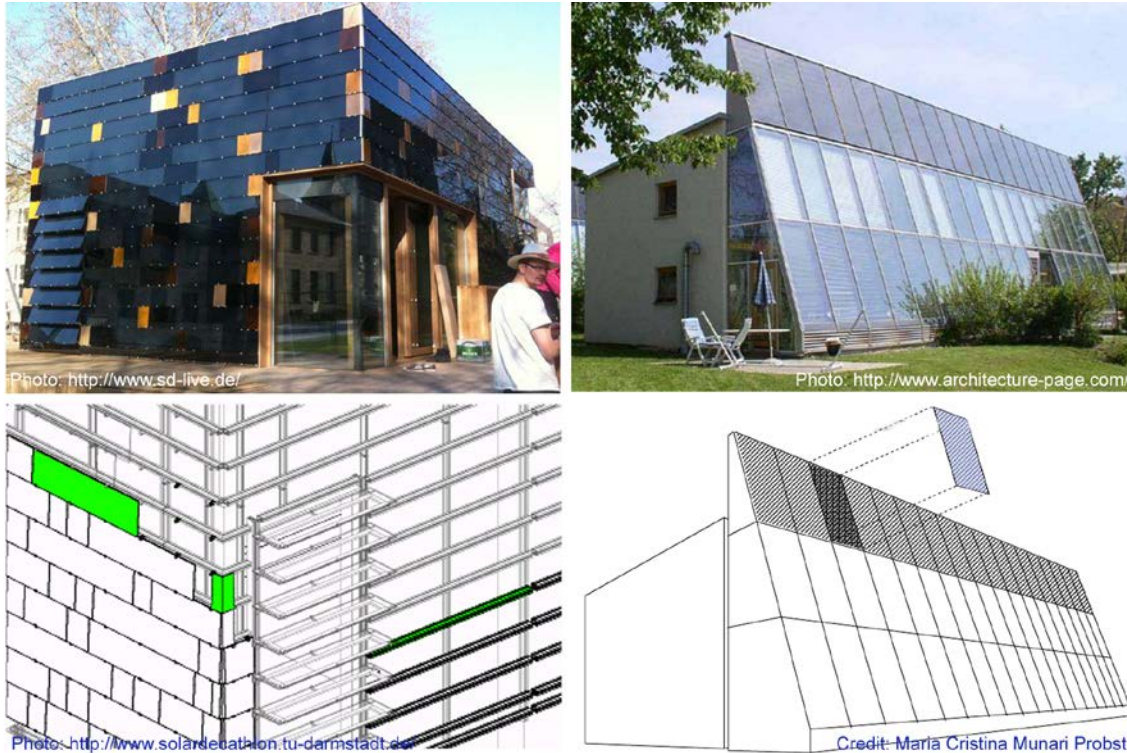
#### 7.4 Shape and size of the modules

The shapes of the module of the PV and collector systems have to be compatible with the building composition grid and with the various dimensions of the other façade elements (Probst and Roecker, 2011). It is actually the choice of the technology that affects the basic form of the module. For PV systems, mono and polycrystalline modules come in standard sizes and can be bulky while thin films can have varied shape and sizes. The development of cut-to-size module prototypes had the aim of providing modules whose size can be adapted directly on site as in the Surplus-home of team Germany for the Solar Decathlon 2009 (fig 7.5, top-left). Even though most of the products in the market come in standard module size, there is maximum freedom in the use of PVs on roofs and façade elements. There will be variations in the basic form of collector module shape and size as according to the exposed available surface and type of collectors chosen.

#### 7.5 Type of Jointing

Jointing types must be carefully considered while choosing the product as different jointing types differently underline the modular grid of the system in relation to the building (Probst and Roecker, 2011). In the surplus-home by TU Darmstadt for the Solar Decathlon 2009, the PV facade cladding was done in the traditional shingles principle. It is also the jointing that makes the PV

module much similar to the roofing shingles (fig 7.5, bottom-left). The appearance of the jointing in the collectors used in the multifamily dwelling in Gleisdorf is made to look similar in size and proportion to that of the glass facade which has added to the value of the integrated appearance.



**FIG 7.5: (top-left): Integration of PV shingles on the façade of Surplus-home of team Germany, (Bottom-left): Jointing of PV shingles used, (Top-right): Integration of STC system in the multifamily dwelling, Gleisdorf, Austria, (Bottom-right): Jointing of STC in the multifamily dwelling,**

Credit: <http://www.sd-live.de/>, <http://www.solardecathlon.tu-darmstadt.de/>, <http://www.architecture-page.com/>, Maria Cristina Munari Probst

## 7.6 Multifunctional Elements

The best part of integration is the possibility of using PV and collector systems as part of multifunctional elements, thereby replacing the conventional building elements. Multi-functionality of the systems makes it easier to deal with the formal aspects of the integration. It provides the decisive advantage for the designer to architecturally compose with fewer elements, as each fulfils several functions. In the Surplus-home (fig 7.5, top-left), PV shingles are used as multifunctional cladding element and same is the case with STC system that is used on the façade of the multifamily housing, Austria (fig 7.5, top-right).

## **8 PV OR STC: BETTER ABILITY TO ARCHITECTURAL INTEGRATION?**

With the increasing awareness over the environment and climate change; government of different nationals formulating policies in favour of renewable energy, energy efficiency, on-site renewable energy production to reducing CO<sub>2</sub> emissions; even more and more homes will definitely be powered by solar energy in the days to come. This gives an overview that, PV and STC systems which are common and reliable on-site renewable solar energy generators will abundantly be used in buildings. So, if the integration of these systems into buildings is done wisely and cleverly, they will not only generate energy but will also add to the overall architectural expression of the building. Within this context of fulfilling the integration requirements and rendering quality integration, there has been a debate as to which systems among the two would best suit for architectural integration.

PV and STC systems are fundamentally different, as the former is designed to transform the solar radiation into electricity, while the latter is designed to transform it into heat. So, these systems are used to produce completely two different types of energy and hence have very different transportation and storage issues. This brings different formal and operating constraints, leading to different building integration possibilities (Probst and Roecker, 2011).

Photovoltaic systems have a number of merits and unique advantages over conventional power-generating technologies. These systems can be designed for a variety of applications and operational requirements, and can be used for either centralised or distributed power generation. PV systems have no moving parts, are modular, easily expandable and even transportable in some cases. Energy independence and environmental compatibility are two attractive features of PV systems. The fuel (sunlight) is free, and no noise or pollution is created from operating PV systems. At present, the high cost of PV modules and equipment (as compared to conventional energy sources) is the primary limiting factor for the technology. Consequently, the economic value of PV systems is realised over many years. In some cases, the surface area requirements for PV arrays may be a limiting factor (GreenSpec, 2012; Hestnes, 2012).

Even though PV and STC systems are fundamentally different, one common feature between them is that they are both powered by the sun. The differences in their ability to architecturally integrate into buildings are discussed in the following points.

### **8.1 Shape and size**

STC systems available in the market are manufactured usually in larger and bulky sizes compared to a PV system. So in general even smaller buildings will have to use STC systems of larger sizes. Smaller custom sized STC can be manufactured, however the sizes will still be larger than PVs as the former has number of other parts like the hydraulic system which involves liquid transportation. Integrating large sized collectors into smaller buildings architecturally, will certainly require extra effort for architects. The smaller the unit, the easier it is to integrate. So, the freedom offered by available STC products in terms of shape and size is not that convenient (Probst and Roecker, 2011). The PV systems definitely do have an advantage over STC in shape and size as they can be produced in very small sizes and in any shapes which become easier to integrate (Hestnes, 2012). Mono and poly-crystalline cells are available in sizes as small as 10 to 12 cm and module size as small as  $0.1\text{m}^2$ . As these crystalline cells are produced by cutting silicon ingots, they have limitations in shape and size of cells. However, thin film has no limitations due to different technology (Farkas, Formal characteristics of Photovoltaics and their architectural expression). STC, usually glazed flat plate collectors are much larger with their dimensions ranging from 1.5 to  $3\text{m}^2$ . Evacuated tube collectors are equally large with tube lengths from 1 to 2m and diameters from 6 to 10 cm (Probst and Roecker, 2011).

The characteristics of the cells, the framing and the added elements together with the conceptual grid of the facade define the shape and size of the module. The classic roof integration/addition of STC systems as in (fig 4.3, left; ) can be considered a failure in terms of integration as the collectors are used only in their primary function of heat generation. Due to less 'integrability' compared in terms of a PV system, STC systems are added to the roof as independent roof elements and do not go in co-relation with the tiles used. The same problem



will not be faced while integrating PV on the roof which can be seen in the integration of PV roof tiles in a building in Delamont Country Park Ireland (fig 4.5, top; fig 8.1, bottom-left). The black PV tiles perfectly match with the normal tile used for roofing in both shape and size.

In case of STC systems, The Techtile Therma, produced by company called REM can be a new and innovative way of integrating into tiled roofs. It is equipped with a solar collector consisting of a series of 6 glass tubes with dia. 47mm, length 1,500 mm, double cavity borosilicate, welded at the ends, creating a vacuum inside (fig 8.1, centre & right) With this, the integration looks clean and each tile appear to be separate unit even though six such tiles integrate one vacuum tube. However, this method is certainly not that easy in terms of installation compared to that of a PV system and hence have not produced examples of their integration. We can find few more examples of this kind of products but they have not usually been commercially used (REM, 2012).



**FIG 8.1: (top-left): PV tiles on the roof, (bottom-left): PV on the roof Delamont Country Park Ireland building, (center & right): Techtile Therma STC systems on the roof**

credit: <http://solarpowerpanels.ws/>, <http://www.horizonrenewables.co.uk/>, <http://www.remenergies.it/>

## 8.2 Positioning

The positioning of both PV and STC systems is defined by energy and architectural needs. It is only the suitable locations on the building which is determined by solar exposure, suitable area, energy production goals, etc that is equipped with PV and STC systems. In case of specific architectural needs, the remaining spaces can be covered or clad with dummy elements (Probst and

Roecker, 2011). The positioning of STC field on the roof provides a little more flexibility than on the facades. It is normally the modules produced for the roof that are also used in the facades which of course is not ideal for facade application. This is mainly because solar collectors are little available commercially for facade application. So, there is even less possibility of dummy elements being available so that these could be used in areas where 'real' collectors have not been integrated. In case of integrating PVs, more positioning options are available. There are separate modules available for roof and facade integration including the dummy elements.

STC systems are comparatively more efficient and hence needs less space for integration as compared to PV systems since the building does not need that much thermal energy as it requires electricity. This can be further explained as: the covered area of the PV required to produce the amount of electricity if used to heat water is more than that of a STC system to heat the same quantity of water. Although electricity cannot be compared to a low grade energy like heat, in case of producing heat energy, a STC system needs comparatively less area than that of a PV system if we happen to use the electricity to heat water.

### **8.3 Flexibility in integration**

Due to the availability in smaller sizes and possibility of the modules to be produced in any shapes, PV systems have far more flexibility than STC systems in terms of architectural integration. There is possibility of partial transparency through the use of glass-glass modules. Thin film modules can be built over flexible metal or plastic sheets offering new level of freedom. Comparatively, STC systems with their bulkier size and fixed shapes are less flexible. This is mainly due to the need for a non-flexible hydraulic circuit fixed to the solar absorber to collect the heat. The freedom in module shape and size would require reconsidering the hydraulic system pattern each time and so is not that practical (Probst and Roecker, 2011).

For architectural integration, the shape and size of the solar module should be compatible with the building composition grid and with the various dimensions of the other envelop elements. It is difficult to achieve this kind of results with

the integration of STC systems while with the PV system it is fairly easy mainly because of their flexibility. This difference in flexibilities imply very different constraints when choosing the shape and placement of these solar elements especially for façade integration (Probst and Roecker, 2011).

#### 8.4 Range of Colours

The PV cells have a larger variation in the range of colours as compared to that of the absorbers of the solar thermal collectors. This is very advantageous in terms of architectural integration especially in the visible parts of the building where colours play a very important role in aesthetics and architectural concept and expression.

Coloured PV cells open up a new field of design possibilities in architecture. These coloured cells offer a wide range of new design applications adding aesthetic value to the building especially in the facade. PV modules are available in a wide range of colours. Crystalline modules are crystal-blue to black in order to maximise sunlight absorption. Other colours can be achieved by modifying the thickness of the anti-reflection coating on the surface of the solar cell. Lighter the shade, the less efficient the solar cell. Thin-film modules are reddish-brown or black (Solar facade, 2011).

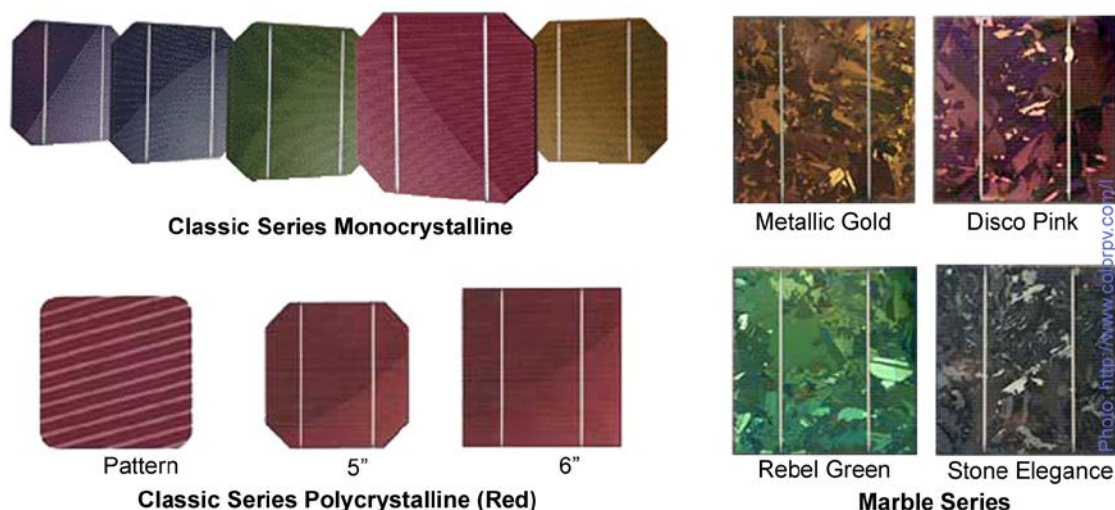


FIG 8.2: Range of colours in PV cells,

credit: <http://www.colorpv.com/>

The blue coloured mono and poly-crystalline are the most efficient of the PVs. Even the coloured PVs seen these days are approaching closer to the blue

ones in terms of efficiency. Solandum Solar Energy Systems & Colour PV (Solandum) have produced PVs in 15 different colours of which green, purple, red, gold and grey are few to mention. High quality coloured mono- and polycrystalline PV cells are available in the market. The cells are colorized with a patented method which guarantees a high cell performance of upto 16.6%. The colour cells are designed in two basic series called Classic Series and the Marble Series (fig 8.2). The Classic Series are characterized by the even colour appearance. The Marble Series is characterized by its lively colour shades. For these colours only polycrystalline cells are being used. As with all the coloured cells due to the patented colouring process high cell efficiency comparable with conventional blue cells is achieved. Integration of these coloured PV modules can be seen in figure 8.3.



**FIG 8.3: (Left): PV modules based on Metallic Gold cells are integrated in the balcony, rails and facade, Tirol, Austria**

**(Left-top): Part of the BIPV on the China Pavilion during the World Expo 2010 in Shanghai, China.**

**(Left-bottom): PV mounted roof modules made with tile Red coloured Cells on this domestic residence in the south of France**

Credit: <http://www.colorpv.com/>

The "home+" building project submitted by Stuttgart University of Applied Sciences (HFT) has also made use of coloured PV modules. The building envelope is characterised by the beautiful shimmering integrated multi-crystalline photovoltaic (PV) system with bronze and gold coloured silicon solar cells as a distinguishing feature (fig 8.4) (Konstanz, 2010).



**FIG 8.4: Multi-crystalline PV system with bronze and gold coloured silicon solar cells used in the "home+" building project submitted by Stuttgart University of Applied Sciences,**

Credit: <http://www.sunways.eu/>, <http://www.inhabitat.com/>

The integration of solar collectors in buildings should be compatible with the architectural design, and solar collectors with coloured absorbers would be aesthetically preferable. The coloured absorbers are of interest for solar thermal applications, considering that they are more flexible than collectors with black absorbers for a variety of architectural integration which require aesthetic compatibility of solar collectors (Tripanagnostopoulos et al., 2000).

The efficiency of solar collectors is significantly dependent on the absorptance and the emittance of the surface, where the incoming solar radiation is converted to thermal energy, the absorber. The absorber of these collectors is normally black in order to maximize the absorption of the solar spectrum. (Probst and Roecker, 2011; Tripanagnostopoulos et al., 2000). The development of several black selective coatings will certainly result in a wider use of solar collectors with selective absorbers in recent years. Although the general appearance of the selective absorbing surface is black, they appear to be slightly coloured for some angles of view because of the interferential optical properties of coatings. Selective coatings/filters reflect only a small part of the solar spectrum in the visible range while letting the rest of the radiation heat the absorber (fig 7.4, right). These coloured absorbers are available at the cost of reduction in the efficiency. The range of colours may not be available as much as that of PV systems. Variations and availability in range of colours is a very important feature of integration. This will give freedom to the architects to use

these systems in buildings in various innovative ways just as normal conventional building elements are used. Variation in colours can also be achieved by having coloured glazing in case of glazed collectors. The efficiency of collectors with coloured absorbers (with or without glazing) can be close to that of collectors with black absorbers if colour paints of dark tone are used (Tripanagnostopoulos et al., 2000).

Glasses of various colours combined with several diffusing finishings (acid etching, structured glass etc) are produced that are able to hide the absorber. Such glazings will allow the use of the same product both on façade areas equipped with solar absorbers (as collector external glass) and in front of the non exposed areas (as façade cladding), opening the way to a broad variety of active façade designs. The active elements can then be positioned at will on the exposed areas, and their quantity determined only by thermal needs. However, in reality only very few manufacturers have been able to offer the flexibility to choose between different absorber colours. The range have mainly been limited to black, blue and bronze (Probst and Roecker, 2011).

### **8.5 Surface texture and finish**

Visible surface texture and finish should be taken as a characteristic which can add on to the formal expression of the building and not just relate it to energy production or heat optimization. There has been research work done to produce PV cells with different surface texture that is also more efficient. With the new surface structure, the photovoltaic cells can convert more of the sunlight falling on them into energy, achieving greater power density and providing a new class of performance. These variations in the surface texture and finishes will definitely be an added advantage to the integration of PV on to the visible parts of the building.

Normally PV modules come in glossy and shiny finishes and are both opaque and semi-transparent. Reflections on this surface may make the modules highly visible at a distance and occasionally cause undesirable glare. To avoid this, matt finished surface would be desirable. PV modules with matt finish surface would be more suitable to integrate into buildings where exposure of

traditional building materials like brick, render of roof tiles and so on. Usually structured glass is used as glass cover to give a matt finish (Hermannsdorfer and Rub, 2005). The PV cell texture depends on different technology. Monocrystalline have a more solid finish while poly-crystalline cells have marble-like texture (Farkas, Formal characteristics of Photovoltaics and their architectural expression).

The absorbers of the STC also have variations in terms of surface texture and finish. These are available from corrugated, embossed, perforated, regular and irregular in terms of surface geometry. Evacuated tube collectors have exposed glass tubes. The surface is matt, glossy or structured finishes (Probst and Roecker, 2011). The glazing above the absorbers in case of glazed STC systems may shine when sunlight falls on the surface and glare could be a problem. Also, the variations in the surface texture and finish inside the glass covering may not be visible from the outside. However, they can be well integrated to complement with the glass surface of the façade or even roof. In case of unglazed STC, the absorber surface texture and finish is clearly visible and hence can be an option concerning possible patterns on the envelope they are laid to.

With the above mentioned characteristics, PV modules have the flexibility to be integrated both into opaque and transparent facades and roofs. When mounted on a glass-glass module, the PV cells can be freely spaced achieving various designs and pattern and can be best suited in atrium, glazed facades, canopy, and verandah applications. Flat plate solar thermal collectors with their opaque nature can only be integrated into the opaque parts of façade and roof (Probst and Roecker, 2011).

### **8.6 Visible Jointing of Modules**

Jointing between different PV or STC modules has an important influence on the integration quality. The jointing are usually observable and hence must be similar to the jointing of other cladding material on the same surface for uniformity. PV systems with their slim thickness can be clad on to both opaque and transparent facades similar to the installation of conventional cladding with normal jointing. It is comparatively easier to achieve similar modular jointing

grid to that of other cladding used on the façade in case of PV modules. It is equally possible to achieve sized fitting with the modular rhythm of the standard cladding with the same type of jointing in STC systems as it is easier with PV systems. However, to achieve jointing appearance similar to that of the other claddings used on the same façade or sloped roof, custom design modules have to be used in most cases.

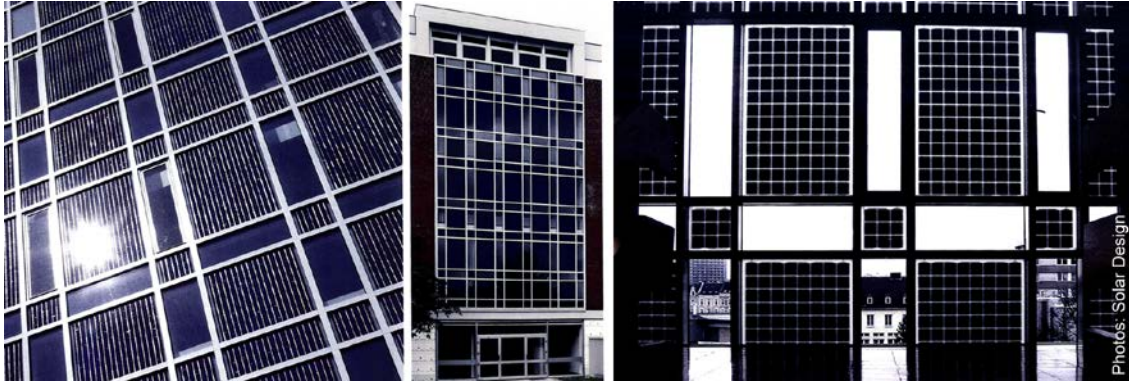
### **8.7 Multi-functionality**

A building's external envelop must not only keep out water and regulate heat loss, it must also regulate the entry of light, provide a sound barrier, offer ease of technical maintenance and also must be aesthetically and architecturally satisfying (Voss et al.) . One of the most important features of integration of PV and STC systems is their possibility to use them not only as energy generators but also as a replacement to other conventional building elements on the external envelop and adding on to the overall expression of the building. PV systems can be used as multifunctional elements in a more diverse form while STC systems have some limitations in this aspect. Both PV and STC systems can be used in place of normal building components with their multifunctional potential as external skin for insulation, waterproofing, fire protection, wind protection, acoustic control and shading (Fuentes, 2007). The STC systems with their bulkier, rigid shapes and greater thickness may not be that easy to integrate as sun shading and cladding on facades. Although daylight control with the use of semi-transparent PV systems is possible, fulfilling the same purpose with the use STC systems is only in the research state.

The use of PV cells on the south-facing glass façade of the 1960s administrative building on the Stadtwerke Aachen in Germany was one of the first multipurpose applications with PV modules (fig 8.5). This was conceived during renovation in 1991. Light-diffusing modules developed especially for this south-east front direct daylight into the staircase behind. The chessboard type combination of glass elements and the modules with dark-blue crystalline silicon cells between the compound glazing offered surprising patterns both outside as well as inside. The PV modules act as semitransparent façade providing sun protection, as wall element including thermal insulation in



addition to power production. The cabling is completely integrated into the metal frames of the façade (Hermannsdorfer and Rub, 2005; Lundgren and Torstensson, 2004).



**FIG 8.5: One of the first applications of the multifunctional use of PV systems in the administrative building on the Stadtwerke, Aachen, Germany,**

Credit: Solar Design

The use of STC system was conceived from the beginning in the housing at Bjoernveien, Oslo (fig 8.6). Solar collectors have been incorporated into the southern façade as multifunctional cladding elements. These attractive collectors with dark, reflecting surfaces in addition to producing energy also act as a sound barrier for road traffic (SHC).



**FIG 8.6: Multifunctional use of STC systems in the façade of the housing in Bjoernveien, Oslo,**

Credit: <http://www.archdaily.com/>

The following points may not be directly related to architectural integration but relevant to be considered while making a choice for integration.

## 8.8 Transportation of Energy

Transportation of electricity is easier than water. For the transfer of hot water, the pipes must be insulated and the temperature of water drops with the length of the pipes. So, hot water cannot be transported over long distances. In the case of electricity generated by PV systems, they can be transmitted over long distances similar to the normal grid over wires with negligible transmission loss. As a result, the energy production does not have to be close to the consumption area (Hestnes, 2012). However, the scope of the thesis is that each house has its own energy generator integrated; be it STC or PV systems.

In cases when there are difficulties to integrate PV and STC systems in the building then of course, they can be placed somewhere else. This is usually done if the integration happens to ruin the appearance of the building or is not permitted by the bylaws. For eg, in historically important buildings when bylaws don't permit; they could be placed somewhere else other than the building.

## 8.9 Storage

As the nature of the energy produced by PV and STC systems is different, the need for energy storage also varies. The electricity produced by the PV modules can be stored in batteries or fed into the grids. With this the sizing of the system is totally independent of the local consumption, and the energy produced can be much more than that needed by the building. However, the heat produced by the STC has to be stored in tanks which of course are limited in terms of storage capacity. Besides, STC are sensitive to damages resulting from overheating. As a result, the heat production ideally should not exceed the storage capacity (Probst and Roecker, 2011).

Because of the difference in principle and size in storage of these two systems, STC systems should be dimensioned according to the specific building needs and the total storage tank capacity, to avoid overheating and the accompanying overheating problems. PV are totally independent of the building energy needs and can be dimensioned according to the size of available exposed areas, or according to architectural criteria (Probst and Roecker, 2011).

### 8.10 Effect of Shading

STC system is not that much affected by shading as compared to a PV system which is very sensitive to any kind of shading. Even if a small portion of a PV array is shaded, for e.g. by a tree, the output power falls dramatically due to internal short-circuiting(Wikipedia). This is very prominent in case of mono and poly-crystalline cells. Thin film PV cells would be the best option to use in this kind of conditions as the affect by shading is very negligible. However, if a part of the STC is shaded, the systems still produce energy only deducting the production from the part which is shaded. Figure (8.7) below illustrates the output from the array by panel at 9:15am - just shortly after the sun first gets on the panels. The two panels on the right (east) are experiencing some shading from the fence rails to the east. The fence rail shadow shades less than 10% of the panel area, but cuts the power drastically by about 75% compared to the panels in full sun (Build It Solar, 2010).

Many modern modules use bypass diodes to minimise shade effects. If shading is unavoidable, or poor light is expected on a regular basis, the best types of PV to use for integration are amorphous thin-film (Green Spec, 2012).

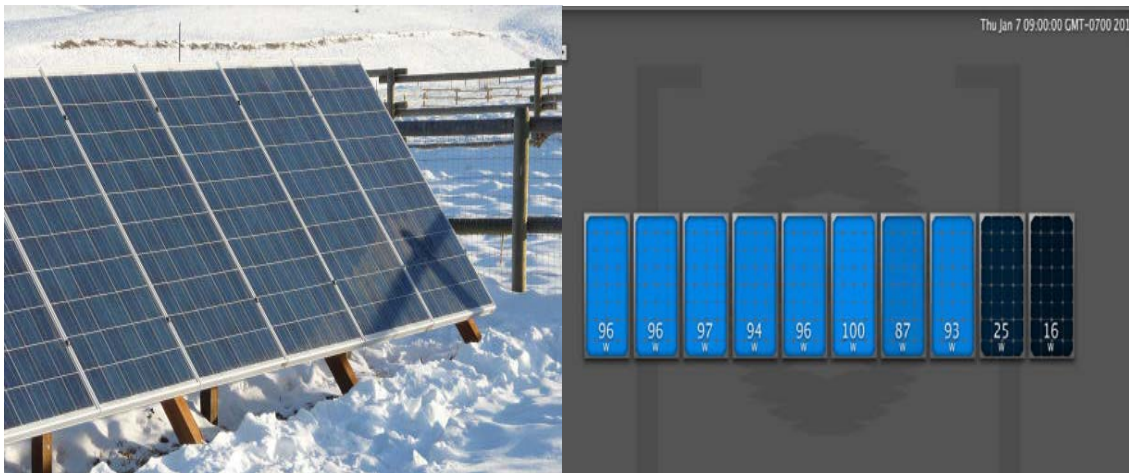


FIG 8.7: Affect of shading to PV modules(right) and the result (left),

credit: <http://www.builditsolar.com/>

### 8.11 Efficiency per unit area

A residential building does not need much STC for hot water and heating the building as they are comparatively more efficient than a PV system per unit area of energy production. But the use of electricity in a house is quite large,

and hence the PV systems cover a large part of the area for more production. PV panels run about 8-20% efficient at converting sunlight into electricity, and this efficiency goes down as the panel gets warmer. Unlike the PV systems, even moderate quality flat-plate thermal collectors operate at about 65 to 70% efficiency when the fluid running through them is not a lot hotter than ambient temperature. And this efficiency stays high as the day heats up and water also heats up. Once the heating target is hot or if the ambient temperature is very cold, collector efficiency declines according to a very predictable slope. Thermal collector ratings are performed by an independent testing agency however there is no equivalent third-party testing for photovoltaic equipment (SolarConsultants, 2009).

### **8.12 Useful life time**

The useful life time of PV systems is much longer and the maintenance requirement is quite less as compared to STC systems. In general, PV systems that are well designed and properly installed require minimal maintenance and have long service lifetimes. PV systems keep on functioning for as long as thirty years while STC systems may function only upto 15 years (Green Spec, 2012). The STC systems have pipes and corroding parts due to flowing liquid unlike in a PV system that only has connecting wires. This accounts for the shorter life time in case STC systems. So, with the PV systems having a longer useful life could be used in place of other conventional cladding elements on roofs and facade.

### **8.13 Temperature**

The higher the temperature rise, the better the efficiency of the solar thermal energy system (Catch Solar, 2012). But this is not the case with PV systems. Temperature rise is inversely proportional to the production efficiency of PV panels, i.e. higher the temperature of the panels, lower is the output (REUK). Hence, this fact must be considered while integrating these systems into buildings so that maximum output is achieved by careful consideration of minimizing self heating of the systems. PV modules should be back-ventilated for higher efficiency while solar thermal absorbers require back-insulation to minimize heat losses. Integrating the collectors directly in the building envelop

layers, possibly without an air gap is ideal in this sense for solar thermal systems, while freestanding or ventilated applications would be preferable for PV (Probst and Roecker, 2011).

The performance of PV modules decreases with increasing temperature and the drop in performance is more significant for crystalline silicon than amorphous silicon (SEAI). Designs for building-integrated PVs need to consider this from the outset in order to allow air to flow over the backs of the modules to cool and maintain high performance. It is also necessary with all types of module to avoid unwanted heat gain into the occupied space that could cause discomfort and increase any cooling load.

Building integrated modules can reach 20-40°C above ambient in conditions of high radiation. For each 10°C increase in cell temperature above 25°C the power output decreases by about 0.4-0.5% (SEAI). It is therefore important to ensure excessive temperature is avoided as far as possible.

#### **8.14 Cost**

Leaving tax credits and incentives out of the figures, for each kilowatt-hour of electricity produced, a typical PV system costs much more than the solar thermal collector systems (SolarConsultants, 2009). The study made by Ben Croxford and Kat Scott have found out that the STC systems are superior to PV systems in terms of installation cost, annual saving, maintenance and payback. The carbon payback for the solar thermal system is 2 years and for BIPV, it is around 6 years (Croxford and Scott).

Looking at the current trend of falling price of PV systems, at some point in the future, if the price happens to be even lower than the price of the collectors, PV produced electricity could also be used to heat water and space. However, we must also consider resource use and embodied energy for the manufacture of these two systems. Croxford and Scott in their study have found out that the embodied energy of PV system is larger compared to STC systems. Among the two, the one that is more resource friendly should of course be considered.

## 9 ARCHITECTURE INTEGRATION EVALUATION OF SELECTED PROJECTS

The illustrated examples of PV and STC systems integration are successful implementations with the main focus on building facades. Integration of both PV and STC systems are analysed according to the criteria explained in chapters 6 & 7.

### 9.1 Photovoltaic: Mono-crystalline cells

#### BP Solar Skin, NTNU, Trondheim

Onto the existing office building at NTNU, a glass façade with PV cells embedded in parts of the glazing to work both in conserving heat by reducing heat loss and preheating ventilation air and producing electricity is added. The PV systems have been integrated into the façade because at higher latitudes, the solar radiation on a vertical south-facing wall is not much less than on a sloped surface oriented optimally for maximum radiation. Hence, PV cladding on the façade will not be less efficient in terms of production of electricity. Since the PV output is dependent on the module temperature, 0.8m cavity created between the glass façade and the adjacent building's wall assists in venting the cells thereby increasing efficiency. The PV cells are arranged such that they provide shade for the windows during summer. The 455m<sup>2</sup> of façade is integrated with 192m<sup>2</sup> of high-efficiency mono crystalline PV cells. With the efficiency of around 16%, the system's estimated peak performance is 16kW. BP's main objective in initiating the project was to demonstrate an attractive and intelligent solution to building integration of PV (Aschehoug et al., 2003; Aschehoug and Bell, 2006).

<b>Shape and size</b>	The shape and size of the PV modules fit with the modular rhythm of the glass facade. Two PV modules cover the space of one glass module.
<b>Positioning</b>	The modules are positioned at regular intervals horizontally outside the facade section without windows following the horizontal grid of the facade.

<b>Colour</b>	Cells are of standard blue colour which is in harmony with the glass used.
<b>Material and surface texture</b>	As the PV cells are embedded in a resin layer in laminated glass modules, the cells look like small square dots at regular intervals creating a pattern
<b>Flexibility in integration</b>	With the small sized PV cells used, much freedom existed in integration
<b>Types of Jointing</b>	As the PV cells are laminated on the glass modules, the jointing are similar to the normal glass on the facade
<b>Composition of the module</b>	PV modules are linear horizontally following the grid of the facade
<b>Multi-functionality</b>	The PV cells provide shading for the windows for summer high sun



**FIG 9.1: Mono-crystalline PV cladding on the glass façade, BP Solar building, NTNU, Trondheim,**

credit: Author

## 9.2 Photovoltaic: Poly-crystalline cells

### Paul Horn Arena, Tübingen Germany

Architect: Alman-Sattler-Wappner

The southwest façade of the Paul Horn Arena is the world's largest photovoltaic façade using coloured poly-crystalline solar cells. The 20,000 plus integrated Sunways solar cells, each with a 2-watt output, not only produce clean energy to meet part of the energy demand of the sports complex but also adds to the economics by replacing the conventional cladding on the entire facade. The photovoltaic system integrates perfectly into the overall architectural concept of the building; especially successful is the combination of aesthetical and functional aspects on the southwest façade(Sunways).

<b>Shape and size</b>	The dimension of the modules have been customised to fit exactly on the facade without cut sizes
<b>Positioning</b>	The modules are positioned with the length vertically to balance the horizontality of the facade.
<b>Colour</b>	The emerald-green Sunways cells with visible crystals give the building a dramatic look
<b>Material and surface texture</b>	The plain borders of the modules seem to cut through the two dimensional crystal surface when seen in the facade.
<b>Flexibility in integration</b>	Since the whole facade is clad with PV, much freedom existed in the layout of integration
<b>Types of Jointing</b>	Again, jointing were only that of the PV modules and no problem existed of having to make them appear similar to that of other claddings.
<b>Multi-functionality</b>	PV modules are used façade cladding elements





**FIG 9.2: Integration of coloured poly-crystalline solar cells, Paul Horn Arena, Tübingen Germany**

### 9.3 Photovoltaic: Thin-film cells

#### Dwelling houses Spinnereistraße

Architect: Kaufmann Hermann

The movable Photovoltaic panels used on the south side of the facade which serve also as sun shades are the most remarkable feature of this house. On the northern side dummy modules have been used of the same blue colour as the PV modules. In combination with the bright wooden exterior cladding of the building the sliding shutters adds on to the facade composition. The effect of the interior quality is also controllable with the moving solar shades that are glued onto the aluminium sliding elements (Kaufmann, 2003).

<b>Shape and size</b>	Modular dimension is the result of the floor height and the window width
<b>Positioning</b>	The modules are positioned such that they can shade each windows whenever necessary by sliding
<b>Colour</b>	The blue colour PV modules are in contrast to the timber facade cladding but look like windows even when the windows are covered
<b>Material and surface texture</b>	The glassy look of the modules makes them appear as windows. Thin white horizontal lines is also noticeable
<b>Flexibility in integration</b>	Use of same sized modules make the integration more flexible and economical
<b>Jointing</b>	PV modules are glued on the aluminium sliding element similar to any conventional sliding panel.
<b>Multi-functionality</b>	PV modules act as shading devices
<b>Dummy elements</b>	Dummies are available



**FIG 9.3: Integration of thin-film PV on the sliding sunshading, Dwelling houses Spinnereistraße, Austria,**

Credit: <http://csc.esbensen.dk/>, <http://www.hermann-kaufmann.at/>

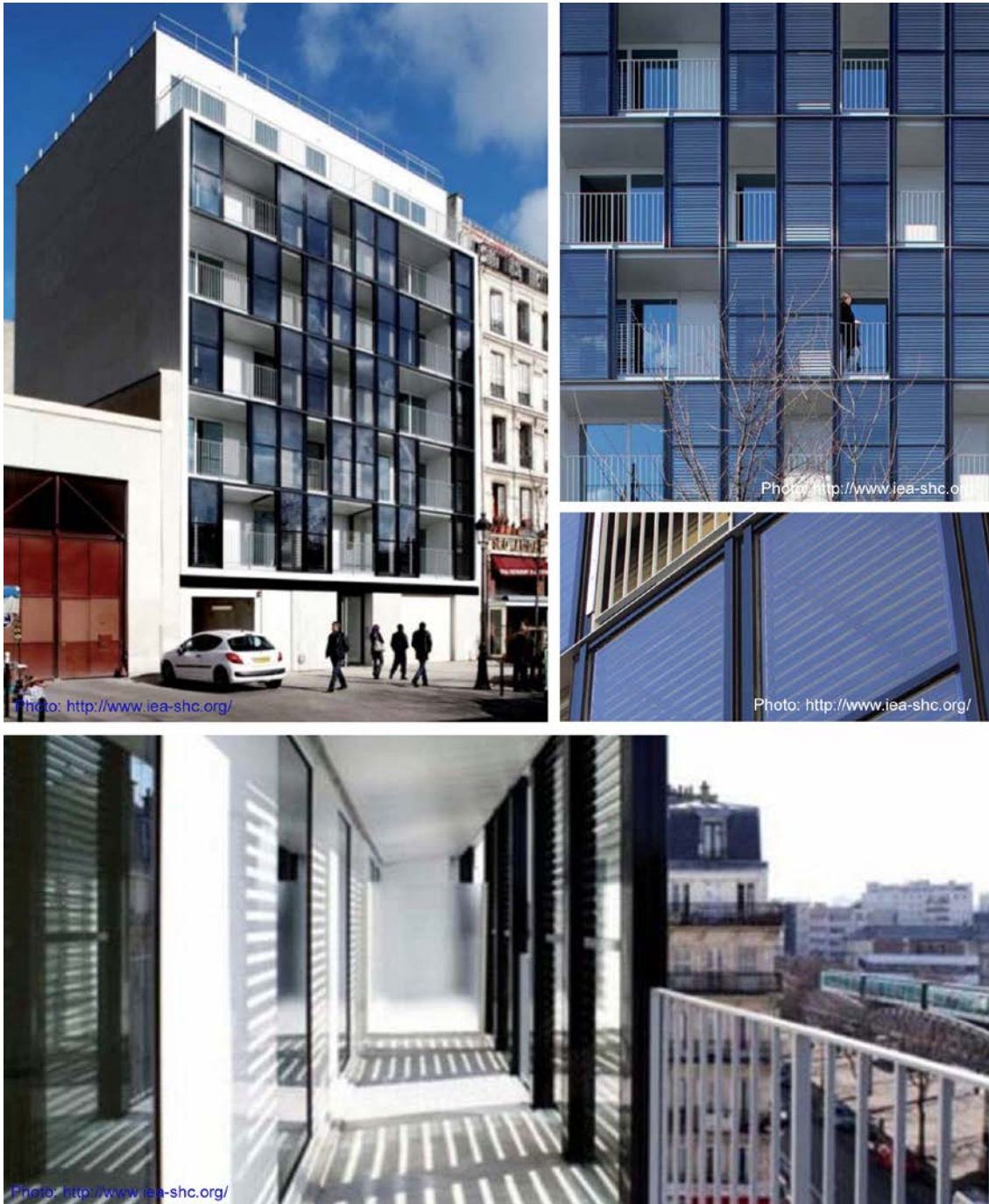
#### 9.4 Solar Thermal Collector: Glazed flat plate

##### Social housing , Paris France

Architect: Philippon – Kalt Architectural limited

The checkerboard-style solar panel façade traps solar energy to produce enough power to meet 40% of the domestic hot water needs of the housing. The multifunctional semitransparent collector encapsulated into a double skin facade offers not only complete privacy from the passengers commuting by the sky-train operating nearby several times a day, but it also restricts the noise. These double-skin, tinted solar panels installed in an asymmetrical pattern have a lot to boast about the elegant and smart way of integration (SHC; Zimmer, 2011).

<b>Shape and size</b>	The height of the module is derived from the height of the floor
<b>Positioning</b>	The modules are placed in a checker board style in asymmetrical pattern in the facade
<b>Colour</b>	Blue colour of the modules is in harmony with the reflecting blue colour of the windows. There is no option for other colours.
<b>Material and surface texture</b>	The horizontal lines seen on the absorber of the collector module break the verticality of the facade
<b>Flexibility in integration</b>	The flexibility in integration is more prevalent with the similar sized modules used.
<b>Multi-functionality</b>	Modules are used as sun shades and noise barriers
<b>Dummy elements</b>	No availability of dummy elements



**FIG 9.4: Integration of glazed-flat plate collectors, Social housing , Paris France**

Credit: <http://www.iea-shc.org/>

## 9.5 Solar thermal collectors: Vacuum tubes

### Sunny Woods, Switzerland

Architect: Beat Kampfen, Regensdorferstrasse

The apartment complex is designed as an energy effective, passive house with PV modules on the roof for necessary energy to run the electrical equipment and solar thermal collectors for hot water. For the first time vacuum tube solar thermal collectors were integrated as an architectural element used as balcony balustrades in the south facade (Kjellerup et al., 2010). The 90 cm high solar module balustrades that look like normal handrails are a stack of nine long glass tubes. Inside each of these glass tubes, a finger-thick pipe with a metal absorber transports water. The collector as a whole is oriented vertically, but each absorber is turned to an optimum angle of about 55° toward the sun, to collect the maximum energy in the fall and spring. If the solar collectors were pitched, too much energy would be produced in the summer and too little in the other seasons. Each of these 18 solar collector modular balconies very much characterize the formal composition of the timber clad facade (Probst and Roecker, 2011). Beside the energy advantage and balcony fencing, the solar collectors create aesthetic value by throwing a changing pattern of light and shadow on the floors of the rooms.

<b>Shape and size</b>	Collector modules each with nine evacuated tubes are dimensioned as standard balcony parapet
<b>Positioning</b>	The modules are positioned at regular intervals in the facade
<b>Colour</b>	Standard reflecting blue colour is in harmony with the colour of the background glazing
<b>Material and surface texture</b>	The horizontal lines created by the solar tubes characterise the horizontal lines of the timber cladding
<b>Flexibility in integration</b>	With the use of evacuated tube collectors, much flexibility was possible for integration
<b>Multi-functionality</b>	The collector modules are used as balcony railing



Photo: <http://www.kaempfen.com/>



Photo: <http://solarpeace.ch/>



Photo: <http://www.kaempfen.com/>



Photo: <http://solarpeace.ch/>

**FIG 9.5: Integration of evacuated collectors as balcony railings, Sunny Woods, Switzerland**

## 9.6 Solar thermal collectors: Unglazed collectors

### New building for Centre d' exploitation des Routes Nationales (CeRN), Bursins, Switzerland

Architect: Niv-o

The unglazed flat metal collectors are integrated into the long south facade of the building as multifunctional facade cladding. Dummy elements have been used on the non-exposed facades with the same appearance as active ones. The architect has worked the building based on the modular dimension of the standard collector size of 86cm. Even though the black collectors were originally produced for the integration on the roof, they have been very well integrated into the façade (Hullmann et al.).

<b>Shape and size</b>	The collector plates have fixed modular width of 86cm and the composition of the facade is based on this width
<b>Positioning</b>	The collectors are integrated all over the opaque part of the south facade
<b>Colour</b>	The plates are standard black colour offering no flexibility for other colours
<b>Material and surface texture</b>	The metallic textured appearance adds on the expression of the facade
<b>Flexibility in integration</b>	There is flexibility in integration if the modular dimension is considered before hand
<b>Types of Jointing</b>	Appearance of clean joints
<b>Multi-functionality</b>	Collector plates are used as external cladding and weather protection
<b>Dummy elements</b>	Dummies have been used in the non-exposed facades





**FIG 9.6: Façade integration of unglazed flat plate collectors as multifunctional cladding element, (CeRN), Switzerland.**

## 10 CONCLUSION

With an aim to look for different possible ways of integrating PV and STC systems giving more emphasis to the formal aspects, the thesis has tried to investigate on relevant methods and requirements to achieve quality in integration. Starting with a brief introduction on the present scenario of energy crisis and hazards related to the use of fossil fuel was an attempt to emphasize on the relevance of using renewable energy especially that from the sun which is very abundantly available that too for free.

PV and STC systems were developed as pure technical elements to make use of solar energy to produce electricity and heat respectively. However, it is realized that without developing these solar elements as some part of the building element and make them acceptable, their utilization in buildings will certainly not develop in terms of quality integration. They will still remain as pure technical additions into the building only fulfilling energy requirements and often ruining the overall architectural expression of the building.

The thesis has made an attempt to understand building and architectural integration and underline their differences. It is possible and logical to integrate PV and STC systems into the external building envelop as multifunctional elements which will in addition improve on the aesthetics. Visible parts of the roof and façade are best suited for this kind of integration. There must be some guidelines or criteria that are to be followed to achieve quality and homogeneity in the integration process which has been described and explored. With these guidelines in mind, some sort of comparison has been made on the integration abilities of both the PV and STC systems. This comparative study is done mainly to give a general overview as to which systems among to two would best suit for particular building integration according to energy needs, site conditions, location, position on the façade or roof and architectural expressions.

To summarize the study, it can be said that PV and STC are very important active systems to produce green and clean energy using sunlight and can be developed as fundamental parts of the building envelop with added aesthetics

to the building. When these systems are considered very early in the design, they can perform very well both technically and aesthetically. The overall reduction in construction cost resulting from the multifunctional use of these systems is another important feature of integration. However, with the availability of less PV and STC systems that can be well integrated into the building envelop, it becomes equally important to develop systems into a more 'integrable' form similar to other building elements. So, designers and manufacturers have a role to play in this regards. STC systems have slightly less 'integrable' ability than the PV systems, so needs special considerations during design and manufacture for architectural integration in terms of size and position, colour, surface texture and materials and module jointing.

Last but not the least, Integration of PV and STC systems into the building as multifunctional building envelop will not only produce renewable energy for building needs but will also add value to the overall building by enriching the architectural expression, thereby increasing its marketability. Also, integration process must be developed in such a way that it is acceptable by people so that in the coming days, more buildings will have PV and STC systems well integrated and not used only as mere technical elements.

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