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Environmental Technology

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CHARACTERIZATION AND INVESTIGATION ON MATERIAL COMPATIBILITIES OF BUILDING INTEGRATED PHOTOVOLTAIC MODULE COMPONENTS

Examiners: Professor Risto Soukka

Professor Lassi Linnanen

ABSTRACT

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Characterization and Investigation on Material Compatibilities of Building Integrated Photovoltaic Module Components

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Building Integrated Photovoltaics (BIPV) are considered as the future of photovoltaic (PV) technology. The advantage of BIPV system is its multi-functionality; they fulfil the functions of a building envelope with the added benefit of generating power by replacing the traditional roofing and façade materials with PV that generate power.

In this thesis, different types of PV cells and modules have been described in detail with their efficiencies and usage trends in the last decade. The different BIPV products for roof and façade are discussed in detail giving several examples. The electricity generation potential of BIPV in selected countries is compared with their actual electricity consumption. Further, the avoided greenhouse gas (GHG) emissions associated with electricity generation from traditional sources and transportation and distribution (T&D) losses are calculated. The results illustrate huge savings in GHGs.

In BIPV different types of façade and backsheets are used. In this thesis, selected backsheets and façade were characterized in terms of their surface structure identification using infrared spectroscopy (FTIR-ATR), scanning electron microscopy with energy dispersive X-ray (SEM-EDX) and physical characterization using surface energy measurements. By using

FTIR-ATR, surface polymeric materials were identified and with SEM-EDX, identification of the surface elements was possible. Surface energy measurements were useful in finding the adhesives and knowing the surface energies of the various backsheets and façade. The strength of adhesion between the facade and backsheets was studied using peel test. Four different types of adhesives were used to study the fracture pattern and peel tests values to identify the most suitable adhesive. It was found out that pretreatment increased the adhesive strength significantly.

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Ashish Gulagi

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List of Abbreviations

BIPV	building integrated photovoltaics
BAPV	building applied photovoltaics
PV	photovoltaics
RES	renewable energy sources
c-Si	crystalline silicon
mc-Si	multi crystalline silicon
a-Si	amorphous silicon
CdTe	Cadmium Telluride
CIS	Copper Indium Selenide
CIGS	Copper Indium Galium Selenide
IEA-PVPS	International Energy Agency Photovoltaic Power Systems Programme
TWh	Tera Watt hour
kWh	Kilo Watt hour
GHG	greenhouse gas
T&D	transmission and distribution
PVB	polyvinyl butyral
EVA	ethylene vinyl acetate
UV	ultra violet
PVF	polyvinyl fluoride
PVDF	polyvinylidene fluoride
ETFE	ethylene tetrafluoroethylene
PA	polyamide
PE	polyethylene
PET	polyethylene terephthalate
FTIR	Fourier transform infrared absorption
ATR	attenuated total reflection
SEM	scanning electron microscopy
EDX	energy dispersive X-ray

1. Introduction

1.1 Motivation

According to a report by the International Energy Agency, the global energy needs have increased significantly in the past decades and it is predicted to rise more than 50% by 2030 (IEA, 2011). The rapid industrialization and development in developing countries is the reason for the unprecedented rise in the energy consumption. The ever increasing energy demands at present are mostly met by the use of conventional fossil fuels such as oil, gas and coal resulting in unsustainable exploitation and exhausting of the global reserves. This large scale energy consumption is having an adverse effect on the environment. Thus the current need is to shift to renewable sources of energy which are environment friendly and sustainable. Solar energy is considered the best choice in the rather small share of renewable energy market. The advantage of being available in abundance and freely all over the globe are in its favor (Sharma et al., 2013). Solar energy can be exploited in many different ways, the most common being the installation of solar panels on the roof tops and the open spaces. Due to scarcity of open spaces in some countries, parts of the building envelope such as facade can be integrated with a photovoltaic (PV) active layer to form Building Integrated Photovoltaics (BIPV) with added feature of generating electricity. The task of combining chemically different materials such as façade and backsheets for BIPV module presents a huge challenge which requires characterization of the materials at every step.

1.2 Use of Solar Energy in Buildings

According to an estimation, building sector accounts for more than 40% of the European total primary energy need and 24% of greenhouse gas emissions (Bradley et al., 2008; EU, 2009). Therefore, zero energy and zero emission buildings are drawing attention. To make the buildings more energy efficient and reduce the greenhouse gases, use of renewable energy is an obvious choice. Therefore experts in the field of building development are trying to use PV technology to produce energy in an environmentally friendly way. Using BIPV makes a great investment for the future and also can upgrade the value of the current renovation projects for existing buildings.

To help integrate use of renewable energy into the buildings in the future, The European Union has come up with two important directives: the RES (Renewable Energy Sources) directive 2009/28/CE (EU, 2009) which states that the new buildings after 2015 should use minimum non-renewable energy sources and the Net Zero Energy Buildings ED 2010/31/EU (EU, 2010), which states that all new buildings after 2021 will have to be nearly zero energy. To achieve the above directives, PV is considered the most promising renewable energy technology currently available. “Photovoltaic is a truly elegant means of producing electricity on site, directly from the sun, without concern for energy supply and environmental harm” (Strong, 2010).

1.3 Building Integration of Photovoltaics (BIPV)

Building Integrated Photovoltaic (BIPV) is the most promising way within the PV technology to achieve the goals of zero energy buildings with respect to aesthetical, economical and technical solutions. These PV materials replace the traditional building materials and systems in the climate envelope of the buildings, such as the façade and roofs (Jelle et al., 2012). Additionally “BIPV are considered the functional part of the building structure or they are architecturally integrated into the building envelope” (Peng, 2011). Hence the BIPV system serves dual purpose of power generation and building envelope (Strong, 2010). BIPVs do not need allocation of additional land or a PV mounting system, they produce electricity on site, also they help save PV mounting costs. (Neuwald, not dated). Due to the above mentioned advantages and numerous market studies, BIPV will be fastest growing segment of the whole PV market in the coming years. Despite the prediction of BIPV market in Europe growing and reaching 2.5 billion Euros till 2015, a great potential of actually utilizing PV systems in architecture still remains unutilized. It is clear that the PV can be more integral part of building design and building energy balance than it is today (Frost and Sullivan, 2011).

A survey carried out among architects and designers outline the main barriers for the spread of BIPV as lack of high quality, economical, appealing and architecturally integrable design to satisfy the needs of an architect. The main barriers that can be attributed to lack of spread of the PV systems integrated in the buildings are: Architectural barriers (lack of interesting designs, no sufficient literature for the architects, no suitable products available for quality building integration, no tools for design and dimensioning of the system), Economic barriers (not many governmental incentives and cost not justifiable), Knowledge barriers (no sufficient technical knowledge about its use) (Farkas et al., 2010).

Research is needed to develop PV integrated facade elements which provides all the function necessary for the protection of the inside of the buildings. The objective should be to develop separate operating elements such as the facade component and PV module and then merge them aesthetically which should fulfill the functions such as insulation, waterproofing, weather protection, etc. in addition to generate `power´.

1.4 Research Objectives

The first objective of the present research is to discuss BIPV, giving several examples of the different types of products currently available and the advantages in using BIPV.

The second objective is to develop and test connection technologies of façade with backsheets. For a normal PV module, backsheets provide the necessary protection to the PV active layer and the encapsulation against the heat, humidity and other environmental factors to ensure proper electrical insulation (Oreski et al., 2005). Backsheet ensures the long term reliability of the PV modules over their lifetime. Fig. 1 shows the structure of a PV module and the location of the backsheet.

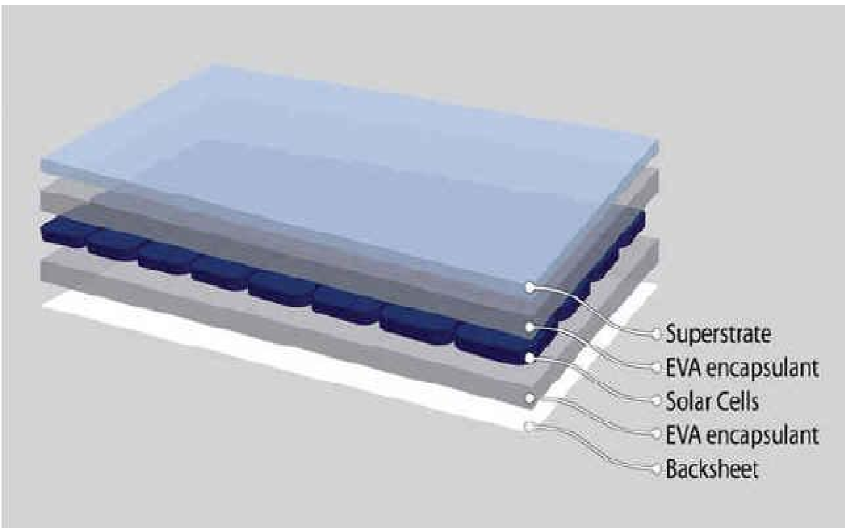

Fig. 1: Schematic of a solar module. Source: www.madico.com

In this thesis, the function of the backsheet is to provide a barrier layer between the façade and the encapsulated PV active layer as shown in Fig. 2

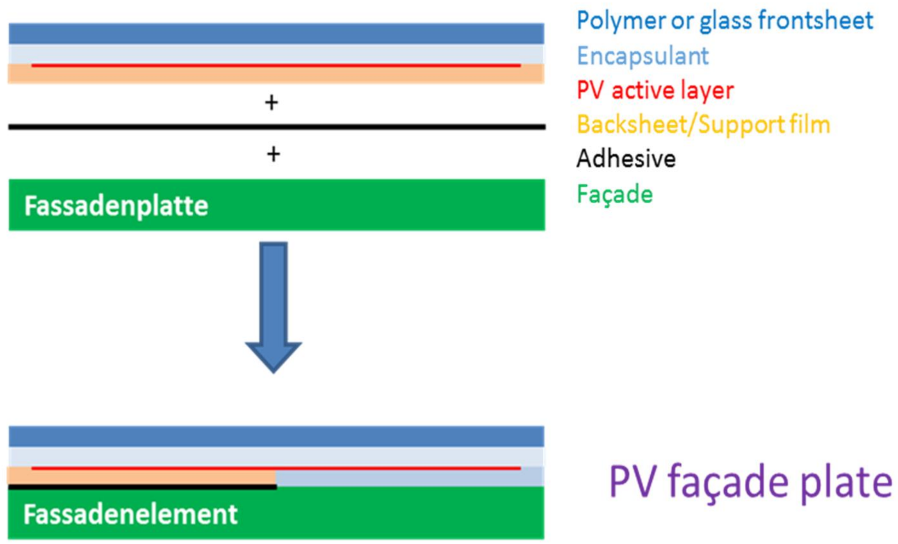

Fig. 2: Schematic representation of multi-material composite PV façade with the backsheet.

The lamination process of the encapsulated PV active film to the façade plate takes place at very high temperature due to high temperature there is outgassing of the façade plate. Due to outgassing, bubbles are formed when there is no barrier film between the facade and encapsulated PV active film as in Fig. 3. Thus backsheet provides the required barrier.

Fig. 3: PV façade with bubbles due to the outgassing of the façade plate

The PV components have to be integrated into the façade surfaces so that they form permanent and long lasting bond. Characterization is required of the surface properties of the façade and polymeric backsheets so they are optimized for maximum adhesion to form a multi material composite.

The façade and the backsheets should be characterized with respect to chemical, physical, thermal and mechanical properties. This is useful for predicting the compatibility of the materials. As these are constructed from different materials (wood based panels, polymers and adhesives). These materials vary greatly in their surface characteristics and adhesion with each other so it is essential to characterize the materials before and after incorporation into the composite.

1.5 Scope of Research

This work includes only the characterization of façade surface and backsheet films which are an important part of the PV structure for the BIPV. This work does not include the electrical, optical characterization and the performance of the PV integrated into façade and with the application of facades plates into the building structure and also the efficiency of the PV films. This work only deals with the initial characterization of façade and backsheet to obtain a proper adhesive for the lamination of backsheet to façade.

1.6 Thesis Structure

This thesis is organized according to the two research objectives stated before. The chapters correspond to the research objectives and are as follows:

- Literature analysis about the photovoltaics in general which includes different types of PV cells, mentioning their general properties and then going on to a PV module. Trends in their development and global PV market
- The second part of the literature analysis is on integration of photovoltaics into the building's outer layers, mentioning different kinds of application types such as Building Added Photovoltaics (BAPV) and Building Integrated Photovoltaics (BIPV). Giving examples on which part of buildings BIPV can be successfully integrated.

Benefits of BIPV including the potential in selected IEA countries and calculation on greenhouse gas (GHGs) emission reduction.

- In the third part, characterization of the two important components in BIPV, façade plate and backsheets is presented. The typical characterization methods used in the PV industry are also used here.
- The fourth part of the thesis is based on finding the right adhesive from the four selected adhesives based on the results from the peel test.
- In the final part, conclusion for the thesis, future work on this subject has been discussed.

2. Photovoltaics: Principles and Types

2.1 Solar Energy to Electricity

A PV cell consists of a semiconductor material, which when exposed to light generates electricity. Multiple PV cells can be connected and encapsulated together depending on the electrical output required. This forms a module which acts as a main building block of a PV system.

The working of photovoltaic cell is based on the absorption of energy by a valence electron of an atom. The energy of the electron is increased by the amount of energy gained by the photon (Kalogirou, 2009). If this increase in energy of the electron is greater than the bandwidth of the semiconductor the electron will jump into the conduction band, where it can move freely and can be removed by applying external electric field. If there is no electric field applied the electron combines with the atom. So an external electric field is required to sweep away the electron and generate current. As only one electron can be freed at a time, this is the reason for the low efficiency of the photovoltaic cells (Kalogirou, 2009). The working of the photovoltaic cell is shown in Fig. 4. The solar cells contain a p-n junction. When the sunlight strikes the solar cell pairs of electron and holes are created. The electric field causes the holes and electrons to separate. The electrons move towards the n-junction and the holes towards the p-junction. If the two sides are connected by an external load, an electric current will flow through it. (Kalogirou, 2009).

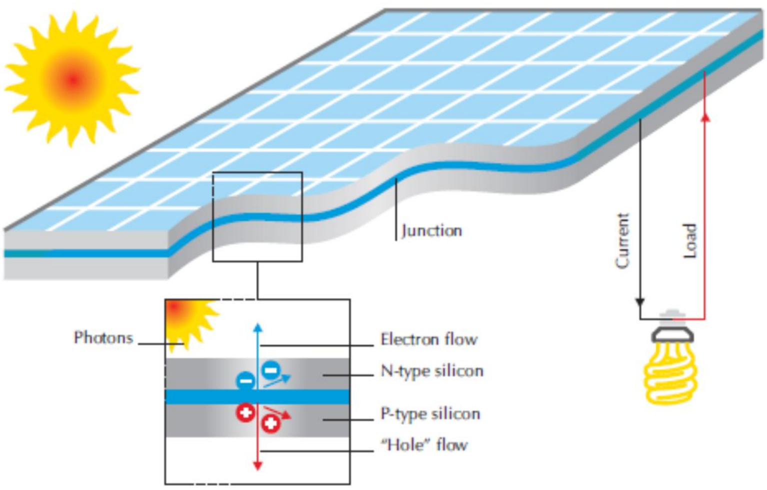

Fig. 4: Working of a Photovoltaic cell, Source: EPIA and Greenpeace, 2011

2.1.1 Advantages of solar electricity

Generating electricity from sun offers many benefits compared to conventional power generating systems which includes (Cholakkal, 2006**).**

- Sun is a reliable source so there will be plenty of energy available.
- Low maintenance as it does not have any moving parts.
- Very modular and can be used on a large scale.
- Emissions only in the manufacturing stage of PV modules. During the working stage no emissions.

2.2 Types of PV Cells

2.2.1 Crystalline silicon cells

Crystalline silicon (c-Si) technology makes up the major part of the current PV market. They constitute about 85% of the modules manufactured (Mints, 2011). These modules have a lifetime of more than 25 years, therefore they have long history of reliable performance (Jordan et al., 2011). The use of crystalline silicone is dominant in the PV industry due to the fact that microelectronics has greatly developed the silicon technology due to the accumulated knowledge due to its use (Tobias, 2004). There are two types of crystalline silicon PV available: monocrystalline and multi-crystalline Fig. 5. Monocrystalline silicon wafers are cut from large cylindrical single crystal silicon ingots. In these cells, the silicon has a single continuous crystal lattice structure with almost no defects or impurities (Kalogirou, 2009). This process is more difficult, energy intensive and expensive. On the other hand, multi-crystalline silicon consists of number of crystals of monocrystalline silicon which are combined to produce an ingot. These cells are cheaper to produce. The record lab efficiency for mono crystalline cell obtained is 25.6% and for multi crystalline cell is 20.8%. (Price et al., 2010; Fraunhofer ISE, 2015). The efficiency of monocrystalline cell is higher than multi-crystalline cell due to the presence of impurities in multi crystalline cells. The single cells are linked and encapsulated together to form modules. The efficiencies of 14% to 16% can be obtained with c-Si PV modules. Using more intense and sophisticated processing and high quality mc-Si wafers, efficiencies of 17% to 21% can be achieved.

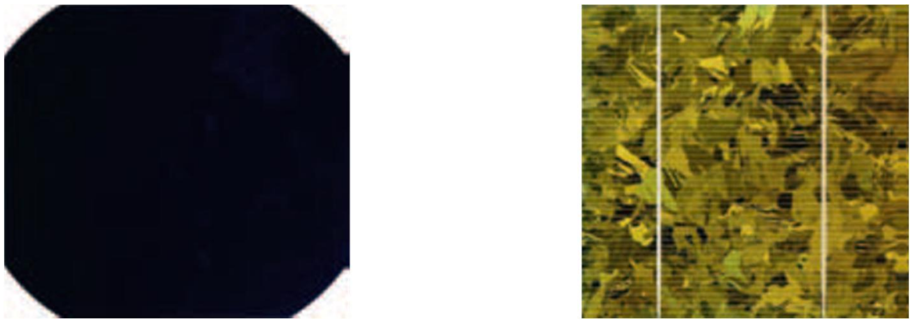

Fig. 5 Mono (left) and Multi (right) crystalline solar cell. Source: www.sapagroup.com

2.2.2 Thin film solar cells

The major cost component for a solar module is the cost of the silicon wafer, which accounts for 40-50% of the total module costs. This cost can be eliminated by using thin films of semiconductors deposited on a glass substrate which is most commonly used (Green, N.D.). Thin film solar cells require very less semiconductor material to manufacture in order to absorb the same amount of sunlight as crystalline solar cells (up to 99% less material) (IRENA, 2012). As thin film are light weight and flexible structures they could be integrated into building components (IRENA, 2012). A thin film solar cell is made up of several layers of different materials in a thin film form (Chopra et al., 2004). Three major types of thin film modules have been described below.

- **Amorphous Silicon (a-Si)**

The use of amorphous silicon in consumer products such as calculators and digital watches have been known since early 1980s. But the use of amorphous silicon in outdoor power modules started recently (Green, N.D.). Amorphous silicon (a-Si) modules make use of thin layer of hydrogenated silicon deposited on glass substrate. Fig. 6 shows the layered structure of the amorphous silicon cell. They generally have lower efficiency.

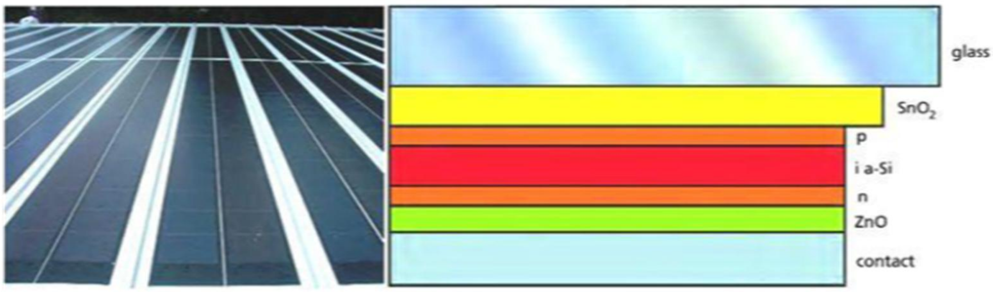

Fig. 6: Amorphous cell (left) and layered structure of the amorphous cell (right). Source: Earthscan, 2008

They have the advantage of low manufacturing cost and high energy production per rated power capacity (kWh/kW_p) (Jardine et al., 2001; Kullmann, 2009). The high power output is achieved as a-Si cells are least affected by heat with the temperature coefficient around -0.2% per degree Celsius (Marion, 2008). Also amorphous silicon is very effective in absorbing the blue wavelength of light that is seen in cloudy conditions. Thus a-Si module can produce more electricity than crystalline module of the same peak power in a year in cloudy and warm conditions. But still they only have efficiencies of around 6-7%. Due to their low cost, they can be applied to different PV systems but the use of a-Si systems is decreasing due to the development of new thin film technologies with higher efficiencies. To increase the efficiency, a-Si modules are combined with layers of multi or mono crystalline silicon to obtain a hybrid. The efficiency of such a hybrid is between 9-10%. The important advantage of a-Si is that they can be deposited on rigid and flexible substrates (Price et al., 2010).

- **Cadmium Telluride (CdTe)**

CdTe cells are considered as one of the most promising thin film technology. The bandgap matches perfectly with the solar spectrum. In laboratories, efficiencies of 16.5% have been achieved (Ullal, 2009; Wu, 2004). These are made using extremely thin (few mm) layers of binary semiconductors electrodeposited on glass panes (Raugei et al., 2009). Fig. 7 shows the structure of the CdTe cell. These are comparatively new technologies, which only began to hit the market in the early 2000s. (Ibid). The thin film market was developed by a single manufacturer, First Solar. They accounted for 59% of the global thin film market in 2008 due to low lost and large production capacity. It was the first company to manufacture PV modules at less than $1 per Watt. (Schreiber, 2009; Runyon, 2012). As of today, due to large scale production of low cost PV modules in China, price advantage of CdTe has fallen. Still CdTe has a fair share of market with the manufacturing cost of less than $0.75/W. CdTe being tolerant to heat has an efficiency of 10% to 11%. The relative low cost, moderate efficiency and large manufacturing volume has created a market for CdTe in large ground mounted installations for commercial electricity generation in recent years (Runyon, 2012).

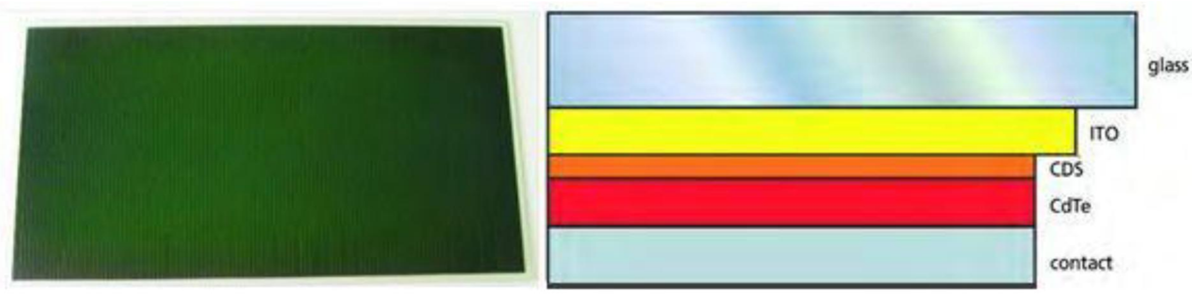

Fig. 7: Cdte module (left) and layered structure of a Cdte cell (right). Source: Earthscan, 2008

The main issue with the use of Cdte modules is the toxicity of cadmium therefore they are banned in some countries such as Netherlands (Green A., N.D.). Some supporters of this technology point out that the required cadmium is a by-product of zinc mining (NREL, 2005). Many module developers are working to eliminate the use of cadmium entirely from their product line citing environmental concern (Schmela et al., 2002).

- **Copper Indium Selenide (CIS)**

In thin film solar cells, highest efficiency on a laboratory scale has been achieved with CIS but has encountered various problems commercializing. The difference between CIS and other thin film technology described above is that in CIS the deposition is on to glass substrate than glass superstrate. (Green, N.D.) The use of copper Indium Selenium or diselenide in solar cell manufacturing is one of the most efficient thin film technologies available today. They have similar advantages as the other thin film technologies like the low cost and high continuous volume of production. Fig. 8 shows the structure of the layered CIS cell. They do not need glass substrate making them light weight and flexible (Earthscan, 2008).

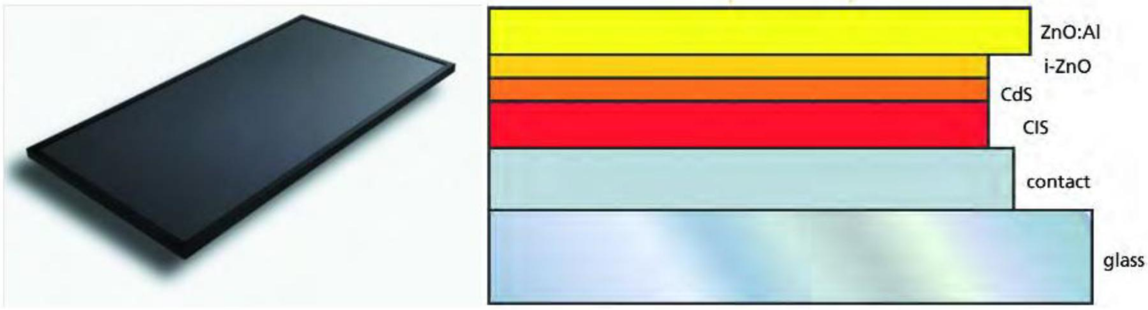

Fig. 8: CIS module (left) and cell structure (right). Source: Earthscan, 2008

The problem encountered in the use of CIS is the instability under moisture in all alloy compositions (Malmström et al., 2002). Due to this problem, it has been a challenge in the past to pass the standard qualification tests for CIS cells than other technologies (Green, N.D.).

There has been a substantial growth in the thin film module production in the last decade Fig. 9. Being light weight and flexible they can be used for BIPV. Also they are tolerant to high temperature, yet they have high efficiency. Copper Indium Gallium Selenide (CIGS) is the most recent thin film technology that has been commercialized. They have the same advantages as the other thin film technologies. Also they have slightly higher conversion efficiencies. They are the most promising technology to be used for BIPV. (Schreiber, 2009)

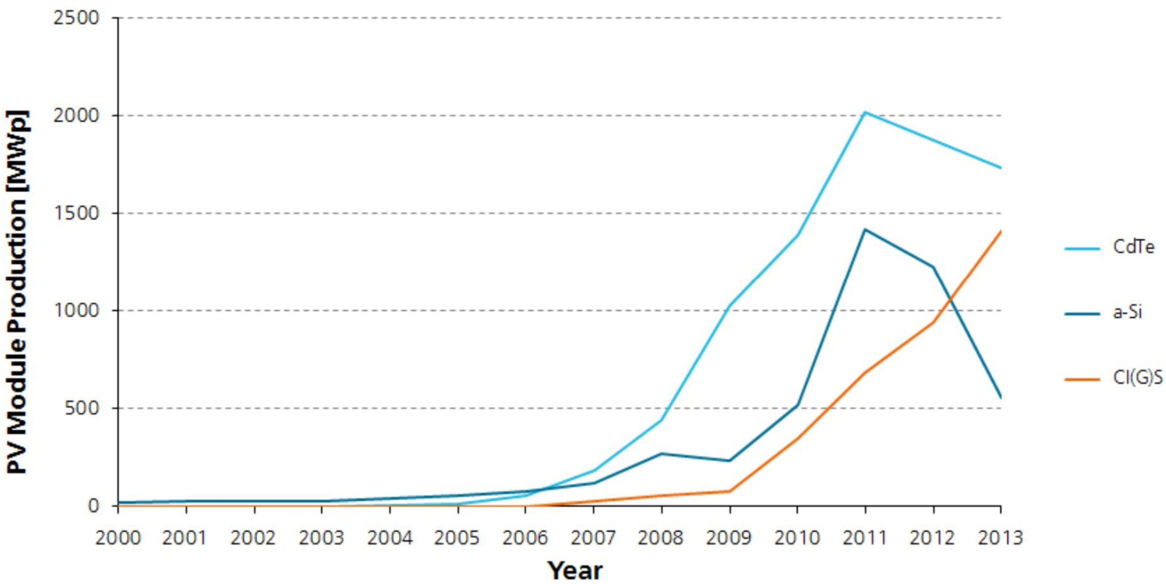

Fig. 9: Annual thin film PV module production in MWp from 2000 to 2010. Source: PSE AG 2014

Temperature and space can determine the choice of module to be used for a given project.

As seen above, crystalline silicon modules are more efficient (i.e., give greater power output per unit area of module) but they cannot be used in higher temperatures. The decrease in power output of crystalline silicon is rapid with increasing cell temperature. Also low light conditions decreases the efficiency of crystalline silicon, whereas the efficiency of thin film modules roughly remains same. (Insight, 2010)

Fig. 10 below gives the development of the PV cells in terms of the efficiency. New technologies such as multi-junction concentrator solar cells have shown high efficiencies but they are still not commercialized. Mono and multi crystalline silicon cells are most widely used due to their higher efficiencies over the years. Also thin film cells have shown promise due to cheaper production costs.

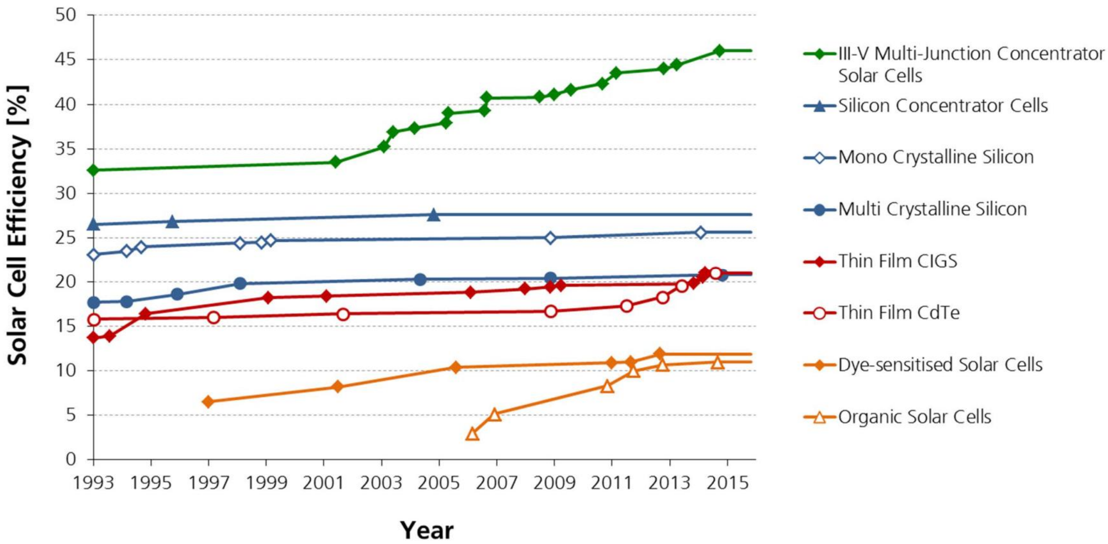

Fig. 10: Solar Cell Efficiency from 1993-2015. Source: Fraunhofer ISE 2015

2.3 Photovoltaic Module

Photovoltaic module can be described as a system of photovoltaic cells that convert the energy from the sun to electricity without using any moving parts. They are easy to maintain and have long life. A photovoltaic system can generate electricity from milliwatts to megawatts which can be done by addition of more panels Multiple PV cells can be connected and encapsulated together depending on the electrical output required. They are enclosed in an external frame and glass casing to protect them from environmental influences. This forms a module which acts as a main building block of a PV system. The power generated by PV modules can be between 50-315W depending on the application (IEA PVPS, 2014)

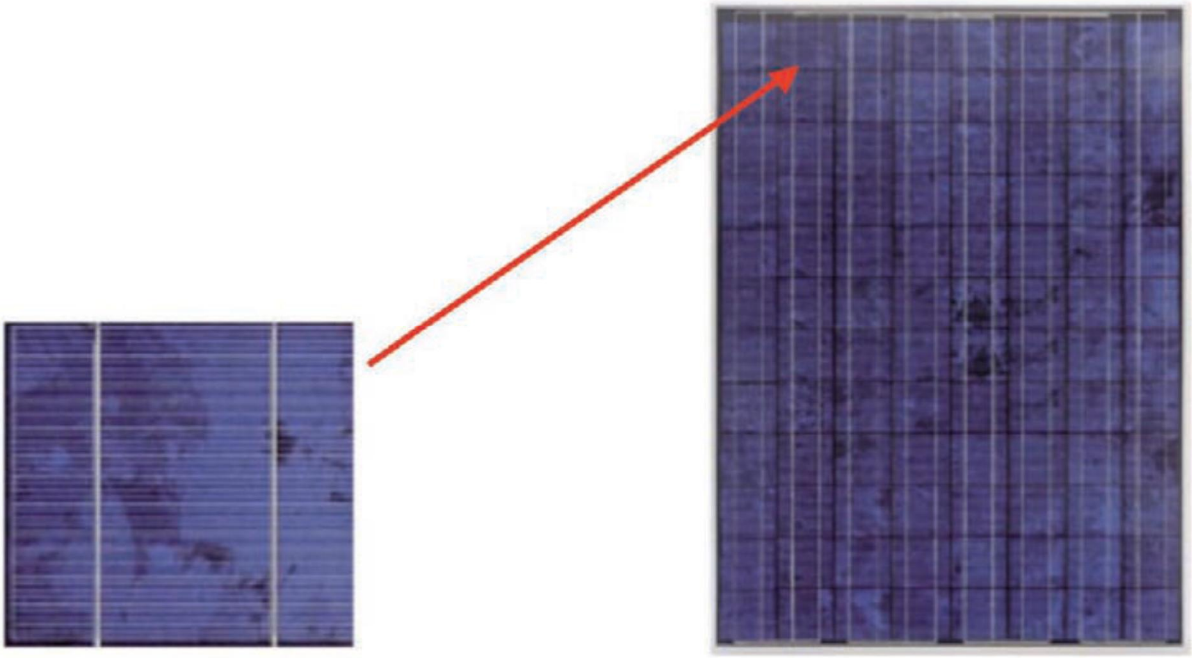

Fig. 11: From a single cell to module

For BIPV, there are specialized modules with larger sizes. The most commonly and widely used crystalline silicon modules have commercial efficiencies between 14-21%. They are manufactured by encapsulating individual PV cells between a glass and a backsheet generally plastic or glass. Thin film modules have an efficiency of 7% for a-Si and 14% for CIGS and CdTe. In thin films the PV cells are encapsulated into flexible or fixed module. The PV modules are typically guaranteed to last 25 years. (IEA PVPS, 2014) Fig. 12 gives the overview of the various types and sizes of the PV modules available in the market.

Fig. 12: Standard modules available in the market. Source: Probst et.al, 2013

A PV system is made up of as several PV modules, connected to an electricity grid network or off grids which can consists of, charge controllers, inverters or batteries. A PV module should have a lower energy payback time for it to be considered as feasible and economical. About 50 years back the energy required to produce the PV panel was more than the panel could produce in its lifetime. But, during the last decades due to the improvements in the efficiency and newer technologies the payback times have decreased to 2-3 years for c-Si systems and one year to some thin film systems considered under normal levels of sunlight. (IEA-PVPS, 2014)

2.3.1 Efficiency of a PV module

The cost of PV modules fell rapidly after 2008 and the cost of the silicon based wafer cells decreased greatly. The market share of crystalline silicon PV modules was 90% in 2012 and was considered the main technology. Fig. 13 gives the module and individual cell efficiencies for various types of technology. The most efficient technology till date available is the mono crystalline silicon which has efficiencies ranging from 14-21%. The poly crystalline module technology has efficiencies between 12-18%. In thin film technologies, CdTe and CIGS have achieved efficiencies till 16% for a module. (Jäger-Waldau, 2012)

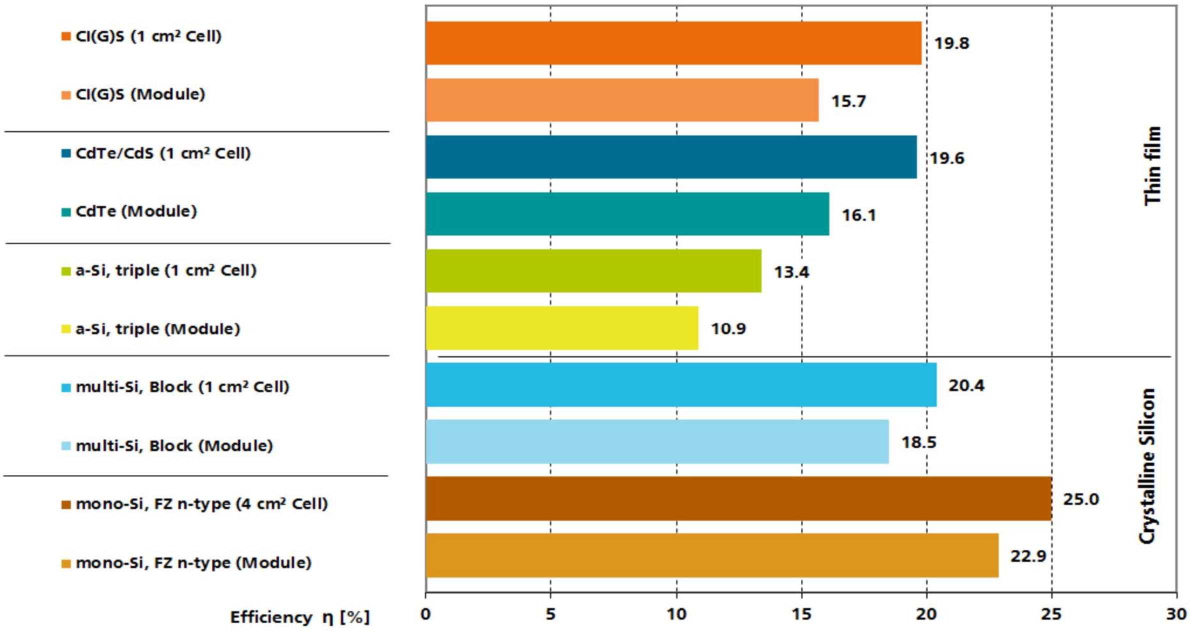

Fig. 13: Comparison of the solar cell and solar module efficiencies. Source: PSE AG 2014

2.4 Development of the PV Market

Till the end of 2013, the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) participating countries had more than 125 GW of PV installations together. The countries which are not the part of IEA PVPS had the capacity of 10.7 GW together. The countries all over the world have started to develop PV systems but have not reached significant figures in terms of installed capacity at the end of 2013. In the countries which are not the part of the IEA PVPS, India reached the capacity of 2.3 GW of installed capacity. (IEA PVPS, 2014). Fig. 14 shows the global PV market in 2013, which is led by China, Japan and USA.

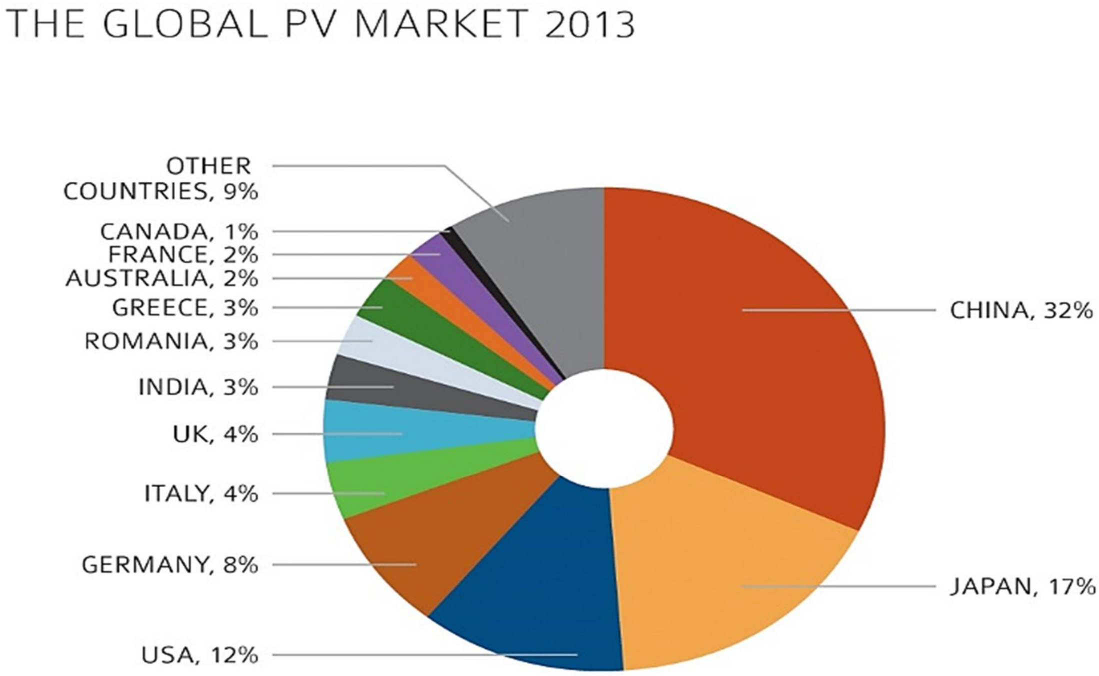

Fig. 14: The global PV market in 2013. Source: IEA PVPS

According to the estimation of European Photovoltaic Industry Association, an additional 3.6 GW of PV systems have been installed in the last twelve years. But the other sources indicate just 1 GW of installed capacity. According to all estimations presently it seems that 136.5 GW is the minimum installed capacity by the end of 2013. Adding to this, the figure stated by European Photovoltaic Industry Association the overall capacity of the installed PV systems would increase to 140 GW. The most eye catching trend in the PV market on the global scale has been the growth of 35% in 2013. According to the Fig. 15, China has the largest number of installations about 12.92 GW in 2013. The second place is taken by Japan which has 6.97 installations in 2013. The capacity installed by USA was 4.75 GW in 2013. (IEA-PVPS, 2014).

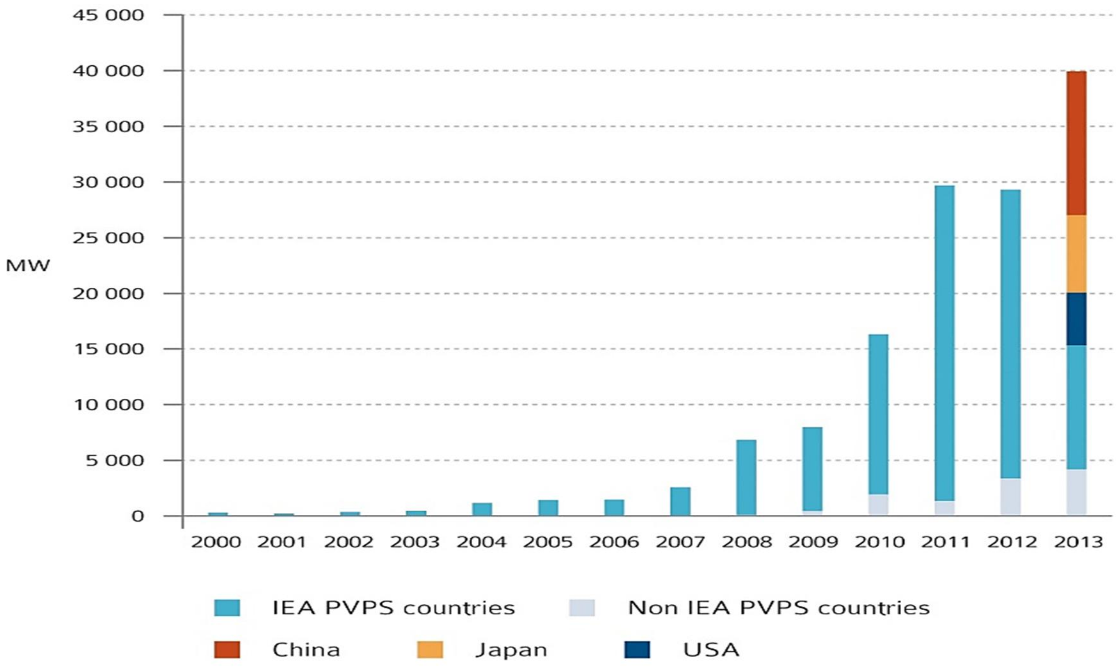

Fig. 15: PV installations per year from 2000 to 2013. Source: IEA, PVPS, 2014

3. Building Integration of Photovoltaics

The development in the field of photovoltaics has transformed buildings from energy consumers to energy producers (Prasad et al., 2014). BIPV is the structural, architectural and aesthetic integration of photovoltaics into buildings which allows for the energy generation from all types of buildings. In BIPV, photovoltaics serve as building's exterior such as roof, façade and skylight which provide protection, aesthetic value and electricity generation. BIPV is a multifunctional technology which provides weather protection, thermal insulation, noise protection and daylight control (Rode et al., 2007). The total net cost of installed BIPV and the additional wiring associated with it can be often less than the conventional façade in a new construction (Archer et al., 2001). The buildings electrical load profile and output power required determines the size and design of the BIPV system. Building's design requirements, local climate, installation angle, orientation, module temperature, shading and possible future load estimation should be considered while installing BIPV and to achieve maximum electrical efficiency and energy performance of the buildings. (Peng et al., 2011; Norton et al., 2011). BIPV can help reduce demand on the power grid due to the generation of power in the building itself and thus helps in improving the reliability of the power supplied to the building (Kalogirou, 2009).

The integration of PV systems into the building envelope can be classified into two main types: BAPV (Building Applied Photovoltaics) and BIPV (Building Integrated Photovoltaics) (Barkaszi et al., 2001).

3.1 Building Applied Photovoltaics (BAPV) Systems

These are applied on the roof of a building and are just considered as technical devices without any architectural function (for example tiles, shingles, flat roofing). They generate electricity without adding aesthetic value to the existing building. Supporting structures are required for the photovoltaic modules. The main aim of BAPV is to generate electricity (Peng et al., 2011).

Fig. 16: An example of BAPV on the roof. Source: www.riddersolar.com

3.2 Building Integrated Photovoltaics (BIPV) Systems

These consist of solar photovoltaic cells and modules that are an integral part of the building structure. They can be integrated into the building structure during the construction phase, thus replacing the conventional materials that are used in roofs and facades. BIPV are often integrated in such a way that they are indistinguishable from normal construction materials (Crawford et al., 2006; Barkaszi et al., 2001). BIPV modules can enhance appearance of the building and create good visual effects. They provide aesthetic value to the buildings and fulfill the main functions such as weather protection, sun protection, noise protection, heat insulation and security (Boemi et al., 2015). Fig. 17 gives the two different applications of the BIPV which are façade and roofing. Some of the product group are described below in detail.

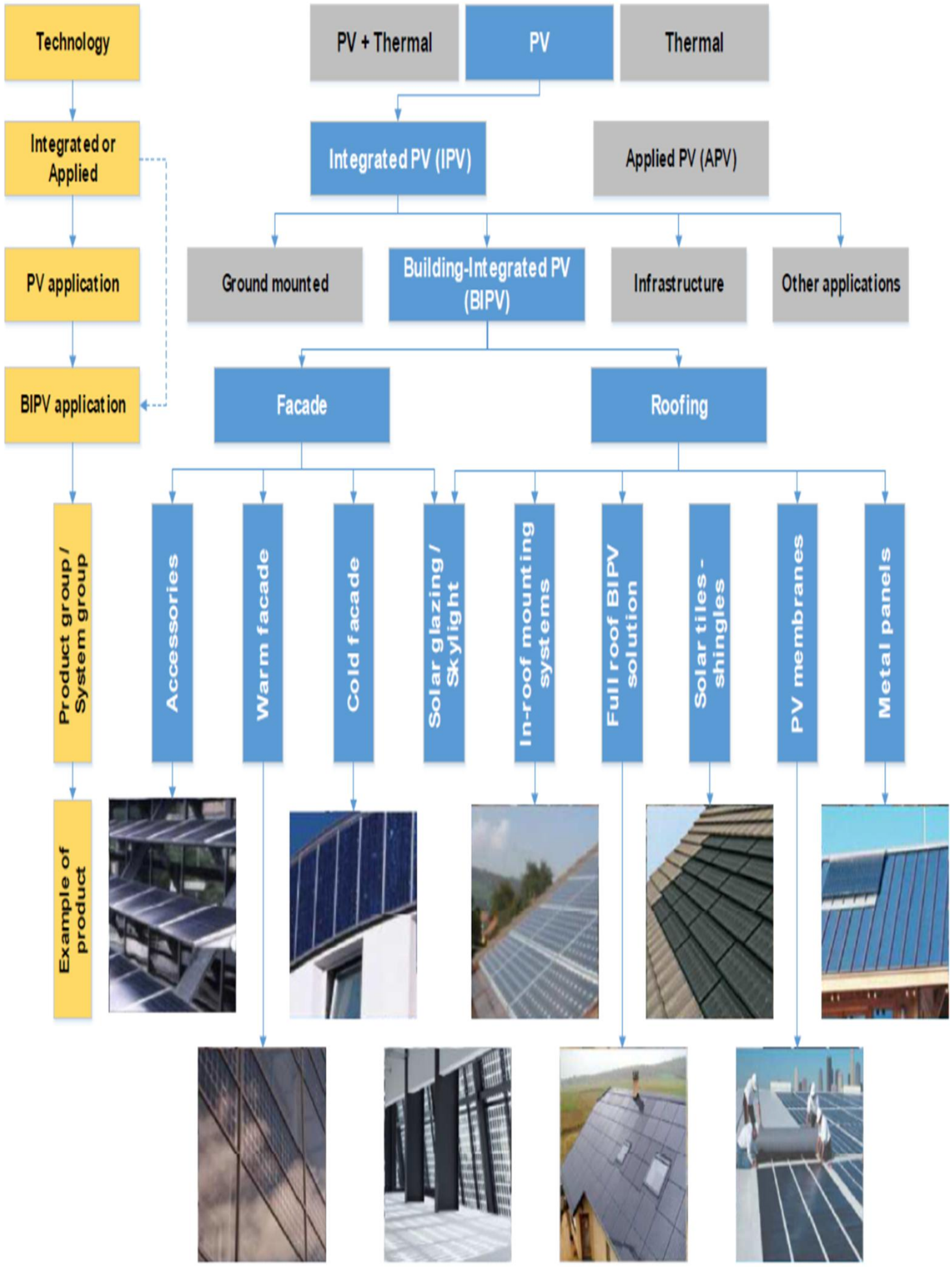

Fig. 17: Different types of BIPV applications. Source: Verberne, et al. 2014

3.2.1 Types of Building integrated photovoltaics

BIPV products are categorized taking into account the installation location on the building (Verberne, et al. 2014).

The main BIPV categories are:

- The roof (which includes tiles, shingles, skylights, slates, standing seam systems, etc.)

- The façade (which includes curtain wall products, spandrel panels, glazing, etc.)

A wide range of BIPV residential applications exists today. PV modules can be mounted on the roofs or replace the conventional building envelopes such as facades. BIPV are considered a functional part of the building structure and they can be architecturally integrated into the building's design. (Breivik, 2012)

The roof

The PV modules can be added to the roofs which is the most common way, they can be integrated into the external layer of the roof or they can be fully integrated to make PV modules act as a roof (semitransparent modules which act as daylight modulators). The choice of the PV component used will depend on the different requirements it has to meet. Below, a general overview of the way PV can be used in roofs is presented.

There are two different alternatives for installing PV modules on the roof (Maturi, 2013):

- *Integrate them to the roof structure*

This method can be used in the integration of the PV modules into the existing flat or tilted roof structures. They may require additional mounting systems and reinforcement to support the additional load by the PV systems.

Fig. 18: Inbuilt roof integration. Source: www.solon.com, www.solarwatt.com

Due to different types of roof shapes and systems, several products are available such as slates, roof tiles and shingles which match the traditional roof products Fig. 19.

Fig. 19: Solar tiles (left) and solar slates (right). Source: www.smartroof.be,www.powerslates.com

Solar tiles and slates use crystalline and thin film technologies. The value in using a smart mounting system enables the panels to be mounted in between the original roofing elements (e.g. solar tiles). Depending on the function, PV products can be used for any type of building (industrial or residential). (Probst et al., 2012)

- *Fully integrated to make PV modules act as roof*

A PV system can be used as a complete roof covering which will fulfill all its required functions. Semi-transparent crystalline or thin film modules can be used where daylight modulation is required while simultaneously performing the function of generating electricity. The PV cells absorb 70-80% of the sun's radiation. The space between the cells as shown in Fig. 20 transmits enough diffused sunlight to achieve a pleasant lighting level. These modules also can be employed for curved roof surface or flat roof surfaces Fig. 20 which uses semi-transparent crystalline silicon roof. (Maturi, 2013)

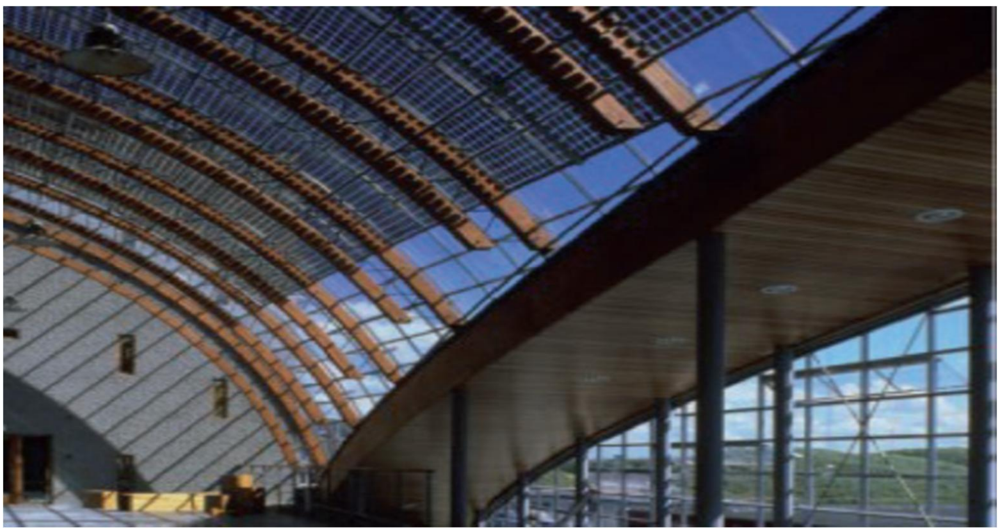

Fig. 20: Semi-transparent and curved c-Si-skylight roof. Source: Bear Architecten, 2001

The façade

A PV system can be substituted as a complete external layer of facade or it can substitute the whole facade (Schittich et al., 2001).Facades need to fulfill the basic functions of the building envelope such as

- Sun protection
- Heat protection
- Noise protection
- Insulation

There are two different ways in which PV can be used in facade (Probst et al., 2012).

Cold and warm facade integration

In cold facade structures, the PV panel is used as a cladding structure which is mounted on a normal facade. In these installations, ventilation is necessary as the performance of the PV modules can be affected due to increase in the temperature (Maturi, 2013). Fig. 21 presents the facade cladding systems, for PV modules.

Fig. 21: Examples of PV integration into the façade. Source: Hermannsdörfer/Rüb Solardesign, 2005, PREDAC 5FP

Semi-transparent façade

These types of facade solution can be used where the intensity of light indoors, needs to be controlled. Intensity of light can be controlled by the spacing between the two cells as shown in Fig. 22. Semitransparent, photovoltaic-glass windows are able to generate electricity as well as providing protection from the ultraviolet and infrared radiation. The windows are generally made of glass PV laminates which are available with a full range of customizable options and can be applied as a semitransparent façade. The transparency is normally achieved either a space left between two solar cells or it is possible to see through thin PV cells. Light effects created due to solar cells leads to an ever-changing pattern of shades in the building. (Pagliaro et al., 2010)

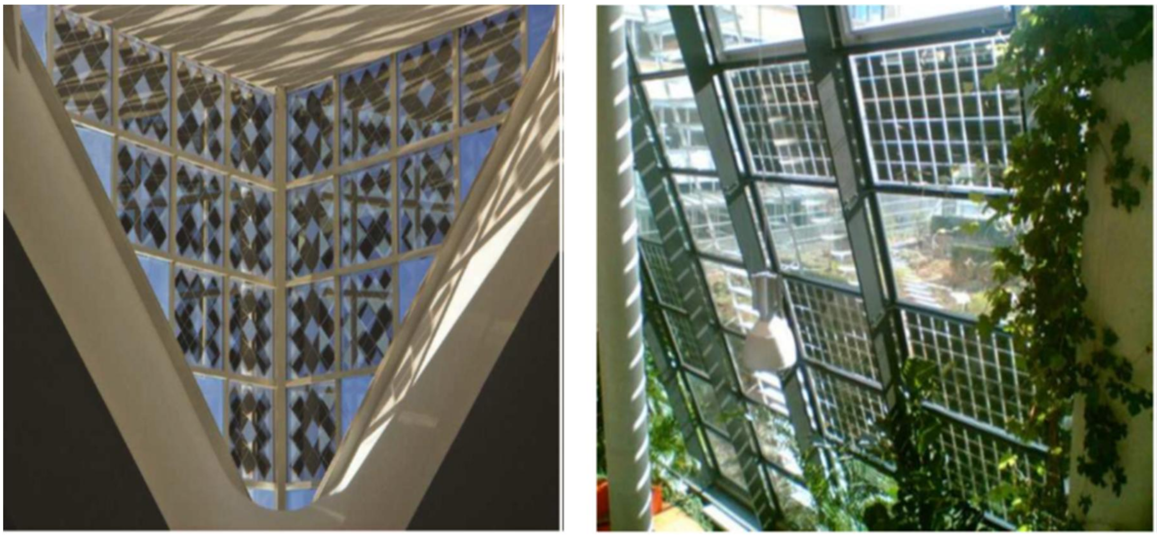

Fig. 22: An example of transparent façade. Source: www.napssystems.com, Solar Consulting

As these solar panels give only partial protection from sun, care should be taken that it does not heat up the inside air. Crystalline cells or thin film modules can be used to for semitrans-parent facade solution. Different types of colored PV panels can be used for aesthetic effect.

3.3 Potential of BIPV

According to Hofierka J. and Kaňuk J. in future, large scale PV applications will be in the urban areas as these will be the main consumption centers. According to statistics, 80% of the people living in the most developed countries live in urban areas. As large amount of energy will be consumed, this will lead to huge production of green-house gases (Hofierka et al., 2009). Decreasing the amount of green-house gases or bringing them down to zero would be the main aim of the future urban centers. To assess the huge potential available for building-integration applications such as PV requires the estimation of the available surface area of the roof and facades (Izquierdo et al., 2008).

As pointed out by Šúri M. et al., in theory the consumption of electricity in many countries could be covered by utilizing only 1% of the area for PV installations (Šúri et al., 2007). In the future a large part of the PV market will be associated with building applications especially in high population density areas such as Europe and Japan where the available land is valuable (Reijenga et al., 2002).

There is a huge potential for integrating photovoltaics into buildings. There are many free surfaces on the roof or facades of the buildings all over Europe which could satisfy a large amount of power consumption, by producing in a clean and environmentally friendly way. The potential for BIPV application requires and in-depth analysis of the building structure with respect to suitability for BIPV utilization. There are number of limitations a building can face such as technical limitations, poor orientation which limits PV power generation, inclination of the roofs and facades and shading effects due to surroundings. So, an accurate BIPV potential calculations studies are important to evaluate the market potential and give out the information to all the concerned groups involved. (Eiffert, 2003)

There are few studies carried out to measure technical potential of PV on buildings, most of them use the basic methodology described in IEA photovoltaic power systems programme (PVPS Task 7) (Nowak et al., 2002; Eiffert, 2003). In this method the authors make use of the statistical information that is readily available such as building stock which is combined with the assumptions to get the real surface areas that are suitable for solar applications. The authors use ground floor areas of the building to get the available roof and façade areas. The most important terms and factors for BIPV potential calculation are given in Fig. 23.

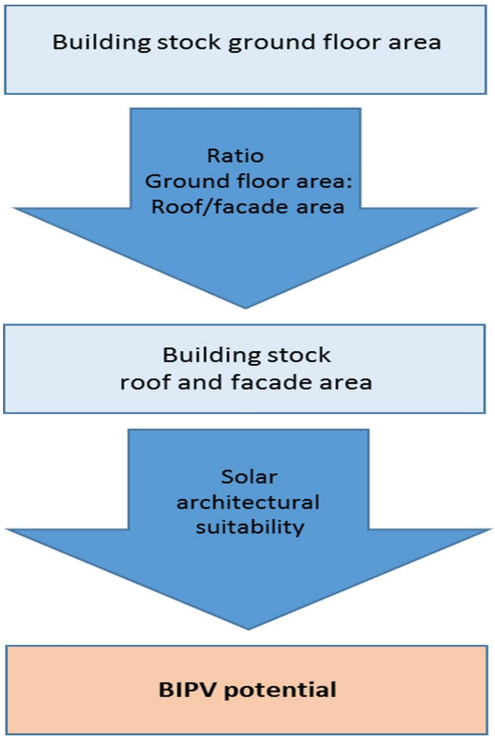

Fig. 23: Important terms and factors for BIPV potential. Source: Nowak et al., 2002

The important factors that are required for obtaining BIPV potential for roof and façade from ground floor area and the solar and architectural suitability can be obtained by analyzing representative sample set of building stock and then on different segments of a particular building stock and then upscaling the results to all other buildings stocks available in the region. From this, sufficient data and methodological knowledge is available to derive some general factors for calculating BIPV potential. (Gutschner et al., 1998) The methodology for calculating the suitable area for BIPV installations on façade and roof is based on simple rule of thumb, for every m^2 of building ground floor area there is on average $0.4m^2$ of rooftop and $0.15\ m^2$ of façade area with good BIPV potential (IEA-PVPS, 2002).

Table 1 provides the BIPV potential of all buildings (residential, industrial, commercial and other buildings) in km^2 for some selected IEA countries and fulfilling the criteria of 80% of maximum annual solar input for roofs and facades.

Table 1: BIPV area potential in selected IEA countries (Nowak S. et al. 2002)

Countries	Potential Roof (km^2)	Potential Façade (km^2)
Australia	422.25	158.34

Austria	139.62	52.36
Canada	963.54	361.33
Denmark	87.98	32.99
Finland	127.31	32.99
Germany	1295.92	485.97
Italy	763.53	286.32
Japan	966.38	362.39
Netherlands	259.36	97.26
Spain	448.82	168.31
Sweden	218.77	82.04
Switzerland	138.22	51.83
United Kingdom	914.67	343.00
United States	10096.26	3786.10

The electricity generation potential by BIPV can be calculated by multiplying average area per capita suitable for solar architecture to specific country data such as population size and annual solar irradiation based on the formula given in Fig. 26.

$$\text{Production of solar electricity} = \text{Available area per capita} * \text{Population size} * \text{Utilization factor} * \text{Solar yield} * \text{Solar irradiation} * \text{Global conversion effficiency}$$

Fig. 26: Formula for production of solar electricity from BIPV. Source: (Nowak et al. 2002)

More detailed description of the formula is given below (Nowak et al. 2002):

- Production of solar electricity: Given in TWh/y as the product of all above factors.
- Available area per capita: Obtained as standard average figures and standard per country given in m^2.
- Population size: Number of people living in a country, given in millions.
- Utilization factor: Solar and architectural suitability obtained in relative terms, 0.4 for roofs and 0.15 for facades.
- Solar yield: weighted average relative yield of good areas per geographical unit

- Solar irradiation: Maximum annual solar input calculated as country specific weighted value given in kWh/yr/m^2.
- Global conversion efficiency: Ratio of “electricity output/solar irradiation” (generally 10%).

Table 2: Solar electricity production potential for roofs and facades for selected IEA countries

Countries	Potential solar electricity production Roof (TWh/y)	Potential solar electricity production Façade (TWh/y)
Australia	68,176	15,881
Austria	15,197	3,528
Canada	118,708	33.054
Denmark	8,710	2,155
Finland	11,763	3,063
Germany	128,296	31,745
Italy	103,077	23,827
Japan	117,416	29,456
Netherlands	25,677	6,210
Spain	70,689	15,784
Sweden	21,177	5,515
Switzerland	15,044	3,367
United Kingdom	83,235	22,160
United States	1662,349	418,312

According to IEA, in 2010, buildings consumed 65% of the total electricity generated in OECD countries. This confirms the importance of this sector and the impact it will have on the GHG emissions or to reduce it (IEA, 2013). Table 3 provides the information on the electricity requirements of the buildings in selected IEA countries calculated from the total electricity production in that country (IEA, 2012)

Table 3: Ratio of "Total BIPV potential/Buildings electricity requirements" for selected IEA countries.

Countries	Total electricity generation (TWh)[1]	Buildings electricity requirements (TWh/y)	Total BIPV potential (TWh/y)	Ratio "Total BIPV potential/Buildings electricity requirements" (%)
Australia	**241,6**	157,04	84,057	53,53
Austria	71,1	46,215	18,725	40,52
Canada	608	395,2	151,762	38,40
Denmark	38,8	25,22	10,865	43,08
Finland	80,7	52,455	14,826	28,26
Germany	629	408,85	160,041	39,14
Italy	302,1	196,365	126,904	64,63
Japan	1119,2	727,48	146,872	20,19
Netherlands	118,1	76,765	31,887	41,54
Spain	303,1	197,015	86,473	43,89
Sweden	148,6	96,59	26,692	27,63
Switzerland	67,8	44,07	18,411	41,78
United Kingdom	381,1	247,715	105,395	42,55
United States	4378,4	2845,96	2080,661	73,11

This analysis suggests that BIPV could satisfy electricity requirements of a building ranging from 20% to 75% for different countries assuming good solar yield criteria of about 80% (Nowak et al., 2002). The lowest is for Japan and highest is for United States, which suggests that the BIPV could supply 2080,7 TWh of electricity of the required 2846 TWh for United States. The ratio of total BIPV potential to buildings electricity requirement highly depends on technical aspects of PV, building areas available, solar irradiation and electricity consumption of buildings sector in a particular country. The big differences in the percentages

[1] Total electricity generation is taken for the year 2010.

of the buildings electricity requirements satisfied by BIPV between United States, Australia and Japan is due to availability of building areas. The densely populated areas generally have less roof area available per capita that can be potentially used for BIPV. On an average Japan has only 8 m^2 of area available per capita in comparison to United States and Australia which have 36 m^2. (Nowak et al., 2002).

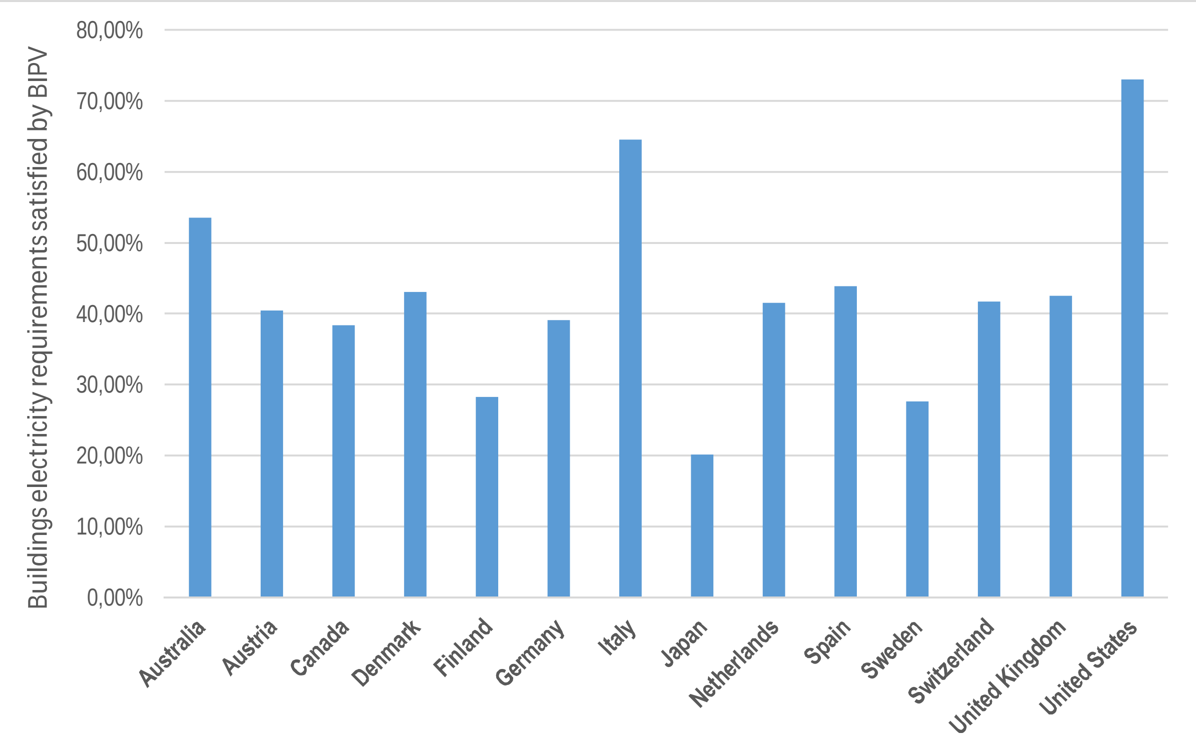

Fig 24: Buildings electricity requirement satisfied by BIPV

3.4 Advantages of BIPV

While generating electricity, BIPV systems produce no harmful GHG emissions. This can avoid the extra costs for the treatment of emissions and help save the environment. This cost savings can be included in the Life Cycle Costs analysis of the entire BIPV system. As an example, an Australian high rise PV-integrated building has reported reductions of 1640 tons of CO_2 per annum (Wren et al., 2000). Table 4 summarizes the benefits of the BIPV according to environmental, architectural and socioeconomic aspects (Eiffert, 2003).

Table 4: Summary of the benefits that can add value to the BIPV systems (Eiffert, 2003)

Category	Potential Values
Environmental	Reduced air emissions of particulates, heavy metals, CO_2, NO_X and SO_2 resulting in lower greenhouse gases, reduced acid rain, and lower smog levels; reduced power station land and water use; reduced impact of urban development; reduced risks of nuclear accidents, significant net energy generator over life time
Architectural	Substituting the building component; multifunction potential for insulation, waterproofing, fire protection, wind protection, daylighting, shading; aesthetic appeal through color, transparency and non-reflective surfaces
Socioeconomic	New industries, products, markets; local employment for installation and servicing; reduced fuel imports; urban development and renewal; lower impacts than fossil fuels and nuclear

3.4.1 Potential for reduction in greenhouse gas emissions

The greenhouse gas emission reduction for selected IEA countries was estimated by calculating the greenhouse gas emissions that can be avoided annually by replacing the equivalent amount of electricity generated by current sources by the same amount of electricity generated by BIPV (Pelland et al., 2006).

The reduction in GHG emissions for a given country can be calculated as:

$G = E \times g$

where E = BIPV electricity generation potential

g = amount of GHG emitted per kWh of generated electricity (emission intensity)

The emission intensity values for all countries were taken from Department of Energy and Climate Change, Government of UK and Brander et al., The emission intensity factors for CO_2, CH_4 and N_2O are provided in Table 5 for some selected IEA countries (Brander et al., 2011; Defra/DECC 2011a). In the calculations hereafter, all the emission intensity factors are in the units of kilograms of carbon dioxide equivalent of Y per X (kg CO_2e of Y per X), Y is the gas emitted and X is the unit activity. To indicate the global warming potential (GWP) of GHGs, CO_2e is the universal unit of measurement. Here the emission intensity factor is split out into separate factors for each gas i.e. kg CO_2 of $CO_2/CH_4/N_2O$ per unit of electricity generated or T&D losses of electricity, which is the sum of the total kg of CO_2e per unit of the above mentioned activities (Defra/DECC 2011a).

Table 5: Emission intensity factors for kWh of electricity generated

Countries	**kgCO_2/kWh**	**kgCH_4/kWh**	**kgN_2O/kWh**
Australia	0.991757127	0.00001100373	0.00001378366
Austria	0.176796609	0.00000221471	0.00000113728
Canada	0.179763325	0.00000224792	0.00000237433
Denmark	0.374745583	0.00000489961	0.00000478713
Finland	0.225457295	0.00000260698	0.00000243179
Germany	0.672220452	0.00000721994	0.00000909965
Italy	0.410898038	0.00000707784	0.00000280634
Japan	0.443356848	0.00000709862	0.00000396430
Netherlands	0.413302564	0.00000553629	0.00000286965
Spain	0.34287509	0.00000553451	0.00000307467
Sweden	0.023033883	0.00000025655	0.00000013911
Switzerland	0.003177437	0.00000007019	0.00000000947
United Kingdom	0.508501975	0.00000675405	0.00000512153
United States	0.547096737	0.00000655331	0.00000724137

3.4.2 Results and Discussion

It is assumed GHG electricity intensity is 0 for PV as PV systems produce no GHG emissions during operation (Pelland et al., 2006). The potential of electricity generation from BIPV is given in Table 3 and the emissions intensity factors are used to get the yearly emissions reduction. Table 6 gives the yearly GHG emissions reductions for electricity generated by PV integrated into the roof. Table 7 gives the yearly GHG emissions reductions for electricity generated by PV integrated into the façade

Table 6: GHG emission reduction per year for PV integrated into the roof.

	Megatonnes CO_2e			
Countries	**CO_2**	**CH_4**	**N_2O**	**Total**
Australia	67,61403	0,00075	0,00094	67,62
Austria	2,68678	0,00003	0,00002	2,68683
Canada	21,33934	0,00027	0,00028	21,33989
Denmark	3,26403	0,00004	0,00004	3,26412
Finland	2,65205	0,00003	0,00003	2,65211
Germany	86,24320	0,00093	0,00117	86,24529
Italy	42,35414	0,00073	0,00029	42,35516
Japan	52,05719	0,00083	0,00047	52,05849
Netherlands	10,61237	0,00014	0,00007	10,61259
Spain	24,23750	0,00039	0,00022	24,23811
Sweden	0,48779	0,00001	0,00000	0,48780
Switzerland	0,04780	0,00000	0,00000	0,04780
United Kingdom	42,32516	0,00056	0,00043	42,32615
United States	909,46571	0,01089	0,01204	909,48865

Table 7: GHG emission reduction per year for PV integrated into the façade.

	Megatonnes CO_2e			
Countries	**CO_2 kg**	**CH_4**	**N_2O**	**Total**
Australia	15,75009	0,00017	0,00022	15,75
Austria	0,62374	0,00001	0,00000	0,62

Canada	5,94190	0,00007	0,00008	5,94
Denmark	0,80758	0,00001	0,00001	0,81
Finland	0,69058	0,00001	0,00001	0,69
Germany	21,33964	0,00023	0,00029	21,34
Italy	9,79047	0,00017	0,00007	9,79
Japan	13,05952	0,00021	0,00012	13,06
Netherlands	2,56661	0,00003	0,00002	2,57
Spain	5,41194	0,00009	0,00005	5,41
Sweden	0,12703	0,00000	0,00000	0,13
Switzerland	0,01070	0,00000	0,00000	0,01
United Kingdom	11,26840	0,00015	0,00011	11,27
United States	228,85713	0,00274	0,00303	228,86

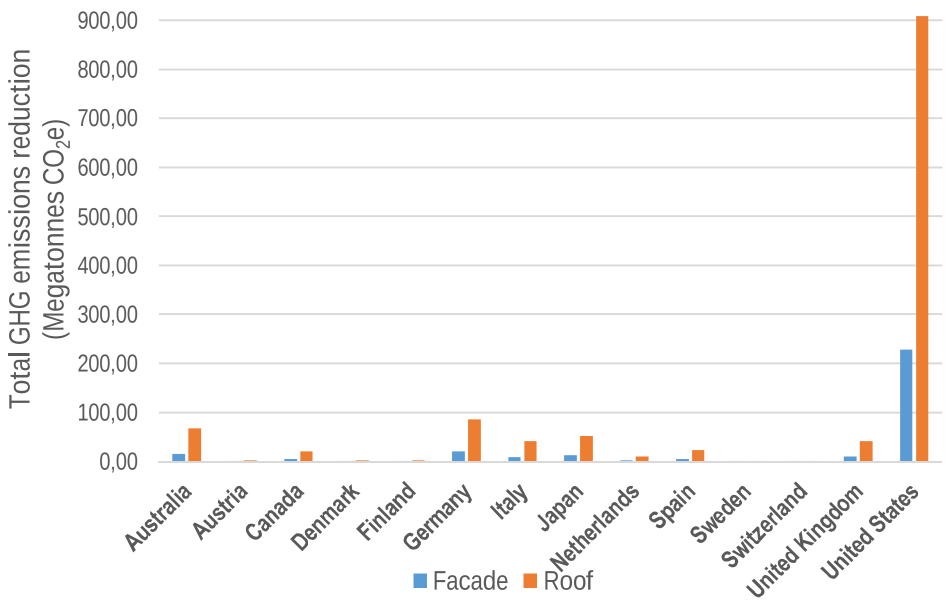

Fig. 24: Total GHG emission reduction when using BIPV.

From Fig. 24, it can be seen that the total GHG emissions reduction is highest for United States as it has higher potential for BIPV electricity generation and high GHG emitted per kWh of electricity generated.

The emissions associated with transportation and distribution (T&D) losses of electricity are also calculated from the data available for emission factor values (kgCO_2e/kWh) for electricity transmitted and distributed (Defra/DECC 2011a). The T&D loss emissions factors are given in Table 8. According to IEA, buildings consume 65% of the total generated electricity (IEA, 2013). So the total yearly electricity requirement for buildings in calculated from the total electricity generation. The emissions due to transportation and distribution are calculated on the assumption that all the electricity required by the buildings is transmitted from the electricity generation site to the final consumption point (buildings) and the losses are calculated with respect to this transmitted electricity.

Table 8: Total Transmission and Distribution losses emissions per year

Countries	**T&D loss emissions factor kgCO_2/kWh**	**Total emissions due to T&D losses of electricity per year Megatonnes(CO_2e)**	**Total GHG emissions per year (all sources) Megatonnes (CO_2e)**	**Emissions that can be avoided per year (%)**
Australia	0,08413	13,21173	340,9	3,87
Austria	0,01148	0,53054	62,67	0,85
Canada	0,01670	6,59821	503,07	1,31
Denmark	0,05047	1,27287	40,17	3,17
Finland	0,01044	0,54766	50,43	1,09
Germany	0,04242	17,34225	758,59	2,29
Italy	0,02437	4,78500	352,66	1,36
Japan	0,02259	16,43714	1246,21	1,32
Netherlands	0,03115	2,39133	164,87	1,45
Spain	0,02637	5,19446	239,87	2,17
Sweden	0,00165	0,15913	45,13	0,35
Switzerland	0,00024	0,01050	40,27	0,03

United Kingdom	0,03990	9,88391	462,05	2,14
United States	0,03957	112,61397	5233,16	2,15

Table 8 shows that the emissions due to T&D loss of electricity that can be avoided due to BIPV. Here it is assumed that the total building's sector electricity requirement is satisfied by BIPV to calculate the total emissions due to T&D losses of electricity. Percentage of avoided emissions is calculated by taking the ratio of total emissions due to T&D losses of electricity and total GHG emissions all sources.

There is a huge potential of integrating PV into the building envelope and for reducing GHG emissions from electricity generation and transmission as most of the demand for electricity will be in the urban areas. The impact of BIPV can be maximized through various energy efficiency techniques such as super insulation, air tight construction and passive solar design (Pelland et al., 2006).

4. Characterization of Façade and Backsheets

In this part of the thesis, characterization of two important components of BIPV, façade which is the normal outer layer of a building and backsheets which are to be attached to the façade. Fig. 25 gives the facades on a buildings where PV active layer could be easily integrated.

Fig. 25: Examples of façade on buildings

Photovoltaic module consists of a glass, polyvinyl butyral (PVB), active layer, PVB and backsheet which is enclosed in an aluminum frame. In the case of modules used for BIPV the order is glass-PVB-active layer-PVB-backsheet-facade. In this work, facades and backsheets are characterized as these form the backbone of the façade module. In a façade module a backsheet forms a barrier layer between the façade and the encapsulated PV active film to protect it from the gasses released (outgassing) from the façade plate which can delaminate, form bubbles in the encapsulation film. So, initial surface characterization of the façade and backsheets to study the surface properties is required for the selection of proper adhesives which will form a long lasting bond which is not affected by environmental influences. Samples of the various backsheet films and facades were taken and investigated by means of the spectroscopy and thermo-analytical methods.

Backsheet provide the required protection to the ethylene vinyl acetate (EVA) encapsulation and to the PV active layer. They are usually made up of multilayer polymeric films to get the combination of required properties which cannot be achieved by one material alone and be cost effective. The polymeric materials used have to provide protection from various environmental factors and provide mechanical strength to the PV structure. The other requirements are low water absorption and permeability, high resistance to UV degradation and thermal oxidation, good adhesion to the façade and the encapsulation, chemical inertness and low cost (Czanderna et al., 1995).

The outer layer of the multi material backsheet serves mainly as a weather protection for the PV module. Fluoropolymers such as polyvinyl fluoride (PVF), polyvinylidene fluoride (PVDF) or ethylene tetrafluoroethylene (ETFE) are mainly used for the outer layers. New materials such as polyethylene terephthalate (PET), polyamide (PA) and modified polyethylene (PE) were developed and used in the last years. The core layers are made of polyethylene terephthalate (PET) or polyamide (PA) which provide high mechanical strength, electrical insulation, high barrier to water vapor and oxygen. (Oreski et al, 2013) In certain cases thin aluminum layer is applied as a back cover for the module to provide more effective barrier against the gases (Voronko et al., 2014). So characterization in terms of physical, chemical, mechanical before and after aging is an important tool for knowing the degradation behavior of the polymeric films.

4.1 Experimental

4.1.1 Materials

The backsheets used for the investigation were standard backsheets used in a PV module manufactured from Isovoltaic Gmbh. Facades plates were provided by the project partner Egger Gmbh. Table 9 gives the list of the materials characterized.

Table 9: List of the façade and backsheets characterized with physical properties

Sample	Surface Structure	Thickness (mm)
Facade	even	12,8
Crystalsol TPA 3G Al	even	0,22
Crystalsol 3374	even	0,35
Sunplugged composite	even	-

Sunplugged metalfoil	even	-

Fig. 26: Façade plate used for characterization

Fig. 27: Backsheets used for characterization, Crystalsol TPA 3G ALU (top-left), Crystalsol 3374 (top-right), Sunplugged composite (bottom-left), Sunplugged metalfoil (bottom-right).

These materials were put through different chemical and thermomechanical analysis. The initial structure and the functional groups present on the surface of the backsheets and facades were characterized for the initial characterization before any weathering treatment. The characterization of the materials are done by the analytical methods which are commonly used in the PV industry.

4.1.2 Analytical methods used for characterization

- **FTIR-ATR spectroscopy**

The infrared radiation has a spectral region which is divided into three parts: the near-, mid-, far-infrared. The high energy near-infrared ranges from 14,000-4000 cm^{-1} and can excite overtone and harmonic vibrations. The mid-infrared which ranges from 4000-400 cm^{-1} and is commonly used to study polymer characterization and degradation. Due to the low energy (400-10 cm^{-1}) of far-infrared region they are used for rotational spectroscopy. (Planes et al., 2014)

The absorption spectrum is described as, when an infrared radiation falls on a molecule some of the electromagnetic radiation is absorbed by the molecule due to the interaction of the molecule and the radiation. The spectrum obtained can be produced by the Fourier Transform Infrared Absorption (FTIR) technique (Planes et al., 2014). Fourier transform infrared spectrometers consists of a radiation source, sampling devices, detectors and a mirror system to produce the interference of the two IR beams. FTIR spectroscopy is a nondestructive technique which is quick and easy for quality control, trace analysis and polymer identification (Bart, 2005).

Attenuated total reflection (ATR) is a technique which is used for opaque or thick samples and is based on the phenomenon of total internal reflection. The important and the additional part of this technique is the prism on which the sample to be measured is totally reflected at the prism-sample interface. Due to the selective absorption at certain wavelengths, the beam leaving the prism is attenuated by the sample. (Planes et al., 2014)

The original surface of the backsheets and facades were analyzed with a FTIR spectrometer (Perkin Elmer model Spectrum One) combined with an AutoImage microscope (Perkin Elmer Spotlight 400) which is equipped with a nitrogen cooled mercury-cadmium-telluride detector. The measurements were performed on a universal attenuated total reflection (ATR) unit which has a diamond ATR crystal having a contact area of ~1.5 mm in diameter. With this device, surface of the backsheets can be analyzed but for analyzing the core layers cross section of the backsheets needs to be taken and analyzed using a miniaturized FTIR ATR measuring setup placed in the optical focus of the FTIR microscope. The Micro-ATR uses a germanium crystal with a round contact area of only 50μm. ATR FTIR imaging is used to analyze the sample as it is not possible to image in transmission and reflection. (Voronko et al., 2014) The set-up for FTIR-ATR is shown in Fig. 28.

Fig. 28: FTIR-ATR spectroscope. Source: www.perkinelmer.com

- **Scanning Electron Microscopy**

The surface was investigated for the elemental analysis which is an important step in the characterization of the backsheets and facades before accelerated aging. The surface elements were investigated using Scanning Electron Microscope (SEM) of the type Zeiss Evo MA10 connected with an energy dispersive X-ray (EDX) detection system (Oxford Inca x-act) for elemental analysis. The measurements were performed in a low vacuum conditions and a high voltage of 15kV. (Chernev et al., 2011) A SEM with an EDX system attached to it is shown in Fig. 29

Fig. 29: SEM with EDX system attached to it.

- **Drop shape analysis for surface energy measurement**

Drop shape analysis is an image analysis method for determining the contact angle from the shadow image of the sessile drop (standard arrangement for measuring the contact angle using DSA) and the surface tension from the shadow image of the pendant drop. A drop of a liquid is metered onto the solid surface. The camera records the image of the drop and transfers it to the drop shape analysis software. Based on the grey scale analysis of the image, contour recognition is initially carried out. In the next step, a geometrical model same as the shape of the drop is fitted to the contour. The angle between the calculated drop shape function and the sample surface (baseline in the drop image as in Fig. 30) is called the contact angle. This contact angle is used to calculate the surface free energy of the solid from the contact angle with several liquids by standard method known as Owens, Wendt, Rabel, Kaelble method. (www.kruss.de)

The analysis was done using Drop Shape Analyzer DSA100 which is a fully automatic for the measurement of contact angle and the surface free energy of the solid samples. This gives an in depth analysis of the wetting and coating processes which can be used to calculate adhesion and long term stability of the coatings.

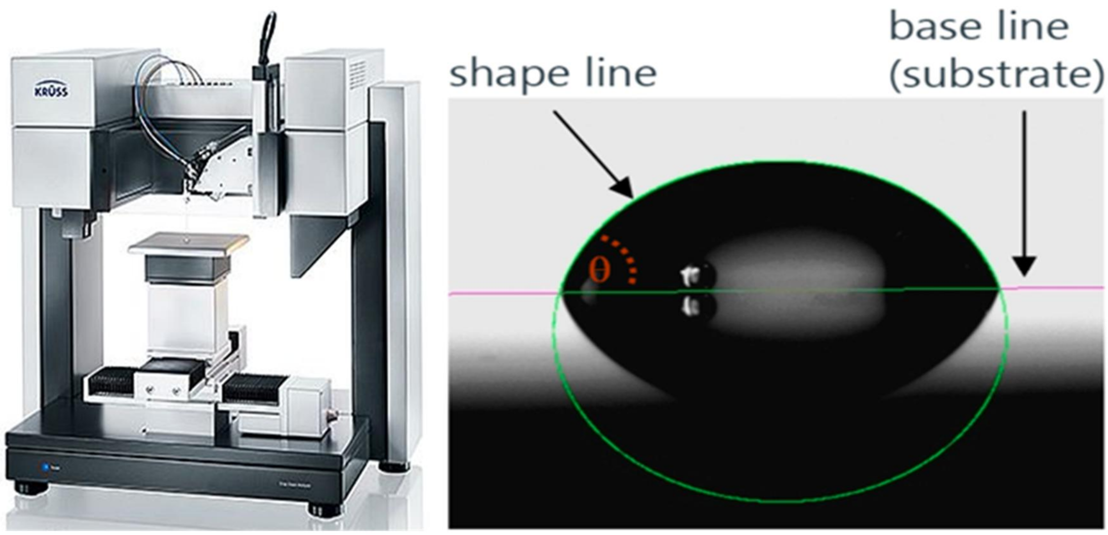

Fig. 30: Drop Shape Analyzer -DSA100 (left) and Sessile drop with fitted contour shown in green. Source: www.kruss.de

Table 10: Summary of the analytical methods used for the characterization of the backsheet and the façade.

Samples	ATR FTIR imaging spectroscopy	Scanning electron microscopy (SEM)	Surface Energy
Façade plate	✓	✓	✓
Façade plate with aluminum layer	✓		
Crystalsol 3374	✓	✓	✓
Crystalsol TPA 3G Al	✓	✓	✓
Sunplugged composite	✓	✓	✓
Sunplugged metalfoil	✓	✓	✓

4.2 Results and Discussion

4.2.1 Identity of the components by FTIR-ATR

The presence of high performance fluoropolymers such as polyvinyl fluoride (PVF) and engineering thermoplastic such as Polyamide (PA) was observed by FTIR-ATR spectroscopy. The spectra of the façade plate confirmed the presence of Melamine Fluoride resin. The infrared spectra of the backsheet Crystalsol 3G Al confirms the presence of polyamide in the modified form. Infrared transmission spectra of Sunplugged film reveals significant bands of polyamide as shown in Fig. 31. CH_2 is found at 1466, 2849 and 2917 cm^{-1}. The transmission spectra of C=O is found at 1635 cm^{-1}. The obtained polyamide spectra was compared with reference from Geretschläger et al. and with the database of the FTIR spectra and the findings are in good correlation with the corresponding literature (Geretschläger et al., 2013)

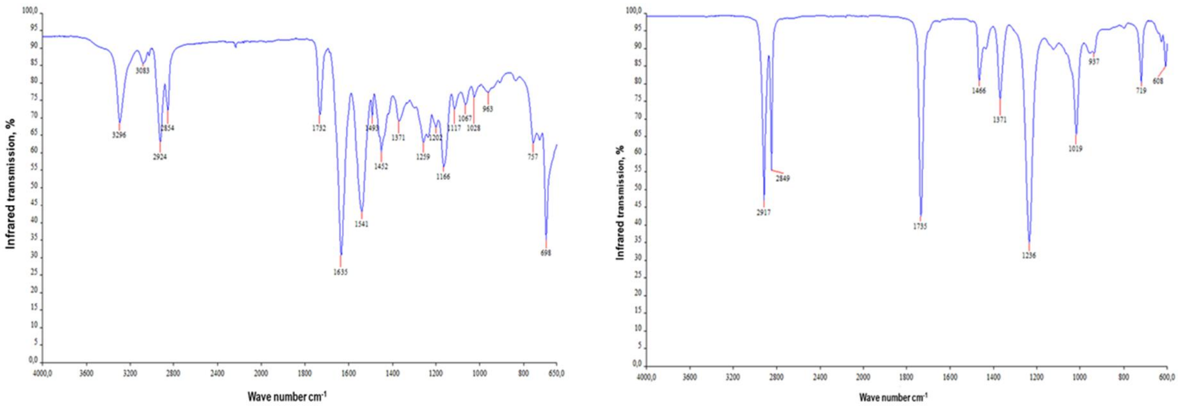

Fig. 31: Infrared transmission spectra of Crystalsol 3G Al (left) and Sunplugged composite (right)

The infrared spectra for Crystalsol 3374 confirms the surface layer is of polyvinyl fluoride and CH_2 is found at 809, 1408 and 2928 cm^{-1}.The carbon-carbon single bond is found at 1086 and 1350 cm^{-1}. Carbon and Fluorine (C-F) bond is found at 1018 cm^{-1}(Hong et al., 1992)

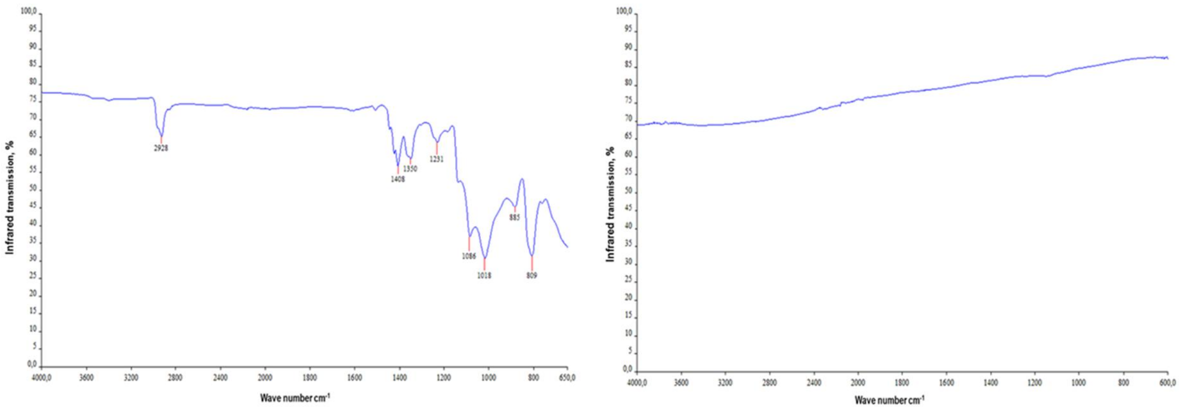

Fig. 32: Infrared transmission spectra of Crystalsol 3374 (left) and Sunplugged metalfoil (right)

From the infrared spectra, the surface layer of the aluminum sheet is made up of acrylate with a nitrile function which is confirmed with the presence of a nitrile function 2249 cm^{-1}. From the infrared spectra of the Egger façade, the surface is layer is made up of melamine formaldehyde resin, which is confirmed by the small peak for O-H at 3291 cm-1 and the peak at 2941 cm-1 is for the C-H. The triazinyl peak is located between 812 to 815 cm^{-1} (Dongwei et al., 2013)

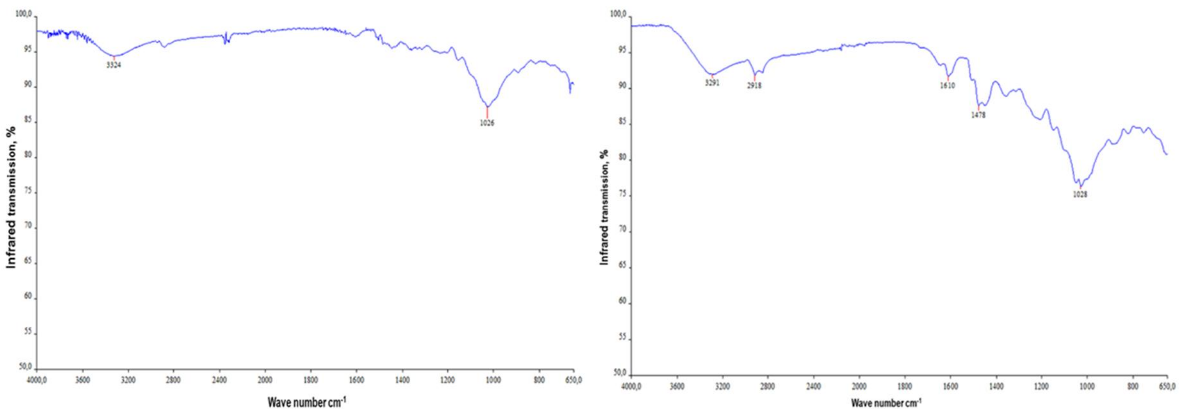

Fig. 33: Infrared transmission spectra of façade with metal sheet (left) and normal façade (right).

4.2.2 Elemental analysis by SEM- EDX

The changes in the surface structure and the crystalline deposits can be detected by comparing the surface images upon accelerated aging by scanning electron microscopy. The SEM images obtained for the original/unaged samples are shown in Fig. 34. The change in the structure at the surface is detected by the formations of precipitations/deposits, formation of new structures and changes in the elements present on the surface.

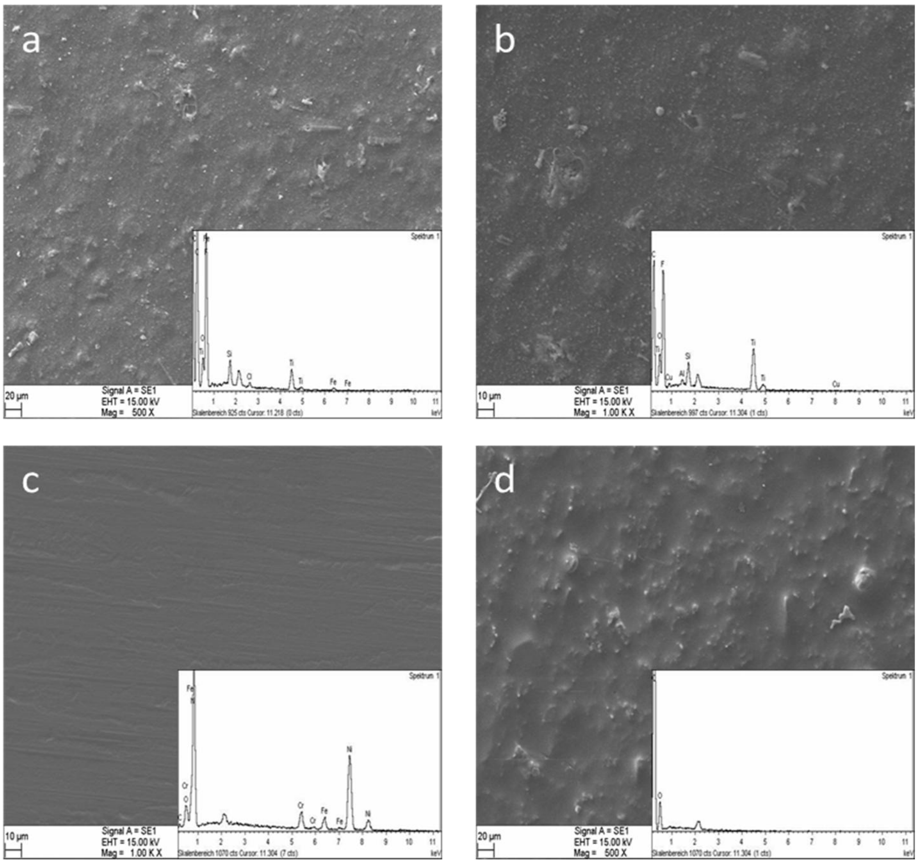

Fig. 34: SEM images of the surface of the original samples and inset elemental analysis of the surfaces a) Crystalsol 3374 b) Crystalsol TPA 3G Al c) Sunplugged metalfoil d) Sunplugged composite-foil.

The elemental analysis of the sample surfaces was performed with energy dispersive X-ray (EDX) system connected to the SEM (Fig. 34 inset). Elemental analysis is important for the surface characterization and the detection elemental distribution between the original sample and aged sample. The results of the elemental analysis are summarized in Table 11. The original surface of the façade plate as detected by the SEM is shown in Fig. 35.

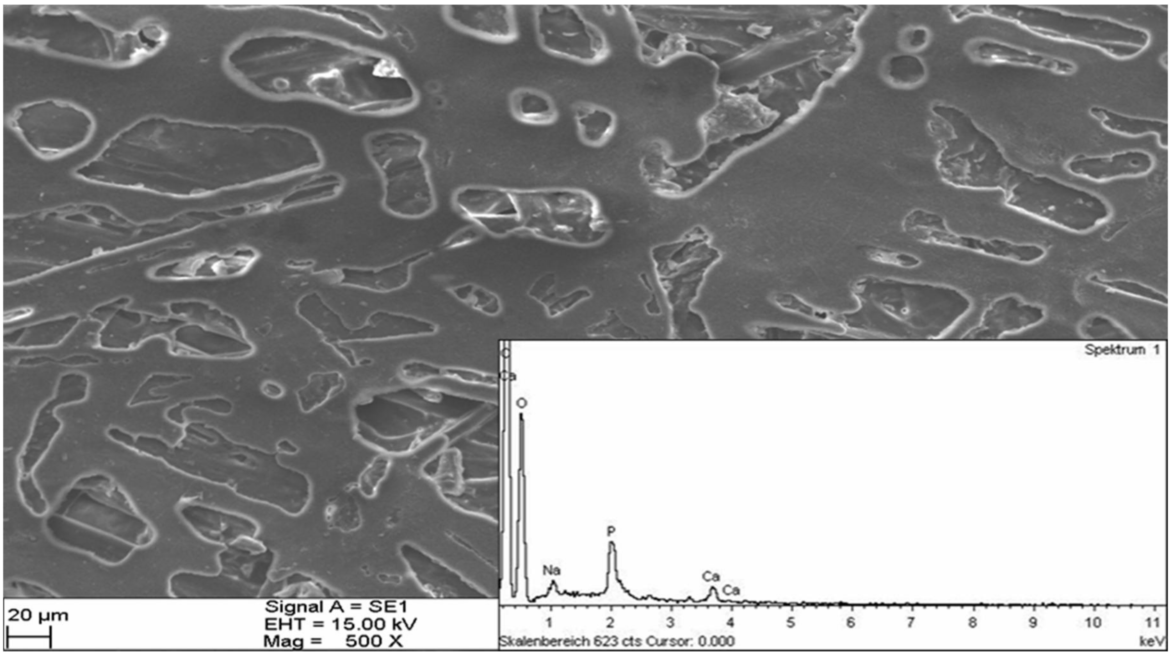

Fig. 35: SEM image of the façade plate surface and inset elemental analysis.

The presence of Ti on the surface of Crystalsol 3374 and Crystalsol TPA 3G Al indicates the presence of titanium dioxide which is added for improving the solar reflectance which improves module performance and reducing operating temperature (Wallner et al., 2013).

Table 11: Composition of the surface (atomic percent) of the samples as determined by SEM-EDX.

Sample	C (%)	F (%)	O (%)	Ni (%)	Ti (%)
Façade plate	57.38	-	38.1	-	-
Crystalsol 3374	43.9	40.5	7.5	-	4.4
Crystalsol TPA 3G Al	38.2	37.54	10.7	-	9.97
Sunplugged composite	79.4	-	20.06	-	-
Sunplugged metalfoil	4.8	-	2.67	80.74	-

Since there are further elements present the sum of the concentrations above may not be 100%.

4.2.3 Physical analysis from surface energy measurements

For obtaining maximum adhesion, an adhesive must completely wet out or cover the surface to maximize the contact area between the surfaces to be bonded. The difference between the surface energies of an adhesive and the substrate should be as high as possible.

Table 12: Surface energy for all the samples

Sample	Surface Energy (mJ/m)
Façade plate	17,62
Crystalsol 3374	32,46
Crystalsol TPA 3G Al	27,91
Sunplugged composite	23,61
Sunplugged metalfoil	35,26

From the Table 12, it can be observed that surface energy for the Sunplugged metalfoil is the highest as its surface is made up of Fe and Ni as seen from the SEM analysis and metals have high surface energy than the polymers and polyamides (Concord, 2012). Crystalsol 3374 due to the presence polyvinyl fluoride (PVF) has a surface energy of 32,46 mJ/m which is consistent when compared polymer surface energy database (www.accudynetest.com).

Knowing the surface energy of the individual samples is important for selection of proper adhesives for bonding of the different components. But surface treatment can be used to modify a surface or to increase the surface energy and make it possible to have adhesion between two surfaces. A good bond between two surfaces depends on different factors which have to be combined and interaction between the surfaces has to be increased (Concord, 2012).

5. Peel test for Determining the Adhesive Strength between Façade and Backsheet

In BIPV, long term adhesion durability between the backsheets and facade is important for protecting the PV active layer from external environmental influences and internal influences such as outgassing due to facades. Also it helps to increase the lifetime of the BIPV module.

The peel test is very simple and fast method to determine the adhesive strength between two surfaces. In the PV industry, peel tests are used to measure the adhesive strength between EVA (encapsulant) and the backsheet, between glass and encapsulant. The peel test mainly used in the field of adhesives and is described in many international standards for adhesive testing such as EN 1895, EN 28510 (Krauter et al., 2011).The floating roller peel method measures the adhesive strength between a rigid substrate and a flexible substrate. The test specimens can be prepared individually or cut from bonded panels into specific lengths as required for the test. One end of the flexible substrate is left unbonded (free) so that it can be gripped by the test system Fig. 36. It is necessary that substrate is strong enough to not bend or distort during the test.

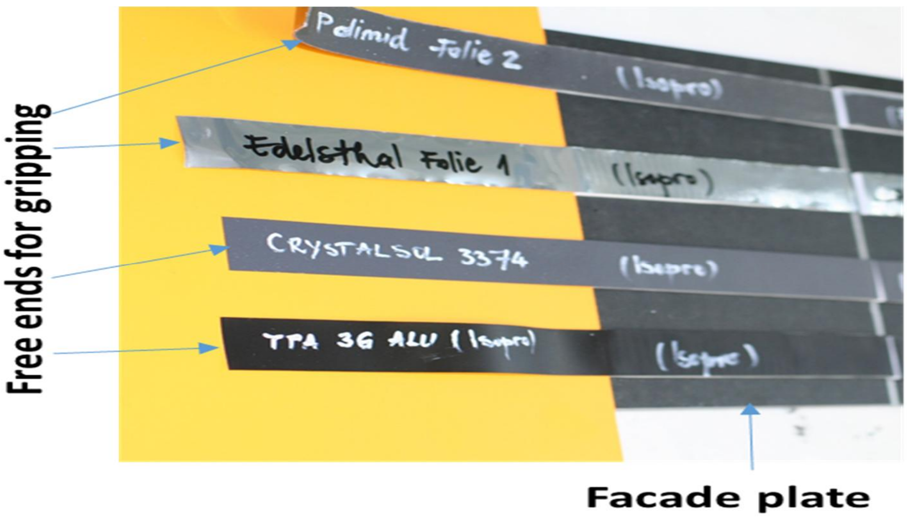

Fig. 36: Flexible substrate with free end for gripping.

In this thesis, the principle of the peel test is the pulling of the thin flexible backsheet from the rigid substrate (façade). The peel test was performed on ZWICK Universalprüfmaschine 1474. The standard used EN 1464 and SOP 112.021 gives the peel force for the bonds between two substrates using a floating roller method. The roller bearings are connected to the testing system via an adapter Fig. 37. This design ensures that alignment between the fixture and the test specimen occurs as soon as force is applied and the direction of the applied force is through the centerline of the fixture Fig. 37. The peel off test is carried out by cutting off stripes from the façade and backsheet lamination.

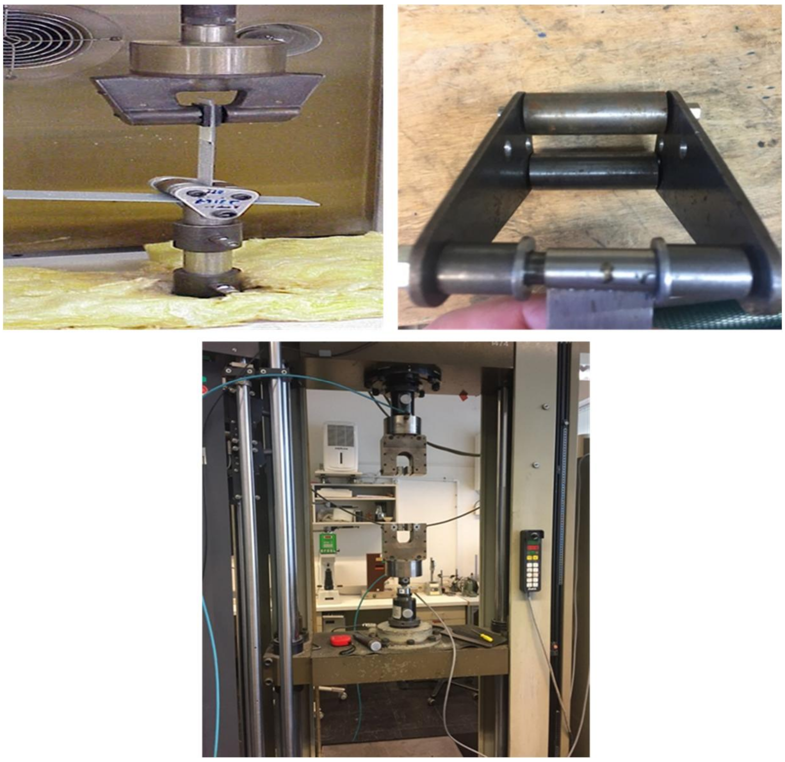

Fig. 37: Working of a floating roller (top-left), roller bearing (top-right), setup of the peel test instrument (bottom)

For the test, speed of the peel is always constant and the force required for peel is recorded. Fig. 38 shows the graph which is used to calculate the result for a peel test. The vertical axis is the force applied for the peel and on horizontal axis are the measurement points. (Krauter et al., 2011)

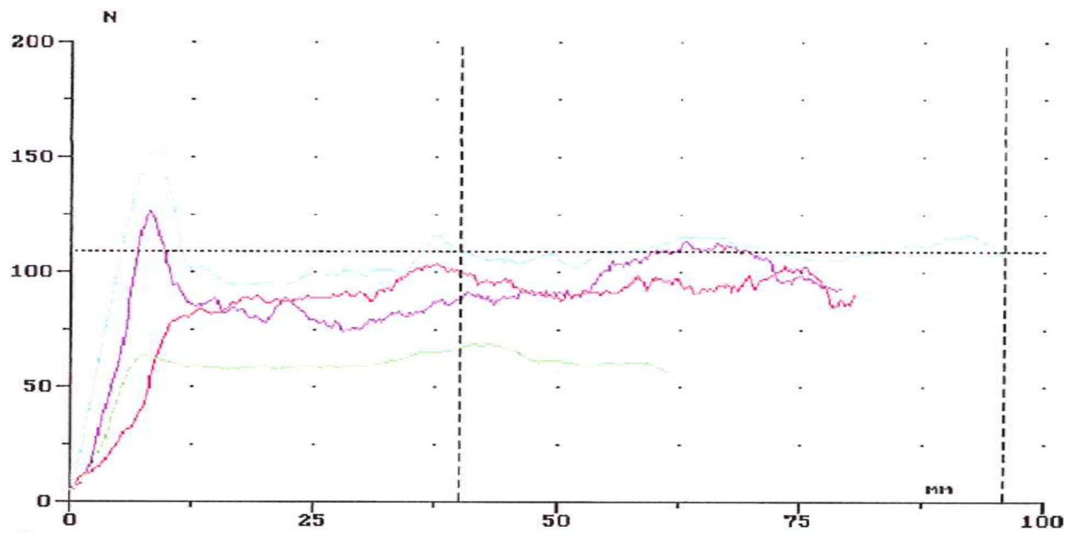

Fig. 38: Peel off force as a function of measurement points and the dotted interval lines used to calculate the result.

The experimental conditions for the test are:

Peel tests on: ZWICK Universalprüfmaschine 1474, Device no. 289

Standards: EN 1464 + SOP 112.021

Climate: 23°C/50% rH

Velocity: 100 mm/min

Pre-force: 5 N

Precarriage: 25 mm

Measured displacement: 115 mm

5.1 Types of Bond Failures

Interpreting the results of peel tests requires understanding of different types of adhesive bond failures. The concept of adhesive bond failure depends on understanding how the adhesives function. The function of the adhesives depends on the chemical bonds formed at the interface between the adhesive and the substrate when the curing of the adhesive takes place. If the chemical bond between the adhesive and substrate is strong, failure will occur in the structure of the adhesive and the bond strength is high. If the failure occurs at the interface between the adhesive and substrate, the chemical bonds are weak and the bond strength is low. (Davis et al., 2010).

- **Adhesive failure**

The bond between the substrate and the adhesive is broken when the forces exerted on the connection is greater than the force created between the substrate and the adhesive. This is characterized by the absence of adhesive on one of the substrate (Davis et al., 1999). Adhesive failure takes place due to the weak chemical bonds at the interface between the adhesive and the substrate. This results in the adhesive staying on the other substrate completely. The surface of the adhesive is smooth, as the failure is even without trace of substrate staying and often imitates surface features of the substrate (Davis et al., 2010).

- **Cohesive failure**

Cohesion bond failures are due to the fracture of the adhesive and the adhesive material is present on the two substrate surfaces. The adhesive surface usually appears rough and is distinguished by the lighter color than the bulk adhesive material. Generally bonds which fail by cohesion exhibit high strength. (Davis et al., 1999)

- **Structural failure**

In this case the substrate is weaker than the forces of the adhesive and cohesive bonds. This results in the substrate breaking apart and the substrate is separated into pieces. This is considered as a good bond between the adhesive and the substrate.

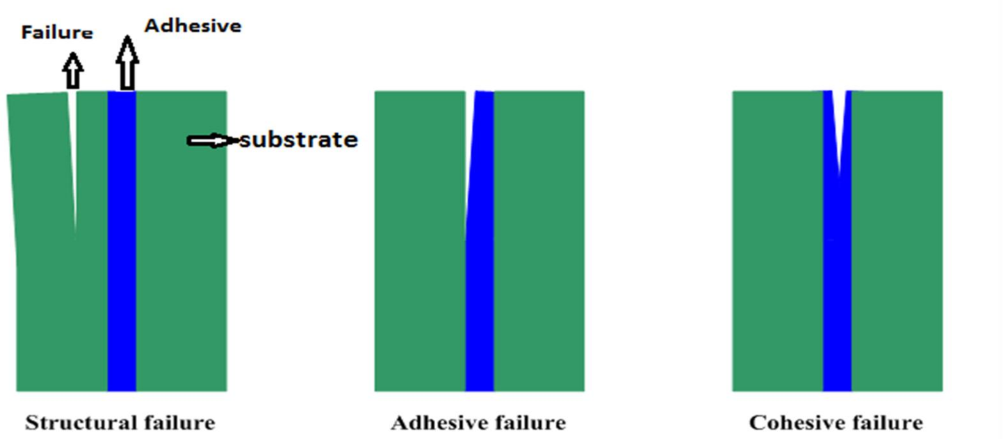

Fig. 39: Different types of bond failures

5.2 Results and Discussion

The main aim of this part is to show the adhesion of the backsheets to the façade plate with using different adhesives and techniques. The materials used in this part of the research are the different facades, adhesives and various types of backsheets. The adhesives were selected on the basis of surface characterization of the materials and providing this information to the various adhesive manufacturers. The adhesives were selected based on recommendations from the adhesive manufacturers. The different types of adhesives selected for the initial testing are:

5.2.1 3M Tape VHB 4959

These tapes can be used for interior and exterior bonding applications and can be used to replace rivets, spot welds, liquid adhesives and other permanent fasteners. Outstanding durability is achieved due to the acrylic chemistry. These tapes can be used where the bonded surfaces expand and contract differentially like in the case of facades. They can be used in the temperature range from -35 to 120^{0}C (www.3M.com). The application procedure of the 3M tape involves the cleaning of the surfaces of the foil and the façade plate with isopropanol for removing the dirt and grease and application of the tape. The 3M tape applied to a façade plate is shown in Fig. 40.

Fig. 40: 3M adhesive tape applied to a façade before applying different foils.

Table 13 provides information about the adhesive strength of 3M tape VHB 4959 on the façade plate when there is no pretreatment involved on the foil or the façade plate. There is a common fracture pattern involved, which is the adhesive breaking of the bond from the façade plate. This is due to the weak chemical bond created at the interface between the 3M tape and the façade plate. So, after applying the peel test the adhesive comes with the foil with no trace of adhesive found on the façade plate. Fig. 41 shows the adhesive breaking of the 3M tape from the façade plate. This can be attributed to the fact that there is no chemical bond formation between façade and the adhesive (3M tape) and there is a strong bond between the different backsheet foils which results in the adhesive fracture.

Table 13: Peel tests results without primer using 3M Tape VHB 4959

Adhesive	Foil	Pre-treat-ment	Façade plate	Fracture pattern	Peel value[N/mm]
3M Tape VHB 4959	3374	No	HPL	adhesive from HPL	2.44
3M Tape VHB 4959	TPA 3G Al	No	HPL	adhesive from HPL	4.37
3M Tape VHB 4959	Sunplugged metalfoil	No	HPL	adhesive from HPL	3.76
3M Tape VHB 4959	Sunplugged composite	No	HPL	adhesive from foil	3.76

Comparison between the peel tests values suggest that the foil TPA 3G Al has the highest peel force of 4.37 N/mm among the other foils, but as the breaking is adhesive breaking from the façade plate. This is not considered the best bonding between two materials.

Fig. 41: Adhesive breaking of the 3M tape (left) and cohesive breaking of the 3M tape (right).

Adhesive strength is again tested with the application of the 3M tape primer 94, which is specifically designed for using with 3M tapes. A primer is material that enhances the adhesion of two surfaces. In this case application of primer has a huge impact on the adhesion of the foils with façade plates. The fracture pattern is different for different foils when primer is used. Foil Crystalsol 3374 and Sunplugged composite breaks from the foil i.e., the pattern is adhesive fracture from the foil due to weak chemical bond created between the foil and the tape. Crystalsol TPA 3G Al which has the highest peel value among the other foils breaks due to cohesive fracture in which there is the breakage of the adhesive and adhesive is present on foil and façade plate. The bonds which break by cohesion exhibit a high bond strength due to formation of equally strong bond with both substrates.

Table 14: Peel tests results with primer using 3M Tape VHB 4959

Adhesive	Foil	Pre-treatment	Façade plate	Fracture pattern	Peel value[N/mm]
3M Tape VHB 4959	Crystalsol 3374	primer 94/3M	HPL	adhesive from foil	3.12
3M Tape VHB 4959	Crystalsol TPA 3G Al	primer 94/3M	HPL	cohesive	9.24
3M Tape VHB 4959	Sunplugged metalfoil	primer 94/3M	HPL	Adhesion and adhesive very good	Torn foil
3M Tape VHB 4959	Sunplugged composite	primer 94/3M	HPL	adhesive from foil	7.16

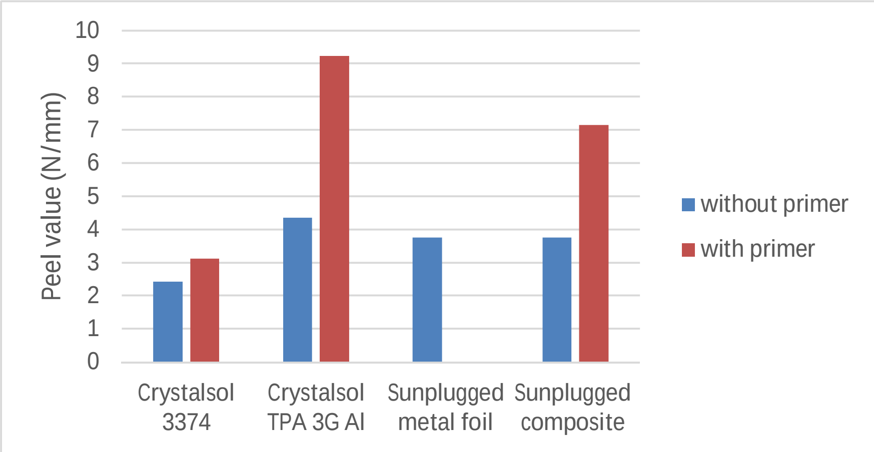

Fig. 42: Comparison between peel tests values for with primer and without primer

From Fig. 42 it can be seen that application of primer doubles the values of peel tests expect for Crystalsol 3374 which has a slight increase and in the case of Sunplugged metalfoil with primer cannot be measured due to breaking of the foil while measuring. This can be interpreted as having a high peel test value.

5.2.2 SIKA PUR-reactive Hotmelt 9632

These are based on polyurethane hotmelt adhesives and are versatile and fast setting. It cures with moisture of the air and forms an elastomer, which cannot be re-melted. They have high final strength and flexibility over a broad temperature range. They have high heat resistance. SIKA hotmelt adhesives are applied by using a heated piston type cartridge gun. (www.sika.com)

Table 15 provides the adhesive strength of the four foils on the façade. The peel test values for SIKA PUR-reactive Hotmelt 9632 are low but the important thing to consider in adhesive bonding is what the nature of the fracture is and this provides the strength of the bond. For the foil 3374, the peeling test results in a mixed break which is a combination of adhesive and cohesive fractures. At some places there is adhesive break and some places cohesive Fig. 43. With TPA 3G Al the break is mixed fracture due to a white thin layer of foil remaining with the adhesive onto the façade and at some places there is a break in the adhesive.

The Sunplugged metalfoil and Sunplugged composite break with cohesive fracture and adhesive fracture respectively with adhesive on the foil.

Table 15: Peel tests results using SIKA PUR reactive Hotmelt 9632

Adhesive	Foil	Pre-Treat-ment	Façade Plate	Fracture Pattern	Peel value [N/mm]
SIKA PUR-reactive Hotmelt 9632	Crystalsol 3374	no	HPL	Mixed break	1.28
SIKA PUR-reactive Hotmelt 9633	Crystalsol TPA 3G Al	no	HPL	Mixed break	1.05
SIKA PUR-reactive Hotmelt 9634	Sunplugged metalfoil	no	HPL	cohesive	2.82
SIKA PUR-reactive Hotmelt 9635	Sunplugged-composite	no	HPL	adhesive	0.93

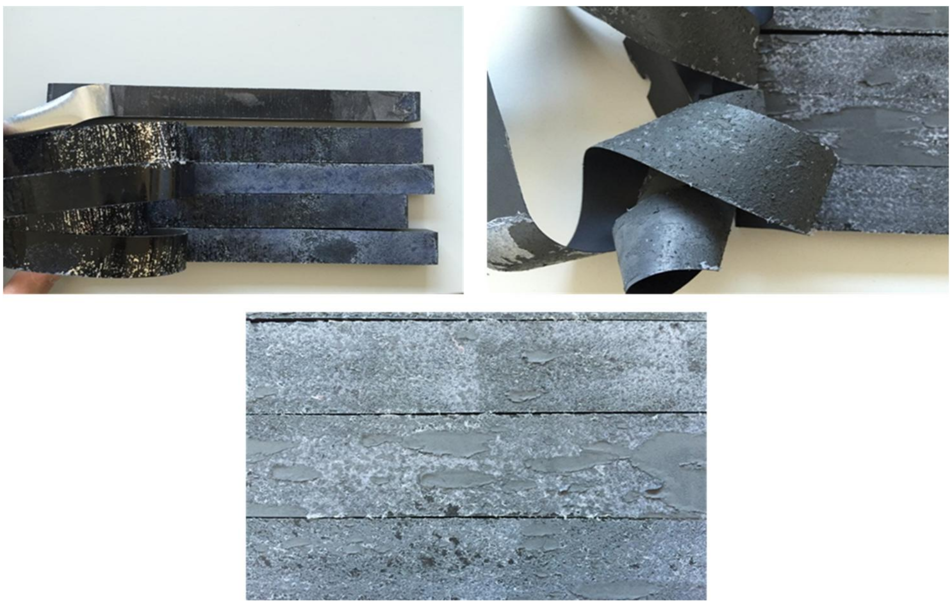

Fig. 43: Fracture pattern for all foils (top-left) and Mixture of adhesive and cohesive breaking for Crystalsol 3374 and Crystalsol TPA 3G Al (top-right and bottom)

5.2.3 Sylgard 184 Dow Corning 2K

Sylgard 184 Dow Corning 2K is a silicon based elastomer used as adhesive or encapsulant for solar applications. It consists of two liquid component kits to be mixed in the ratio of 10:1 by weight or volume. When the two components are thoroughly mixed the mixture cures to form a flexible elastomer which can be used for further applications. (www.dow-corning.com)

The silicon adhesive was tested on three different types of façade plates: normal HCL, HCL plate coated with aluminum sheet on both sides and HCL plate coated with decorative material.

Table 16: Peel tests results using Sylgard 184 Dow Corning 2K

Adhesive	Foil	Pre-Treatment	Plate	Fracture Pattern	Peel value [N/mm]
Sylgard 184 DC, 2K	Crystalsol 3374	No	HPL	Adhesive from foil	0.04
Sylgard 184 DC, 2K	Crystalsol TPA 3G Al	No	HPL	Adhesive from foil	0.05
Sylgard 184 DC, 2K	Sunplugged metalfoil	No	HPL	Adhesive from plate	0.06
Sylgard 184 DC, 2K	Sun-plugged-composite	No	HPL	Adhesive from foil	0.04

Table 16 provides the information on the peel tests values and fracture pattern for the different types of façade plates. The peel test values are pretty low compared to the adhesives used before and the fracture pattern is the same for all the different plates and foils.

To confirm the above results for Sylgard 184 Dow Corning 2K two different types of façade plates were used, façade plate with white decorative layer and façade plate with aluminum layer.

Table 17: Peel tests results using Sylgard 184 2K for HPL with white decorative layer

Adhesive	Foil	Pre-Treat-ment	Plate	Fracture Pattern	Peel value [N/mm]
Sylgard 184 DC, 2K	Sunplugged composite	No	HPL* white decorative layer	Adhesive from plate	0.06
Sylgard 184 DC, 2K	Sunplugged metalfoil	No	HPL* white decorative layer	Adhesive from plate	0.05

The fracture pattern is adhesive from foil or plate which is due to weak chemical bond at the interface between the adhesive and the façade or between the adhesive and foil. This is characterized by the adhesive staying on the facade or the foil. This was the first adhesive where the results have been pretty bad. So pre-treatment on the façade plate is absolutely necessary before using Sylgard 184 silicon elastomer.

Table 18: Peel tests results using Sylgard 184 Dow Corning 2K for HPL with aluminum layer

Adhesive	Foil	Pre-Treat-ment	Plate	Fracture Pattern	Peel value [N/mm]
Sylgard 184 DC, 2K	Crystalsol TPA 3G Al	No	HPL + both sides Al	Adhesive from plate	0.03
Sylgard 184 DC, 2K	Sunplugged metalfoil	No	HPL + both sides Al	Adhesive from plate	0.05
Sylgard 184 DC, 2K	Sunplugged composite	No	HPL + both sides Al	Adhesive from plate	0.03

5.2.4 Silicon 8301 Dow Corning 2K

Silicon 8301 consists of two parts a base and a catalyst. When they are mixed in the ratio of 10 parts base to 1 part catalyst to get a sealant that provides protection against moisture, environmental degradation. It is typically used for structural bonding to attach PV substrates. Adhesion is normally good to most of the substrates without the use of primer or any surface activation methods. It is highly viscous black adhesive which is mixed at room temperature and cured for 4 days at room temperature. (www.dowcorning.com)

This adhesive was tested on three different types of façade plates: normal HCL, HCL plate coated with aluminum sheet on both sides and HCL plate coated with decorative material.

Table 19: Peel tests results using Silicon 8301 Dow Corning 2K

Adhesive	Foil	Pre-Treat-ment	Plate	Fracture Pattern	Peel value [N/mm]
Silicon 8301 DC, 2K	Crystalsol 3374	No	HPL	Cohesive	2.43
Silicon 8301 DC, 2K	Sunplugged metalfoil	No	HPL	Cohesive	2.64

Table 19 provides the information on the peel tests values and the fracture patterns. As can be seen from the fracture pattern which is cohesive, bond formation between the adhesive and the facade surface is strong. Some part of the adhesive is remaining both on the façade and the foil due fracture in the adhesive and this can be distinguished by the lighter color than the original color of the adhesive.

Table 20: Peel tests results using for Silicon 8301 Dow Corning 2K HPL with white decorative layer

Adhesive	Foil	Pre-Treat-ment	Plate	Fracture Pattern	Peel value [N/mm]
Silicon 8301 DC, 2K	Crystalsol 3374	No	HPL-white decorative layer	Cohesive	2.35
Silicon 8301 DC, 2K	Sunplugged metalfoil	No	HPL-white decorative layer	Cohesive	1.87
Silicon 8301 DC, 2K	Sunplugged composite	No	HPL- white decorative layer	Cohesive	1.96

Table 21: Peel tests results using for Silicon 8301 2K HPL with aluminum layer

Adhesive	Foil	Pre-Treat-ment	Plate	Fracture Pattern	Peel value [N/mm]

Silicon 8301 DC, 2K	Crystalsol 3374	No	HPL-both sides Al	Cohesive	0,92
Silicon 8301 DC, 2K	Sunplugged metalfoil	No	HPL- both sides Al	Cohesive	1,71
Silicon 8301 DC, 2K	Sunplugged composite	No	HPL- both sides Al	Cohesive	0,31

Between the two silicon adhesives used, Silicon 8301 Dow Corning 2K gave good results in terms of Peel value and fracture pattern.

The use of different types of adhesives gives insights on the adhesive strength and the fracture pattern of the different foils which can be applied on the façade and used as a barrier. Due to novelty of the present work, there are no documented data about adhesion of back-sheet foils to the façade for comparison of results. For 3M Tape VHB 4959 the peel value approximately doubles when primer is used for pre-treatment and also the fracture pattern changes which suggest that pre-treatment is necessary for strong bond. When two silicon adhesives, Sylgard 184 2K and Silicon 8301 2K are compared the adhesive strength for Sylgard 184 2K is very low. Also the fracture pattern on all the foils is adhesive from plate. So the next step would be the pre-treatment of Sylgard 184 2K and then checking the results.

6. Conclusions

Sun is an abundant source of energy. Harnessing energy from the sun is essential to reduce our dependence on fossil fuels and help save the environment. There are many advantages in using Sun as a source for generating electricity. In this thesis different PV cells have been described with their efficiencies. Comparing crystalline and thin film PV cells, crystalline PV cells are used on a large scale due a more mature technology and higher efficiency but they are more costly than thin film solar cells. Recently, there has been a substantial growth in thin film solar cell market due to their use in special application such as BIPV. As crystalline silicon module cannot operate at high temperatures due to the decrease in power output with increasing cell temperature, they can be replaced with thin film solar cells. Due to their ability to with stand high temperature and the efficiency remaining same in low light conditions thin film solar cells remain an attractive proposition in the future. Due to development of cheaper PV modules with higher efficiencies, there has been a huge growth in the PV market in the last couple of years with countries outside Europe leading the way in the installed capacities. China, Japan and United States combined had more than half of the total installed capacity.

Many new applications of PV have been developed in recent years with integration of PV into the building envelope being the most talked about. With EU setting targets and directives for net zero energy or even energy surplus buildings, the need of the hour is to design or modify buildings such that they minimize energy consumption but also generate electricity for their own consumption and achieve the target for net zero energy buildings. For this the obvious choice is BIPV. Buildings are the biggest source of electricity consumption across all sectors. So it makes sense to generate electricity where it is being consumed. BIPV provide the best possible solution as they can fulfill the same functions as a normal façade or roof in addition generating electricity. There are various types of BIPV products available in the market today for the roofs and facades. They can be used according to the size, design and requirements of the building. In using BIPV, the reduction in costs can be achieved as it eliminates the need for separate support structures and large land area can be saved where there is shortage of available free land. The saved land area can be used for agriculture or other purposes. The technical potential area that can be used for BIPV for selected countries has been shown. It can be concluded that the technical potential area that is available for

BIPV, is the area that can be saved if normal PV have to be installed on rack mounted systems on open grounds. Among the countries selected, United States has the highest technical potential area available due to high available ground floor area per capita. From the analysis it was found out that electricity generation from BIPV could satisfy 20-75% of buildings electricity demand depending on a country's location, solar yield and available roof or façade area per capita.

BIPV systems provide various benefits such as environmental, architectural, and socioeconomic. The most important benefit that can be attributed with BIPV is the savings in GHGs emissions. Total emissions related to electricity generation and transmission and distributions losses of electricity were calculated. The potential GHGs reduction were highest for United States due to high potential for BIPV electricity generation and high GHG emitted per kWh of electricity generated. Percentage of emission that can be avoided was the highest for Australia due to high emission factor and high emissions due to T&D losses.

The characterization of the façade and backsheets by various analytical methods such as infrared spectroscopy, Scanning electron microscopy with energy dispersive X-ray and drop shape analysis for surface energy measurements gave detailed information on the surface structure and composition. The infrared spectra of façade plate indicated the presence of melamine formaldehyde and the infrared spectra of various backsheets indicated the presence of polyamide and polyvinyl fluoride which are the polymers usually used for the backsheets. The SEM-EDX of the façade clearly confirmed the presence of carbon and oxygen. For the backsheets the main elements which were identified were carbon, oxygen, fluorine, titanium. The surface energy analysis indicated highest surface energy of 35,26 mJ/m for Sunplugged metalfoil followed by Crystalsol 3374, Crystalsol TPA 3G Alu, Sunplugged composite and façade plate.

The results of the peel test between façade and backsheet using 3M Tape VHB 4959, adhesive fracture pattern was observed. Pretreatment using a primer, significantly increased the adhesive strength for all the backsheets. Between the two silicon adhesives used, Silicon 8301 2K gave better results than Sylgard 184 2K in terms of adhesive strength and fracture pattern. Pre-treatment is must for using Sylgard 184 2K to increase its adhesive strength.

The adhesive SIKA PUR-reactive Hotmelt 9632 gave low peel test values but cohesive or mixed fracture pattern apart for Sunplugged composite which had an adhesive fracture.

For the future work, more detailed analysis of the façade surface and backsheets is required with different characterization techniques such as Raman spectroscopy. As a backsheet material is made up of various layers studying the various surface layers is important. More analysis is needed for the determining the cut off criteria adhesive strength of backsheets and façade peel tests and to achieve a standard for it. Various pretreatment techniques have to be applied and compared against each other to determine the best pretreatment which is economical and technically feasible.

7. Summary

Global energy needs have increased significantly over the past decades and will continue to rise in the coming decades. The current energy needs are met by conventional fossil fuels such as oil, gas and coal which are unsustainable and have an adverse effect on the environment. Shifting from conventional energy resources to unconventional is need of the hour. Solar energy is the best choice due to its availability all over the world. Most of the electricity consumption is in the urban areas. Having a source of electricity generation near its consumption would be most economical and beneficial.

In this thesis, exploitation of solar energy for its use in Building Integrated Photovoltaics has been discussed. Literature analysis of various PV cell technologies such as multi crystalline, mono crystalline and various thin film cells with their efficiencies suggest the market dominated by crystalline silicon PV cells. They have higher efficiency and a long history of reliable performance. Now-a-days, thin film technologies have found a way into the market due to their thin size and more efficient use of materials required. But the overall efficiency of thin film PV cells is lower than crystalline PV cells.

The integration of PV into the building envelope has transformed buildings into energy producers. This integration can be divided into two types Building applied photovoltaics (BAPV) and Building integrated photovoltaics (BIPV). BIPV is structural, architectural and aesthetic integration of photovoltaics into the building structure. They can be integrated into the roof and façade. Various products are available in the market for façade and roof integration. Due to the free surfaces available on roofs and façade there is a huge untapped potential for generating electricity at the source of consumption. The electricity generated from BIPV can satisfy approximately 20-75% of the buildings electricity requirements depending on the country and its location. BIPV's can help reduce the GHGs emissions and the emissions due to losses of electricity in transmission and distribution.

Before attaching BIPV as outer building layer, various components have to be characterized and combined together to form a multi-material module. The façade and backsheets form the basis of the module structure and initial characterization of these components is important to form a long lasting bond. The characterization of the façade and backsheets was performed with FTIR-ATR, SEM-EDX. Peel test was performed using different adhesives for determining the adhesive strength between the façade. The results from the peel tests indicate for some kind of pretreatment for achieving better adhesion strength.

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