LOW CARBON LIVING CRC

RP1003: PV as an integrated building material: Status report, barriers and opportunities

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“Photovoltaics only has a future, if it can be integrated harmoniously into architecture”, Charles Fritts 1880

CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

Conventional photovoltaic (PV) module costs are reducing as manufacturers scale up PV production. Crystalline silicon (single or multi-crystalline wafers) still dominates the industry while thin film manufacturers, apart from CdTe, are having difficulty competing. The cost of the PV device is decreasing most significantly as production increases. This leaves module costs as well as Balance of Systems costs as being the major barriers to further lowering costs.

As costs fall the levelised cost of electricity (LCOE) from PV is now, in many places cost competitive with retail electricity prices. Hence PV on buildings is the most economic location for installation of PV (the location in the grid is another issue that also needs to be addressed).

To lower the cost further the industry needs to tackle:

- device costs,
- encapsulation costs
- mounting costs
- balance of systems costs (hardware e.g. wires, inverter etc as well as soft costs such as the cost of procurement etc.)

The above means that integrating PV with building materials is a promising pathway to lower the costs, as the multiple benefits of PV as a building element has the potential to lower Balance of Systems costs if PV devices or layers can be deposited, bonded or laminated onto building materials (glass, steel, aluminium, concrete, ceramics, as well as timber). In addition the aesthetic appeal of PV to building designers and developers will be enhanced by the development of cost effective building integrated PV.

Further benefit from this approach is also possible through other multiplicity of uses of PV/building products. For example PV integrated with glazing can deliver daylighting, insulation, low emissivity coatings and solar reflectivity. Another example is hybrid PV/Thermal integrated products which can deliver low grade heat for space heating, cooling pre-heat for hot water. In addition such an approach not only improves the electrical performance of the PV, but also has the potential to improve the lifetime of the PV due to a reduction of the thermal expansion and contraction.

In terms of integrating PV technologies with building products there is a wide range of possibilities. A multitude of approaches have already been explored and many have led to commercial products appearing in the marketplace over the last thirty years. Given the wide range of PV technologies that have been explored and the multitude of building materials required for a building, at this stage there is not one clear winner in terms of BIPV, but that instead we are now at the start of a period of innovation where BIPV/building materials offer both industries a pathway to lower costs and also offer the best pathway to provide cost effective distributed renewable energy.

From a PV/building product integration point of view it is useful to consider two generic approaches: thin film and wafer based technologies. In terms of integration with building products there has been considerable effort in the area of thin film deposition of photovoltaic materials on to a range of substrates (e.g. amorphous silicon has been deposited onto steel, glass, ceramics and plastics). The benefits for this approach are that thin films are flexible, and can conform to a wide range of substrate materials and shapes. In addition to deposition of thin films directly onto building material substrates, thin films can also be integrated using lamination or bonding. Another well know befit of thin films is they have a better tolerance of higher operating temperatures typically encountered with building integrated systems. Some thin film proponents also tend to emphasise that thin film efficiencies increase as illumination intensity decreases. An alternate view is that thin film efficiency decreases as illumination intensity increases.

The disadvantages for thin films is lower conversion efficiency than crystalline silicon and a greater susceptibility to long term degradation through the reaction of the photovoltaically active layers with water and oxygen. All photovoltaic layers need to be portrayed from the elements. However there is a greater need to protect thin film layers due to their greater susceptibility to degradation due to the high porosity, high defects and thinness of the photovoltaically active layers. This may well be less of an issue for such technologies as thin crystalline silicon, however it is not yet a technology that has been developed significantly in terms of commercial production. In addition low efficiency of thin film systems means that balance of systems costs are higher thus increasing the cost of the resulting electricity produced.

Unlike thin films, the traditional crystalline silicon wafer technologies do not easily lend themselves to integration with building products via direct deposition or growth of the photovoltaically active layers. Conventional silicon device processing requires high temperatures and semiconductor processing environments that are typically incompatible with building materials. As such integration of crystalline wafer technologies is usually achieved utilising bonding or laminating strings of PV devices with the building material. This sort of approach has been successfully utilised with a range of material such as steel, glass, ceramics, slate and plastics for utilisation in the building industry. A disadvantage with wafer technologies is that the surface must be essentially flat as wafers are not flexible. However, emerging technologies involving the lift off of thin crystalline silicon from wafers and bonding directly to materials such as glass or steel substrates means that thin flexible crystalline silicon layers are becoming available. This approach may well hold the promise of giving BIPV developers the best of both worlds.

Crystalline silicon is a relatively mature technology and as such incorporation of silicon PV devices with building materials is a less risky pathway given the long history of development of the devices and encapsulation methods. In addition due to its greater structural and material stability, crystalline silicon based technologies are less susceptible to degradation that their thin film counterparts. This is aided also by the greater thickness of the crystalline wafers, however as silicon wafers become thinner this may well change. The higher efficiency of crystalline silicon devices means that BoS costs are higher thus lowering the cost of the resulting electricity produced. This last point may well prove crucial in terms of the development of BIPV products as photovoltaic material costs decrease, BoS costs may well prove to be the dominate barrier to lowering the cost of BIPV products.

As discussed in detail in the body of the report there are a wide range of thin film and silicon wafer technologies that have been integrated with a wide variety of building materials. As the cost of the PV devices continues to fall, the Balance of Systems costs are emerging as a major cost hurdle to be overcome over the next period of time. As such, it is believed that the PV and building industry is at the start of a resurgence of interest in developing cost effective BIPV materials.

From this study further work has been identified:

- Durability of BIPV products needs to match or exceed the expected life of the building material. Limited data exists regarding durability and long term performance of BIPV/building products currently in the marketplace. Need for independent standards for BIPV products as for standard PV and standard building products.
- The dominance of crystalline silicon PV is expected to continue as the industry continues to grow rapidly. This means that integration of PV with building products can be done in the most flexible way possible utilising encapsulation and lamination techniques to bond PV devices to a wide range of materials and hence produce a wide range of PV active building products.
- Thin film products may emerge to challenge the dominance of Si, in which case they could look at deposition onto a limited range of materials that are suitable for vacuum processing (glass, steel etc) as well as being bonded or laminated to a wide range of materials as well.
- Transfer or “lift-off” technologies for producing crystalline thin silicon layers onto a variety of substrates are an emerging technology. This approach holds the promise of being able to deliver the benefits of the flexibility of thin films with the higher efficiency potential of crystalline silicon. In addition by utilising the advantages of a PV/thermal hybrid collector, this approach could reduce the temperature effects on crystalline silicon PV performance as well as gain additional benefit from the extraction of low grade heat.

INTRODUCTION

The building fabric represents around 15% of building lifecycle greenhouse gas emissions, and presents a significant opportunity for carbon reduction. The building fabric is currently a problem in carbon footprint terms, but innovative use of fabric materials and design provides a significant opportunity for incorporating passive and active renewable energy solutions. The potential is evident from the scale of roof area in Australian cities, which receives enough sunlight to power all of Australia's built environment needs. The challenge for Program 1 of the Low Carbon Living CRC ("Integrated Building Systems") is to re-envision Australian building materials, construction practices and appliance technologies as integrated low carbon and renewable energy systems.

This research report focuses on the current progress, opportunities and challenges for photovoltaic (PV) technologies integrated as a building material element. Whilst conventional PV modules, added to the external building, known as Building added PV (BAPV), dominate the current grid-connected market globally, they miss the opportunity of displacing conventional building materials which maximises longer term building asset value.

By substituting rather than overlapping standard building elements, Building integrated PV (BIPV) offers a solution that can completely replace building skin components, maintain the mechanical resistance, thermal insulation, weatherproofing requirements and provide operational energy for the building.

Whilst the current BIPV market has been driven by specific national feed-in-tariffs (for example in 2010 France 0.58, Germany and Italy 0.48, Belgium 0.65 euros/kWh) with a global capacity in 2011 of 400 megawatts (MW) and market value of US$606 million (Pike Research, 2012), the long-term growth projections of a 4-fold increase by 2017 are driving optimism in PV building materials R & D and commercialisation.

Government incentives have been reduced, as have PV module prices which has contributed to a consolidation of PV market players and many of the companies that depended on the BIPV feed in tariff have suffered as these subsidies have been removed. BIPV is still seen as a niche market with BAPV representing the lower risk activity. This, however, is shifting as building owners and investors are looking to future proof their building assets, reduce operational energy needs and aim for Low Carbon, Zero Energy or aspire for Energy Plus building solutions. This is stimulating opportunities for onsite renewable applications given energy efficiency can deliver only a proportion of savings before it becomes more economically prudent to invest in solar building technologies (Pitt & Sherry, 2012).

The aim of this report is to understand what building cladding materials (such as steel, glass, plastics, cement, bitumen and timber materials) are best suited to applying PV. What are the challenges, barriers and risks? What has been manufactured and what has been known to work or not? How do such products lead to better integrated solutions to whole buildings? BIPV, for the purpose of this report is treated as a secondary building cladding solution and the focus is on the integration of PV on building material substrates either through deposition or encapsulation. This can be classified as 2nd generation BIPV whereas 1st generation BIPV typically is characterised by taking a conventional PV module and engineering a mounting solution to the building. Examples of PV building material products are provided, including some practical case study applications and findings.

STATUS OF PV INTEGRATED BUILDING MATERIALS

PV technology typologies – overview

A simplified description of PV technology typologies is presented in Figure 1 below and categorises PV into Silicon Wafer semiconductor elements and Thin Film semiconductor compounds combining a range of different elements. Mono and Poly-crystalline silicon continues to dominate the PV market based on both high efficiency conversion and continued reduction in manufacturing costs as demand has increased.

Fundamentals of Photovoltaic technologies - Photovoltaic technologies still include a number of significant component-performance ‘gaps’ for various crystalline, polycrystalline, and amorphous technologies - both bulk and thin-film technologies. The ‘first gap’ is the breach between the theoretical limits (the attainable levels) and what has been demonstrated under the best conditions in the laboratory (the headline or record cells). These limits range from ~90% of attainable efficiency for crystalline Silicon to 50% for some thin films, to less than 25% for organic cells (Kazmerski, 2012).

Underlying these differences are losses that are inherent to the conversion process (theoretical to attainable), and the ability to fabricate the cell with the ensemble of optimal, interrelated properties and parameters.

The ‘second gap’ is the disparity between the laboratory efficiency of cells and those produced in commercial manufacturing lines. This has to do with scaling up the processing to larger areas, variations of materials (e.g., starting wafers, substrates, and coatings), less-controlled conditions, and higher required throughputs.

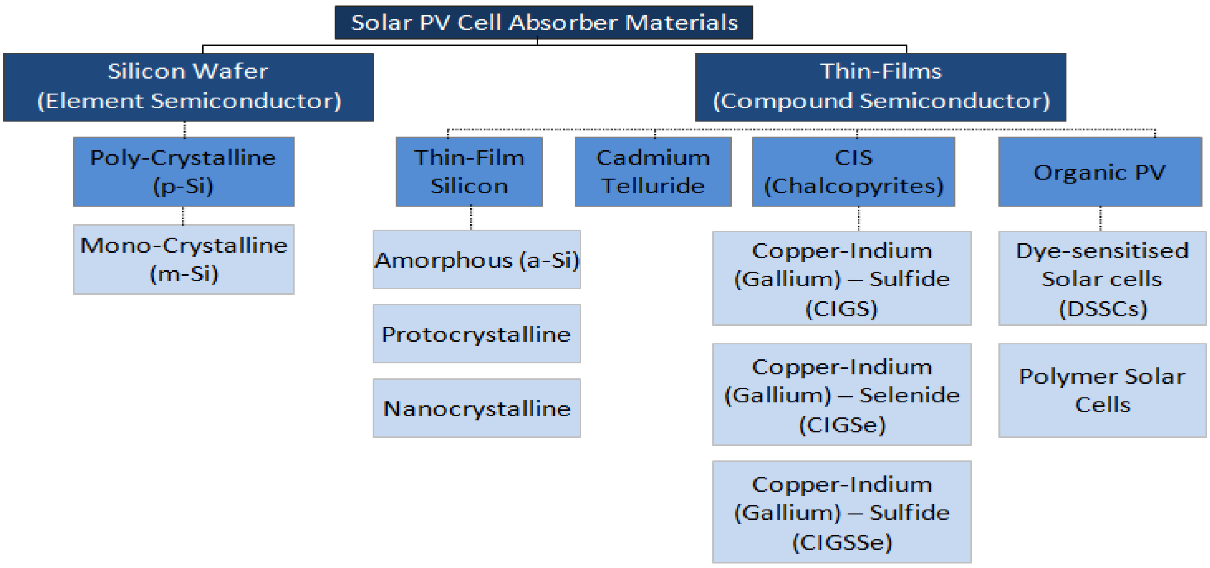


Figure 1: Overview of Solar PV Cell Absorber Materials

Source: adapted after Tyagi, Rahim et al. (2013)

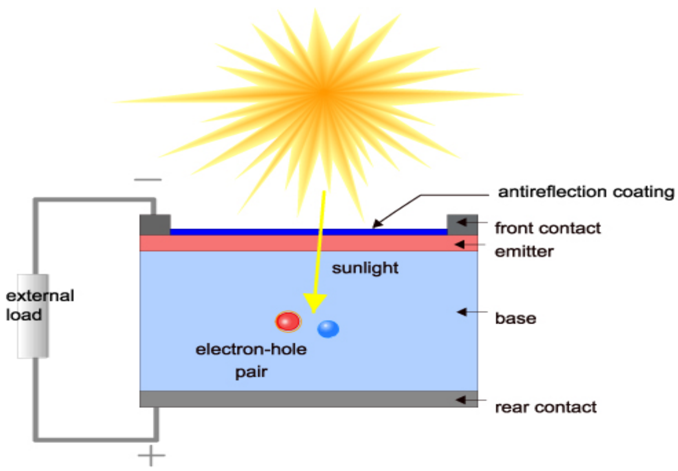


Figure 2: Typical solar cell cross section and operation

Source: Honsberg and Bowden (2013)

The ‘third gap’ is that between the cell efficiencies and those of the modules. This depends on the ability to minimize the losses when wiring the cells into circuits, bringing the active area of the module to be closer to the cell area, and maximizing the optical transmission of the protective or support layers that are positioned between the cells and the incident sunlight.

Standard PV Cells technologies - Photovoltaic cells represent the smallest unit in a photovoltaic power producing device, typically available in 12.5 cm, 15 cm and up to 20 cm square sizes and typically produce between 1 to 3 watts. In general, cells can be classified into three categories:

- Thick crystal: wafer-based crystalline (single crystal and poly-crystalline (p-Si) or also called Multicrystalline silicon (mc-Si), compound semiconductor);
- Thin film: thin layers of photovoltaic active material placed on a substrate (glass or metal) using vacuum deposition process; and
- New generation thin film: more recent technologies with new material and new process aiming at improving the efficiency or reducing the price.

In 2011, bulk crystalline silicon wafer technologies accounted for around 86% of total shipments of 23GWp with mono-crystalline cells comprising 40% of this amount. Cadmium Telluride (CdTe) with 2 GWp of annual production in 2011 dominates thin film which has a market share of 14%.

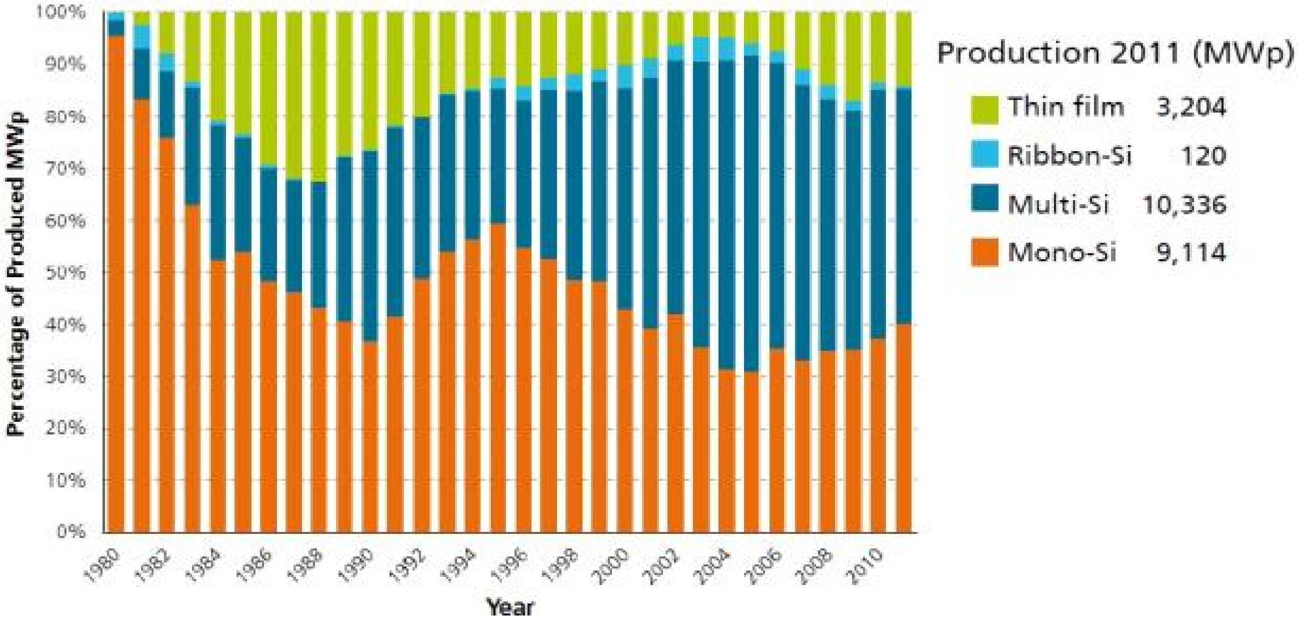


Figure 3: PV Production by Technology 1980-201

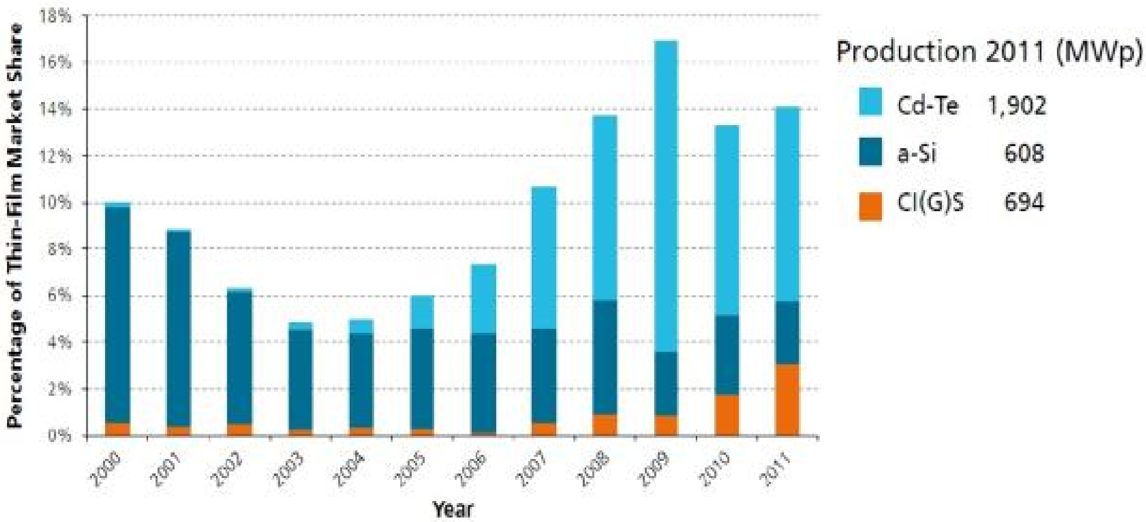


Figure 4: Market share of Thin Film Technologies relative to World Production 2000-2011

Source: Navigant Consulting Graph: PSE AG (Fraunhofer-ISE, 2012)

Thick crystal: Single crystal silicon (sc-Si) PV cells are formed with the wafers manufactured using a single crystal growth method and have commercial efficiencies between 15 and 20 %.

Multicrystalline silicon (mc-Si) cells, usually formed with the multicrystalline wafers manufactured from a bidirectional solidification process, are becoming increasingly popular as they are less expensive to produce but are marginally less efficient, with average conversion efficiencies of around 14%. Quasi-monocrystalline silicon PV cells, manufactured using the same process as multicrystalline silicon PV cells, are gaining attention more recently.

III-V compound semiconductor PV cells are formed by growing materials, which generate electricity, such as GaAs on the Ge substrates and have high conversion efficiencies of 35% and more. Due to the high cost, they are applied for concentrating PV systems with tracking systems.

Thin films: Thin film cells are formed by depositing extremely thin layers of photovoltaic semi-conductor materials onto a backing material such as glass, stainless steel or plastic. Module conversion efficiencies reported for thin film PV are currently ranging from 7% (a-Si) to 13% (CIS) but they are potentially less expensive to manufacture than crystalline cells. The disadvantage of low conversion efficiencies is that larger areas of photovoltaic arrays are required to produce the same amount of electricity. Thin film materials commercially used are amorphous silicon (a-Si), cadmium telluride (CdTe), and copper-indium-gallium-diselenide (CIGS).

Silicon heterojunction technology (Si-HJT) consists of thin amorphous silicon layers on monocrystalline silicon wafers. It allows for solar cells with energy conversion efficiencies above 20%, also at industrial-production level.

Rear contact solar cells (RCC) achieve potentially higher efficiency by moving all or part of the front contact grids to the rear of the device. The higher efficiency potentially results from the reduced shading on the front of the cell and is especially useful in high current cells such as concentrators or large areas.

New Thin Films or Third generation: Other thin film: Organic thin film PV cells (OPV), using organic semiconductors, have created more and more interest on account of their potential low cost. Many research and development activities are underway, and some industrial products begin to appear.

Other thin film: Dye-sensitized solar cell (DSSC, DSC or DYSC) is best considered as artificial photosynthesis. It performs well under indirect radiation. This technology has been dominated by Grätzel titanium dioxide (TiO_2).

Multi-junction solar cells or tandem cells are solar cells containing several p-n junctions. Each junction is tuned to a different wavelength of light, reducing one of the largest inherent sources of losses, and thereby increasing efficiency. Traditional single-junction cells have a maximum theoretical efficiency of 34%, a theoretical "infinite-junction" cell would improve this to 87% under highly concentrated sunlight.

Further research and development is being carried out to improve the efficiency of all the basic types of cells with laboratory efficiency levels for single crystal cells of 25 %, and for thin film technologies of 20 % being achieved.

Performance of Photovoltaic technologies - The measurement of the electrical performance of PV elements has been standardised to a large extent. The performance are defined for “Standard Test Conditions” (STC), which represent an irradiance of 1000W/m^2 at normal incidence, at an Air Mass of AM1.5 (Air Mass defines the direct optical path length through the Earth's atmosphere that characterizes the solar spectrum after solar radiation has travelled through the atmosphere) and a cell junction temperature of 25°C.

Temperature dependence - An important parameter impacting the efficiency of the solar cells is the ambient temperature, also called the operating temperature, and its impact is different depending of the technology. The performance of Crystalline-Si cells declines rapidly with a rise of temperature: the average degradation ratio commonly accepted is -0.4% per degree above 25°C (Skoplaki and Palyvos, 2009). For thin film Amorphous-Si the degradation is about -0.1%.K^{-1} (Staebler and Wronski, 1977). For other thin film, additional effects interact with temperature and the output can be opposite, for instance for CdTe and OPV, the higher the temperature the better the electric output becomes.

Feedstock availability - future increases in rare earth material prices required for thin film production, such as indium and tellurium resulting from demand-supply imbalances, could have a negative impact on CdTe and CIGS cost reduction ambitions. The USGS (U.S Geological Survey) has assessed that the world wide Indium supply could deplete within 10 years and tellurium by 2025 (DOE, 2011). Indium is seen has having a greater supply risk in the short-term, but is not as critical, as it can be replaced with other materials if required. Tellurium's supply risk is rated lower, but the importance of the material causes the DOE to label it as "near-critical" in the medium-term. Tellurium is normally extracted as a by-product of copper and lead production.

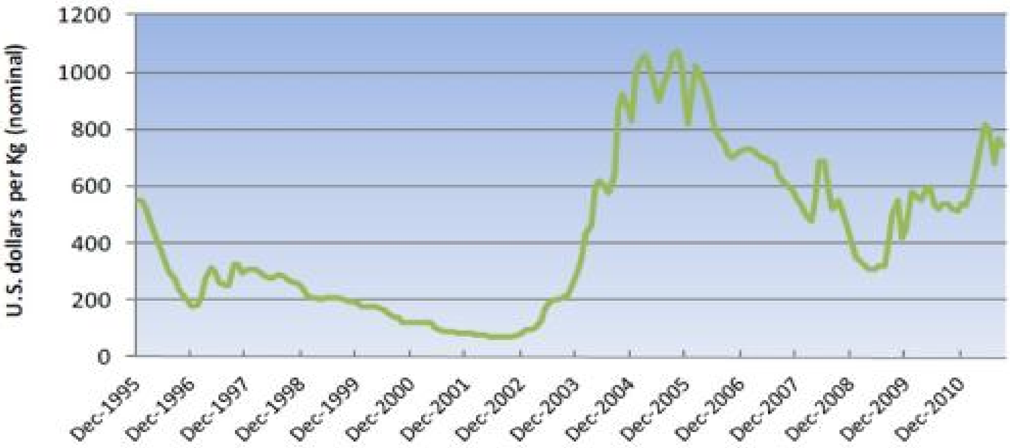


Figure 5: Price of Indium 1995-2010

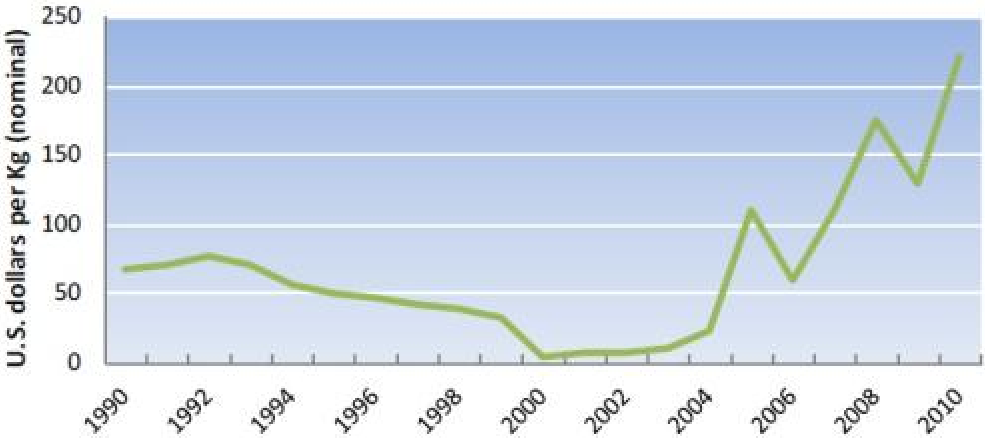
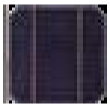
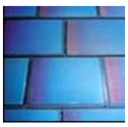
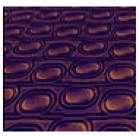


Figure 6: Price of Tellurium 1990-2010

Source: DOE (2011)

A brief overview on material for solar cell production is illustrated in Table 1 below.

Table 1: Main characteristics of PV cell technologies

Technology	Scheme	Efficiency	Thickness	Area /kW	Maturity	Maximum Yield conditions
Crystalline wafer based Technologies						
Single crystal silicon (m-Si) PV		15-22%	150-200 µm	$7m^2$	Industrial Production	Direct / high irradiation, low operative temperature
Poly-crystalline silicon (p-Si)		12-17%	150-200 µm	$8m^2$	Industrial Production	Direct / high irradiation, low operative temperature
Thin Film Technologies						
Amorphous silicon (a-Si) (multijunction)		5-9%	0,2-0,5 µm	$15m^2$	Industrial Production	indirect/diffuse irradiation
HET amorphous silicon and m-Si		20-22%	150-180 µm	$12m^2$	Industrial Production (Sanyo)	indirect/diffuse irradiation, high ambient temperature
RCC (Rear Contact Cell)		20-24%	150-180 µm		Industrial Production (Sunpower)	
Copper-indium-Gallium-Selenide (CIGS)		9-13% lab record 20% (Swiss Lab EMPA)	1- 2 µm	$10m^2$	Industrial Production	indirect/diffuse irradiation, high ambient temperature
Cadmium Telluride (CdTe)		9-12%	2- 5 µm	$11m^2$	Industrial Production (First solar)	indirect/diffuse irradiation, high ambient temperature
Third Generation : New thin Film technologies						
Organic thin film PV cells (OPV)		3-8%	0,1 à 0,2 µm		R&D phase. Some Industrial Production (Konarka)	indirect/diffuse irradiation, high ambient temperature
Grätzel Cells dye-sensitized solar cell		7%	n.a.		R&D phase. Some Industrial Production	
Multi-junction solar cells or tandem cells		35-40% For space application	n.a.		R&D phase. Some Indust. Prod 25-29 % for ground applications with concentration	

Consistent improvements in PV cell efficiency have been realized for virtually every PV technology and module efficiency has followed this trend, albeit with a time and performance lag. This trend is projected to continue, owing to R&D improvements that produce higher best-cell efficiencies and manufacturing technology improvements that advance commercial modules toward best-cell efficiencies. Nevertheless, as shown in Figure 7 there is still significant room for efficiency improvements for many PV technologies.

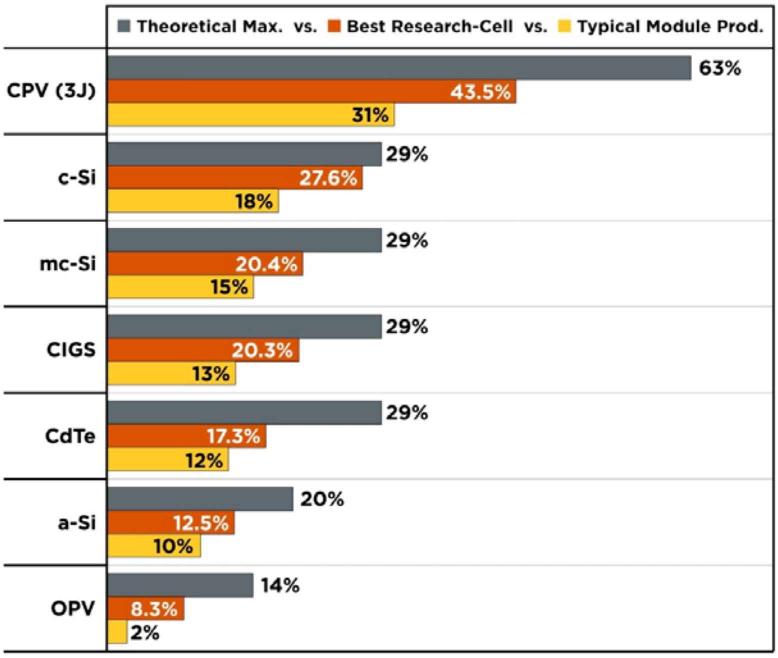


Figure 7: Closing the Gap: Production, Laboratory, and Theoretical PV Module Efficiencies

Source: NREL, 2011

BIPV integration approaches – rigid, flexible and transparent

BIPV categorisation relevant to the building industry can be described as follows:

- rigid (opaque) products
- flexible products
- transparent/semi-transparent products

Rigid BIPV has typically used mono or poly crystalline silicon wafers to build customised building cladding structures. Tiles with PV can be designed to interlace with conventional roofing tiles or cladding materials. Flush mounted panels that overlay conventional roofing are not truly an integrated building material.

Flexible BIPV laminates are designed to be glued onto existing building materials such as metal roofing. Flexible shingles can also interlace with conventional asphalt shingles. PV cells deposited directly on building materials is a growing area of BIPV investment but use newer PV materials which are less well developed than rigid crystalline silicon.

Transparent BIPV are often categorised by the glass industry within a group called ‘smart windows’ and include electrochromic windows that have active electronics to control the translucent properties of the glazing. This is done by passing a voltage through the glass to change the glass properties to opaque and even reflective or transparent. Glass technologies have already achieved a level of sophistication and maturity that lend themselves to PV applications. Amorphous silicon and CIGS thin films are showing real prospect as the PV absorber materials with transparent conductors to compete with electrochromic glass windows. Customised BIPV glass is still in its infancy with varying success of performance yields and profitability. However, the prospects are encouraging as demand drives higher volumes and facilitates manufacturing and cost efficiencies.

Cerón *et. al* (2013) undertook a review of 445 BIPV products and places BIPV into two main groups classified according to their origin:

- BIPV modules (BIPV-M); and
- PV constructive elements (PV-CE).

This report is less concerned with 1st generation BIPV-M which relates to strategies to attach conventional PV technology onto or as part of buildings, but moreso on 2nd generation PV-CE technologies created specifically for the building industry.

Figure 8 provides a breakdown and reveals the simplest and most common application in the BIPV market is a PV-CE roofing system. Interestingly, a high growth area has been in BIPV urban furniture integrating PV into urban lighting (Roth, 2009) and driven by local government green image and progressive approaches.

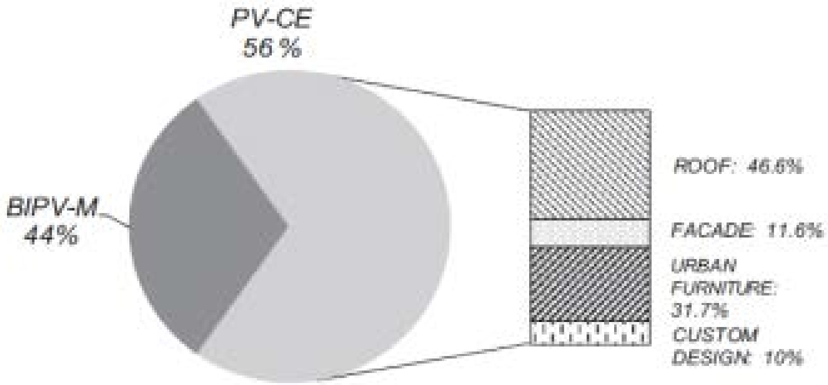


Figure 8: Breakdown of BIPV market

Figure 9 from Cerón *et al* (2013) identifies poly-crystalline (p-Si), also referred to as multi-crystalline (multi-Si) and mono-crystalline silicon (mono-Si) followed by amorphous silicon (a-Si) as the major PV technologies used to date for BIPV applications. Interestingly, a-Si has lost share in market growth at the expense of mono-Si when comparing the 2013 study (*ibid*) to a similar study of BIPV products conducted in 2010 (Cerón *et al*, 2010). This finding is explained in the continued reduction in manufacturing of mono and multi-Si as a mainstay PV product using building mounting systems. It has also followed the improved access to pure silicon feedstock at a suitable price compared to 2007-2008 (poly-silicon was US$500/kg but is typically US$20-30/kg) when thin film a-Si in particular, and Cadmium Telluride (CdTe) and CIGS boomed due to silicon supply not being able to cope with demand (EC, 2012 and Siemer, 2012).

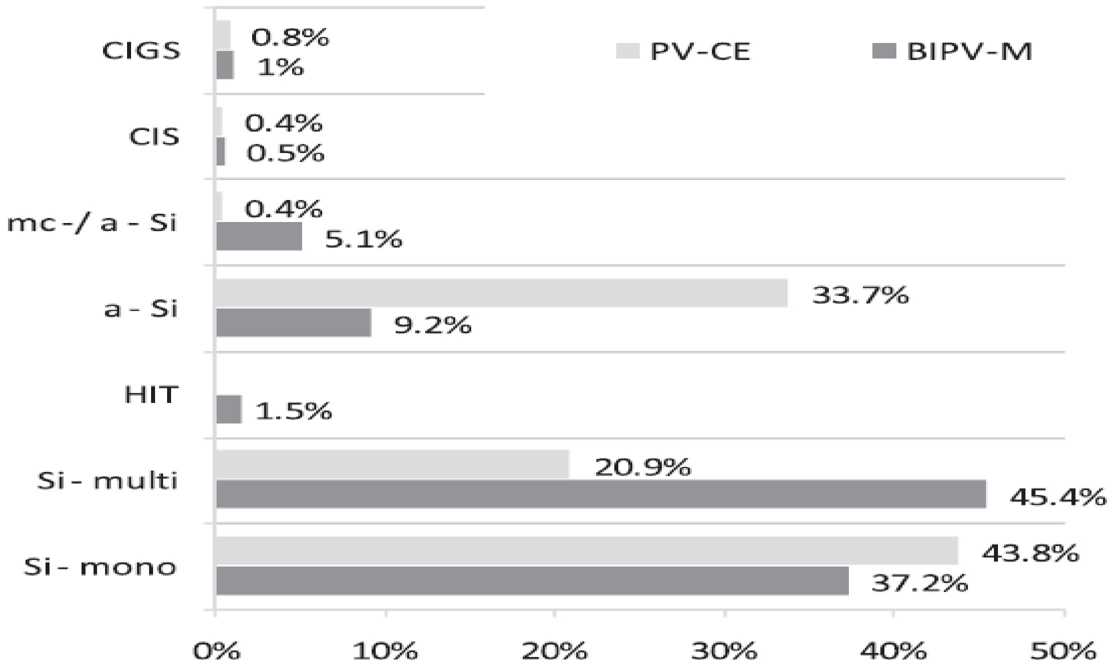


Figure 9: PV technologies of BIPV modules (BIPV-M) and PV constructive elements (PV-CE)

Source: Cerón et. al, 2013

With the BIPV market being driven by BIPV feed-in-tariff incentives in Europe, the major product development has focused on displacing the ubiquitous roof tile with PV shingles using predominately mono-Si given the relative small size of the tiles and need to utilise a high efficiency technology. For façades, thin film amorphous silicon (a-Si) has dominated due to the large size offerings, thinner profile and translucent characteristics.

BIPV-M applications have the advantage of not having to sacrifice performance and, for example, mono-Si from Sunpower and ET Solar and Heterojunction with Intrinsic Thin Layer (HIT) m-Si/a-Si from Sanyo produces more than 150W/m^2 in power density. This may be attractive in urban environments where roof space size is at a premium. As soon as the PV as a construction element (PV-CE) increases its level of building integration there is a trade-off in conversion efficiency. Complex geometries, the use of thin film, colour, translucency resulting in loss of solar grain area and absorptive PV surface area are contributing factors. These are however, compensated by PV-CE becoming a clever building material and displacing conventional products with the possibilities of performance improvements as production processes are refined and scaled up accordingly.

Whilst roof tiles and flexible BIPV products will continue to grow, the major BIPV market player is projected to be BIPV glazing systems (Figure 10) as smart window technology and its mature and sophisticated fabrication processes are coupled with improved PV technologies. Given glazing is a large component of commercial building façades and already commands a premium price for sunlight and thermally responsive products the progression to BIPV glass is a less ambiguous one compared to other PV building element options.

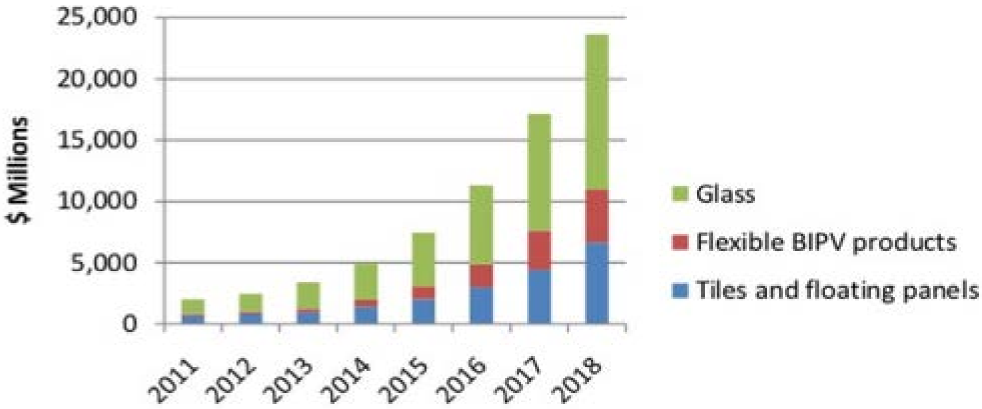


Figure 10: Projected growth of rigid, flexible and glazing BIPV

Source: Nanomarkets, 2011

Modes of Building integration

The main existing options for integration of PV are on roofs either tilt or flat; façade, either walls or shades; and more recently windows (Jelle and Breivik, 2012). Figure 11 highlights the dominance of solar tiles for roofs and continuous (homogenous) systems or window applications for façades based on the BIPV product survey conducted by Cerón et al. (2013). Solar tiles have to date dominated BIPV roofing systems as most experience of BIPV has been carried out in Northern Europe where the tile is a typical roofing system and exhibits simple geometry.

Rooftops modules for sloped roof were the first fully integrated systems to be developed and many suppliers offer standard products. Nevertheless, globally, the BIPV market still suffers from a lack of standardisation and modularity. Most of the systems are custom-made and, hence, do not entirely meet the functional, technical, and economical requirements of the architects and engineering consultants, installers, owners and end users (*ibid*).

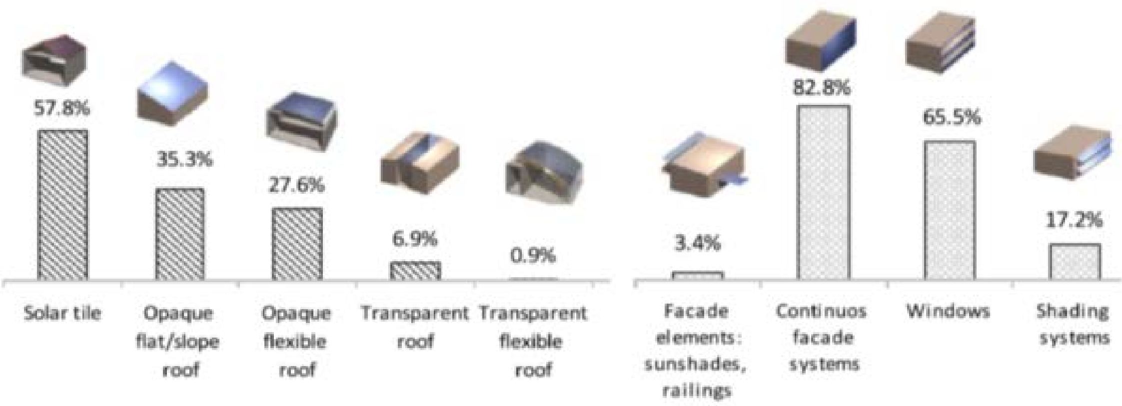
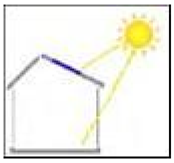
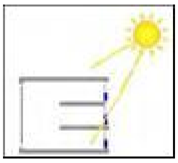
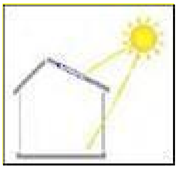
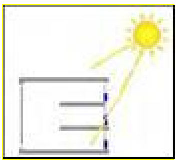
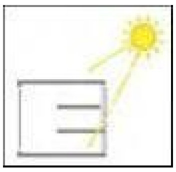
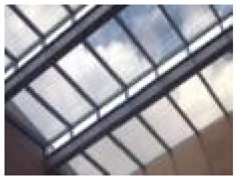
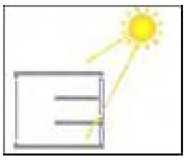
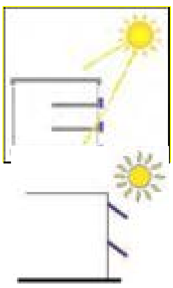


Figure 11: Proportion of BIPV Roof and BIPV Façade systems by building skin application

Source: Cerón et al. (2013) with BIPV typologies adapted from Prasad and Snow (2005)

Table 2: Classification of fully integrated PV systems

Type of product	Integration mode	Sketch	Examples
Opaque rigid PV Modules or PV tiles	Sloped roof covered with discontinuous element		 
PV foils Flexible PV foils	Flat roof or curved roof covered with continuous or discontinuous element		 
Semi-transparent and translucent PV	Skylight Atrium Veranda		 
Opaque PV cladding	Opaque part of a Curtain wall		 
Transparent PV glass	Windows or External part of a glass double skin wall		 
Opaque PV Modules	Light wall made of BIPV modules (PV modules replace the wall itself)		
Opaque PV modules	Sun shade : Awnings Fastenings		

PV material manufacturing – deposition and encapsulation

There are essentially two conventional approaches to PV material manufacturing that has implications for its adaptability as a PV construction element. PV can be deposited and/or grown on a substrate that provides semi-conductor attributes or it can be bonded or encapsulated between different layers. These processes have implications for the level of manufacturing complexity and impact upon key considerations such as cost, performance, flexibility, rigidity, colour, uniformity and design geometry.

Typically, crystalline Silicon (c-Si) PV elements are manufactured through the interconnection of conventional silicon wafers. The main advantages are its proven high reliability and high power efficiency conversion. This offers a BIPV solution that maximises the power density that can be achieved compared to other technologies as highlighted in Table 1.

Thin-film PV is made by depositing thin layers of semiconductor material that can be flat-plate glass (rigid) or flexible PV elements (Paridaa, 2012). The main advantages include the use of thinner materials which allow a wide range of integration possibilities, both geometrical and in terms of dimensional flexibility and transparency. Different materials can be used for the PV cells to be deposited upon such as glass, metal or polymer plastics.

Deposition has been a mainstay process of thin film applications that uses a substrate as a conductor. Until recently, the PV conversion efficiencies have been low and BIPV encapsulation or bonding PV has offered a superior outcome. However, encouraging progress has been made using thin-film CIGS. CIGS deposition process struggled initially as the single-layer polymeric approach used for amorphous silicon was not appropriate due to the grain boundaries in the plasma deposited nitride and pinholes in polymeric films. Plasma-enhanced chemical vapour deposition (PECVD) systems involves using a dyad barrier and combines typically a polymer and a ceramic as multiple layer pairs. The ceramic aims to fill the pinholes and slow diffusion through the polymer and the polymer seals any defects in the ceramic. Three or four layers are needed for CIGS PV and importantly reduces moisture penetration.

Dyad films use expensive vacuum deposition and need to be repeated to provide the necessary layering. Atomic Layer Deposition (ALD) barrier films only require one or two layers of alternating polymer and inorganic ceramic. The ALD atomic layer deposition rate is currently low, however, DOE and DuPont have been successful in depositing a thin ALD layer on polyethylene terephthalate (PET) with less than a 2% degradation in efficiency of CIGS flexible modules at international IEC61646 standard package level at 1,000 hours in 85^{o}C/85% humidity.

The product stack of flexible BIPV is moving towards a heavy weathering film on top such as fluorinated ethylene propylene (FEP), a thin ALD Al_2O_3 layer on a thick UV-PET polymer layer and a CIGS cell on either a polyimide or steel substrate. Also, Ionomer films are now surpassing polyvinyl butyral (PVB) and ethyl vinyl acetate (EVA) as having better resistance to moisture ingress.

Metal substrates such as stainless steel and aluminium are a good fit for flexible substrates for thin film PV due to tensile strength, inert properties and comparatively low cost. Metal foils for flexible thin film PV substrates provides a more suitable layer than polymers for the back side of the cell. Also, glass-coated stainless steel offers monolithic integration, an ion barrier, thermal stability and a good surface smoothness for added deposition layers. Molybdenum back conductors are also able to be deposited on the glass for growth of CIGS. Dow Solar Shingles using CIGS from Global Solar and Corus steel using DSC cells have had success with this approach.

Encapsulation using advanced plastics as substrates are growing in interest such as polymides which are cheaper that stainless steel but is one of the more expensive polymeric materials. Polyamide films are most likely to succeed in the long run where processing conditions are gentlest such as printed PV. Thin-film PVs high sensitivity to air and water vapour is restricting the market development of this potentially promising technology. Most new PV developments are predominately full glass-encapsulated modules rather than flexible products. This focus on rigid substrates also prevent new types of PV achieving cost advantages to the extent that they are unable to justify at this point in time Roll-to Roll (R2R) manufacturing processes.

CIGS (Copper indium gallium (di)selenide), OPV (Organic Photovoltaics) and DSC (Dye-sensitized Solar Cell) thin film are presenting opportunities for monolithic integration but given their delicate structural properties there is a need for encapsulation that provides the PV material rigidity without adversely compromising performance, longevity and market affordability.

In the short term, rigid PV materials are expected to be preferred as their cost structures and manufacturing processes are well defined. Flexible PV materials are forecast by some to dominate in the longer term as current a-Si modules are overtaken by flexible high efficiency CIGS technologies as they become more mainstream as a manufacturing process. Another major advantage for flexible PV materials is their module weight compared to rigid modules. Current rigid modules can weigh between 10 to 30 kg/m^2, where as flexible modules are in the order of 3 to 5 kg/m^2. Amorphous-Si has less stringent encapsulation needs for oxygen and moisture penetration than high efficiency CIGS modules, limiting performance to around 8-9%. CIGS dyadic encapsulation approach has promise using alternating layers of polymer and thin ceramic to eliminate pinholes and increase its resilience to outdoor conditions. Thin layers of silicon oxy nitride and silicon nitride, use plasma-enhanced chemical vapour deposition (PECVD) or atomic layer deposition methods which are common in the semiconductor industry.

These systems have already shown some success in greatly improving OLED (Organic Light-emitting diode) barrier performance, and are used in volume manufacturing as a protective overcoat in semiconductor devices before packaging. It is still unclear if such systems, which provide such good encapsulation on chips up to a centimetre on a side, can be scaled to provide pinhole-free protection over areas of multiple metres necessary for PV panel mass production.

Another barrier system that has shown success in the lab is ultra-thin TaN/Si3H4. TaN is the current barrier used in the semiconductor industry to encapsulate copper metallization in 130 nm and below technologies (e.g. flexible glass such as the lines developed by Corning and Schott. Part of their promise is the likelihood that such materials would retain many of the properties of thicker glass, such as dimensional stability, heat tolerance, and impermeability while permitting roll-to-roll processing and limited flexible applications.

While pinholes are still an issue for most organic polymer-only encapsulation systems, several organic-based encapsulation materials are still being investigated. A transparent poly (ethylene naphthalate) (PEN)-based ultra-high barrier material has been demonstrated in the lab as a possible organic encapsulation material for organic- based flexible PV modules. It is still to be proved if a single layer organic material can be deposited pinhole free and meet all of the BIPV reliability metrics.

Flexible substrates have, up to now, fallen into two general categories: metal foils and polymer films. Metal foils like aluminium and stainless steel have taken the lead in flexible PV, because they are generally more heat resistant and less easy to deform than polymers while still offering good flexibility. They also offer a higher level of barrier protection for the back side of the PV cell versus polymer films.

Looking ahead, the growth in substrates will likely be in polymer films, as they are lighter weight and cheaper than metal and are optically clear in many instances. A significant challenge to wide adoption of current polymer materials is lower deposition temperature requirements. Currently, only the polyimides are compatible with current thin-film PV deposition conditions for flexible substrate materials.

An additional advantage of polymer substrate films is that they can be extremely thin and, hence, a much smaller proportion of total thin-film PV device costs especially if process development allows cheaper, less temperature-tolerant plastics to be used. Metal foils are, however, a mature product with the potential for further thinning and thus cost reduction.

Another photovoltaic material that has potential as a BIPV product is thin crystalline silicon layers that can be produced using a variety of approaches such as exfoliation, growth from melt and epitaxial CVD, often on sacrificial (porous silicon) layer (for example for details see Lochtefeld et.al. (2013), Ravi (2013), Saha et. al. (2013), Schubert and Werner (2006), Haase et. al. (2013), Lin et. al. (2014)). An excellent overview of pathways for lowering the costs of crystalline silicon technologies, including the aforementioned *kerfless* processes, is a paper by a group from MIT (Powell et. al, 2012). The advantage of such kerfless processes such as the lift-off process (thin crystalline silicon layers are peeled away from a crystalline substrate and bonded to a variety of substrates, typically thin steel) is that it combines the high efficiency advantage, abundance and low toxicity of c-Si with the potential for lower material usage and hence lower cost of thin film photovoltaic. The technology has been worked on for some time in the laboratory but more recently a number of start-up companies have begun to promote this technology[3] (after Powell et. al, 2012).

As an example of the lift-off technology, AmberWave in conjunction with UNSW has developed thin (10-20 μm) kerfless silicon wafers which are grown using epitaxy on a porous silicon layer with in-situ doping. Etching of the porous silicon layer allows the c-Si epi-layer to be separated from the reusable crystalline silicon substrate. The epi-layer is bonded to conductive steel substrates resulting in thin c-Si solar cells that are flexible and mechanically robust (Lochtefeld et.al. (2013)) – see Figure 12.

These kerfelss approaches can reduce silicon material requirements by 80-90%, which represents a significant potential reduction in costs. Some industry analysts would argue that this advantage is being lessened by the already low costs associated with traditional silicon wafers. However what this has done is expose the higher costs associated with other parts of the photovoltaic process. In addition high efficiency approaches that utilise c-Si offer additional advantages in that Balance of Systems costs are also reduced. Solexel has reported large area, 43 μm thin, 156 x 156 mm^2 wafers bonded to thin steel substrates with an independently confirmed efficiency of 20.1% (measured by NREL). (M. Moslehi, 2012.) Ultimately it can be argued that the PV industry will continually seek to lower costs across all aspects of the production process and hence a technology such as thin lift-off silicon could play a significant role.

[3] Some example organizations include: *Exfoliation*: AstroWatt, IBM, IMEC, SiGen, and Twin Creeks. *Growth from Melt*: 1366 Technologies, CEA-INES, and University of Lisbon. *Epitaxial CVD, often on sacrificial (porous silicon) layer*: Amberwave, Ampulse, Anaxtal, Crystal Solar, Fraunhofer ISE, Nanogram, NREL, Sierra Solar, Solexel, Thin Silicon and UNSW.

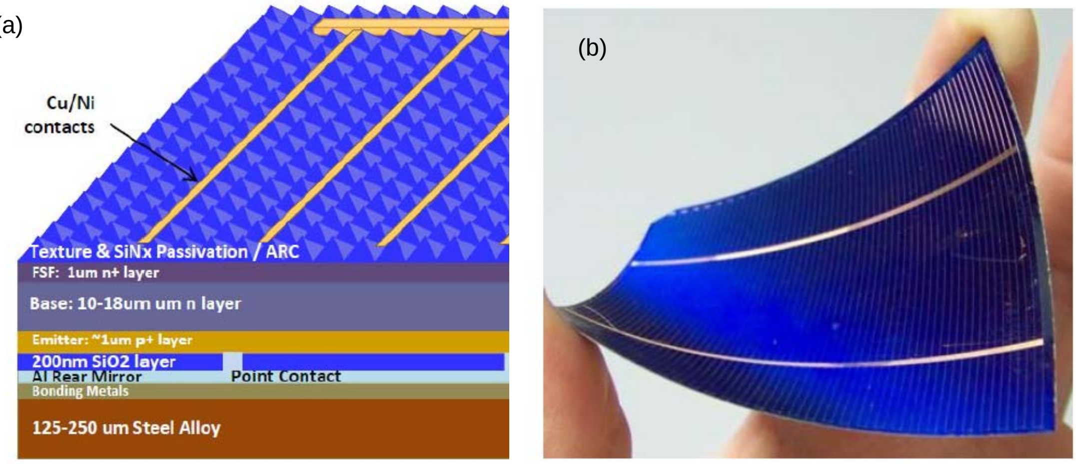


Figure 12: (a) The UTSi (Ultra-Thin Si) cell structure. Top grid is defined by UNSW selective n+ laser doping followed by Ni/Cu plating. (b) Completed cell example (50 cm2 area) Lochtefeld et.al. (2013).

PV and Concrete/Clay

A popular integrated roof system consists of PV modules using mono- or polycrystalline cells to replace conventional cement tiles. These PV tiles are installed on roofs in a way that blends in with cement tiles, following the contours of the roof. In many cases, one module can replace up to three or four tiles and reduce the number of necessary connections. The PV array weighs less than the cement tiles but the roof has to be engineered for the correct weight and compliant with local and national roofing requirements for wind loading and weatherproofing.

Each Lumeta Solar S Tile displaces approximately three traditional concrete or clay tiles customised to replicate the dimensions of major tile manufacturers. The actual solar laminate is a standard glass superstrate, with EVA encapsulation and TPT™ (Tedlar®/ Polyester /Tedlar®) substrate construction, and uses monocrystalline cell technology.

A similar approach has been used by Solardachstein, translated as "solar-roof-tile" using a STEPdesign embedding a PhotoWatt polycrystalline PV cell into a conventional clay tile. This is a simple approach and uses the conventional material of cement or clay as the support structure for the PV.

Figure 13 – Lumeta Solar S tile replacing a traditional clay and concrete tile

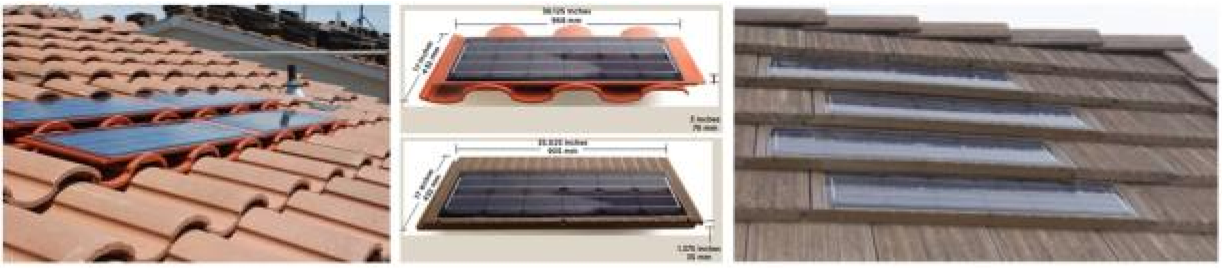


Figure 14 – STEPdesign solar roof tile on clay tile

Area Industrie Ceramiche produced a Tegolasolare monocrystalline PV tile. An area of $40m^2$ is required to provide around 3kWp of power. The red ceramic tile uses a spray-dried red porcelain mix and the PV is encapsulated in glass with the aim of maintaining the traditional red tile aesthetic. Combining the PV with a porcelain brick tile the thermal properties allow performance improvements of up to 8% compared to PV on clay tiles.

SRS Energy and US Tile which is part of the Boral Roofing Company partnered to produce the Solé Power Tile. The blue glaze tile is a barrel-style technology designed for a clay tile curved roofing system using thin film solar.

Sun Energy Tile™ from $BIPV_{INC}$ integrates a 52W polycrystalline module with cement tile roofs from a number of manufacturers or as a composition shingle for low profile roof products.

Figure 15: Tegolasolar tile, Area Industrie Ceramiche

Figure 16: SRS Energy and US Tile - Solé Power Tile

Figure 17: Sun Energy Tile™ from BIPVINC

Another product, the Monier SolarTile has been developed specifically to work seamlessly with Monier's roofing range. Again, it follows the approach of replacing conventional flat profiled concrete roof tiles and shingles using a composite subframe to house mono-crystalline PV cells delivering 30Wp per tile or 120Wp per square metre.

Hering have bonded the PV modules directly to an architecturally precast concrete frame using a polytransitter so that it can be integrated seamlessly into a concrete façade without any variation in the fastening system. A polytransmitter, for this purpose, is a cement coating which serves as a voltage bridge between the glass and the substrate material.

Figure 18: Monier SolarTile

Figure 19: Hering precast concrete with integrated PV

Figure 20: Suntech PV to replace clay tiles and compliment existing roof colour

PV and Slate

Not a common roofing material in Australia but certainly in the UK, there are very limited examples of PV and slates beyond products that replace slates but use plastic or glass as a substrate. The one product that tries to push the boundaries, but more so from an aesthetic perspective, is a product produced by RES called the SolarSlate. The product mimics slate but is actually frosted glass produced using sandblasted grits of different sizes. This obscures the blue solar cells and stops the slate looking shiny, delivering a finish very similar to natural Welsh slate. The slate is 6.5Wp weighing 1.8kg with 500mm x 256mm dimensions. For 1kWp it requires 154 roof slates covering 7.8m^2 to deliver 1kWp.The expense is AU$65-70 a roof tile or around AU$10Wp but the market is focused on a planning approval solution on protected traditional buildings and in conservation areas.

Figure 21: SunSlates Heritage approved product

Figure 22: Atlantis PV Roofing Sunslates

65KWp Atlantis Energy Sun slates, Bergdorf Hospital

PV and Timber

Timber for PV is used as a support structure or a complementary cladding material for architecturally appealing façade integration. Using wood as a substrate does not make practical sense from a performance or a warranty perspective and to date has not gained any traction in research and development. The Earth Centre, UK timber frame solar canopy structure included 3.5 tonnes of regular roundwood, or 800 timbers of between 125mm to 250mm in diameter needed to make 221 nodes to support an aluminium framing system to house the PV modules. Aesthetically, timber and PV complement each other extremely well and allow for creative architectural outcomes and daylighting effects as demonstrated in the examples below.

Figure 23: Earth Centre Timber PV structure
Source: Carpenter Oak & Woodland; Terry Miller

Figure 24: Shorne Wood Country Park (UK) PV integrated within a timber shingle roof

Figure 25: Timber beam solar canopy support structure, ECN Building, The Netherlands

1MWp Mont-Cenis timber frame PV, Germany | PV glass timber façade MGT Energy System, Austria

Figure 26: Timber and PV cladding

PV and Steel/Aluminium

Whilst glass is the most utilised material for encapsulation and substrates in the BIPV market offering a rigid BIPV solution, there is growing interest in lightweight, aesthetically pleasing flexible PV presenting opportunities for metal substrate manufacturers. These meet the needs of curved building surfaces, customised to deliver a uniform building skin function. Photovoltaic roofing membranes can be easily fixed to conventional metal sheet roofing products such as aluminium and steel. Typically, styrene butadiene styrene (SBS) bitumen membranes are used, composed of many layers adhered to flexible thin-film photovoltaic cells, usually multiple junction technology composed of (2-3) superimposed layers of photovoltaic cells to produce maximum electrical output across the entire solar spectrum. Placing the thin-film photovoltaic laminates directly on the roofing material helps generate energy in low-light or cloudy days. The laminates are sturdy enough to walk on without being damaged.

Uni-Solar has pioneered the application of flexible, thin-film PV modules to architectural metal roof panels. Its flexible, thin-film amorphous module has a pressure-sensitive, peel-and-stick adhesive on its back surface and can be factory laminated to metal roof panels for new construction. The self-adhesive, flexible, thinfilm PV modules can be applied to existing snap-lock and batten standing seam metal roofs if the metal panels have a flat profile between seams. Other similar examples have been produced by Alwitra Evalon using amorphous silicon (Figure 30). Solopower follow a similar approach but use a more efficient flexible CIGS cell, depositing Copper Indium Gallium di-Selenide (CIGS) in a proprietary electrochemical process. Flexibility is due to their light-gauge and robust foil substrate that is resistant to breakage.

Figure 27: Solopower flexible CIGS PV

Companies such as Dawn Solar have combined flexible solar modules with metal roofing and a concealed radiant heating system under the metal panels, creating both electricity and hot water from the sun. To capture the warmth generated from hot metal roofing, there's a grid of pex-filled purlins with a water and glycol solution for a solar thermal system. Dissipating the heat improves PV performance.

Standard rigid insulated panel (R-panel) metal roofs with complex panel profiles, overlapping seams, exposed fasteners, and stiffener beads or striations have been limited to traditional equipment-mounted, glass, solar modules. A new solar roof system combines certain elastomeric coatings and inter-ply materials with flexible, thin-film PV by Solar-Power Restoration Systems. This bridges the R-panel's compound roof profile and exposed fasteners, creating a flat substrate for the PV modules. The SolarSeal PV System uses thin-film modules and coatings to both waterproof the metal roof and generate solar power. Their SolarSeal PV Magnetic Systems™ uses high-energy flexible magnets for attaching thin-film PV to metal roof panels. The thin nitrile rubber-composite magnets, with a belt and suspender design and thin-film module system, performs well in high-wind conditions and has the advantage of being easily transferable to another roof.

Figure 28:Dawn Solar SunNet BIPV using UniSolar P/Thermal system on an Englert metal roof

Figure 29: SolarSeal PV Magnetic metal roof assembly

Flexible thin-film modules are one of the best options to affix a PV array to metal roofs. Rigid glass silicon PV modules work but they require some form of mechanical attachment. It is important to determine how the additional weight of heavier glass modules and rack attachment systems affects the building structure and metal roof system.

Flexcell's flexible BIPV, amorphous silicon thin film photovoltaic module was designed for quick production of building integrated photovoltaic (BIPV) metal roof products and mobile solar chargers. The Flexcell PV modules feature DuPont™ Solamet® PV414 frontside metallization paste which enables high speed roll to roll (R2R) processing of thin and flexible solar cells and modules.

Another technology which lends itself to metal roof applications is dye-sensitised cells (DSC) which use titanium and stainless steel as the flexible substrate. DSC is a photoelectrochemical device consisting of a dye-coated semiconductor photoelectrode and a counter electrode arranged in a sandwich configuration, with the interelectrode space filled with a liquid electrolyte (Watson, *et.al.*, 2011, 2013). When dye molecules are excited by visible light, they inject electrons into the conduction band of a TiO_2 semiconductor support on which they are anchored. Dyesol and the large steel manufacturer Tata have been collaborating to deliver a roll-to-roll manufacturing line for the mass market. Prototypes have demonstrated the ability to produce a 20m2 PV roof sheet. Challenges still persist in delivering a reliable power output with an industry accepted lifespan of 20+ years similar to the lifespan of the metal roofing product.

Figure 30: Flexible PV membranes on metal roofs

PV and Plastics

Plastics are synonymous with polymer solar cells and lend themselves to organic PV deposition. Plastics are lightweight, rigid or flexible and typically durable. Whilst, they show promise in terms of low production costs they are limited by their efficiency results compared with conventional silicon cells and are susceptible to photochemical degradation. Typically, plastics have been used successfully to house silicon or thin film PV cells or modules to provide roofing applications. Dow Solar, Sun Energy Engineering, Co., SRS Energy, and Centria Services Group are companies using this approach. Dow Solar's Powerhouse Solar Shingle (costing around US$55-60 per tile) is made with CIGS photovoltaic cells in a proprietary shingle design. Roofing contractors do not need any particular knowledge of solar array installations, and installations are typically quick because conventional roofing shingles and Solar Shingles can be applied at the same time. They are half an inch thick requiring 1 square metre to deliver 40Wp.

CertainTeed, similar to other tile manufacturers such as Monier, have produced a PV version to compliment their exiting range using lightweight plastic to house 13.2% efficient poly-crystalline PV cells.

Thinking totally out of the square is a PV plastic product that tries to mimic the natural aesthetics of ivy on the façade of a building. The Solar Ivy come in 1.2m x 2.1m strips capable of generating 85 Watts of solar power. It combines PV technology and photo- piezoelectrics adding power from the movement of the solar ivy and can use thin film CIGS, A-Si or OPV.

Figure 31: Dow Solar CIGS plastic roof shingles

Figure 32:CertainTeed Apollo II™ PV plastic tile to replace asphalt roof shingles

Figure 33: Solar Ivy on a plastic substrate

Source: Solar Ivy solarivy.com

PV and Glass

NanoMarkets (2012) estimates that over the next four years the BIPV glass market could reach more than $6 billion - and identifies a clear role for advanced optics in the development of cutting-edge BIPV technology. BIPV glass is certainly not cheap. One estimate, from a European Photovoltaic Industry Association (EPIA) report on the topic, highlights the significant premiums involved. It suggests a price range of €400-800 per m^2 for a semi-transparent PV module, with some very special products costing more than €1000 per m^2. While glazed BIPV can hardly compete with low-cost laminated glass, it becomes a competitive option if compared to more sophisticated architectural glass (without taking into account the electricity generated).

The cost of architectural glass varies widely, ranging from less than €100 per square metre for basic glass to several times that figure for high-end, multi-pane glass with advanced features such as infrared reflection. The absorption' function of PV and the conventional 'transmission' function of glass are inherently at loggerheads with each other - particularly in terms of the cost implications. Pythagoras Solar, however, use optics to position the PV cells in such a way that they minimize light attenuation.

Table 3: Comparision of power and visibility of translucent PV glass

Company	Pythagoras Solar	Sharp Solar See-Through PV	Tropiglas	RSI	Onyx	SAF-Energy Glass™
Power/m^2	120 watts	60 watts	35 watts	33 watts	25 watts	10 watts
Visibility	50%	20%	>80%	50%	70-90%	100%

Pythagoras Solar's Photovoltaic Glass Unit (PVGU) combines optical technology with high-efficiency crystalline silicon cells and advanced materials to provide what is currently the industry's highest transparency and highest density PV power generation in a standard double-pane window.

The PVGU is designed around the standard approach for an insulating glass unit (IGU), with two panes of glass separated by an air cavity. Within the cavity sits a system of optics and PV cells. The optics direct sunlight from all angles, concentrating it onto PV cells that sit perpendicular to the glass.

More recently, and in response to the growing demand for energy-efficient buildings and BIPV glass technology, Pythagoras is in partnership with the materials and construction company Guardian Glass to produce and market a 'SunGuard' PVGU for commercial buildings.

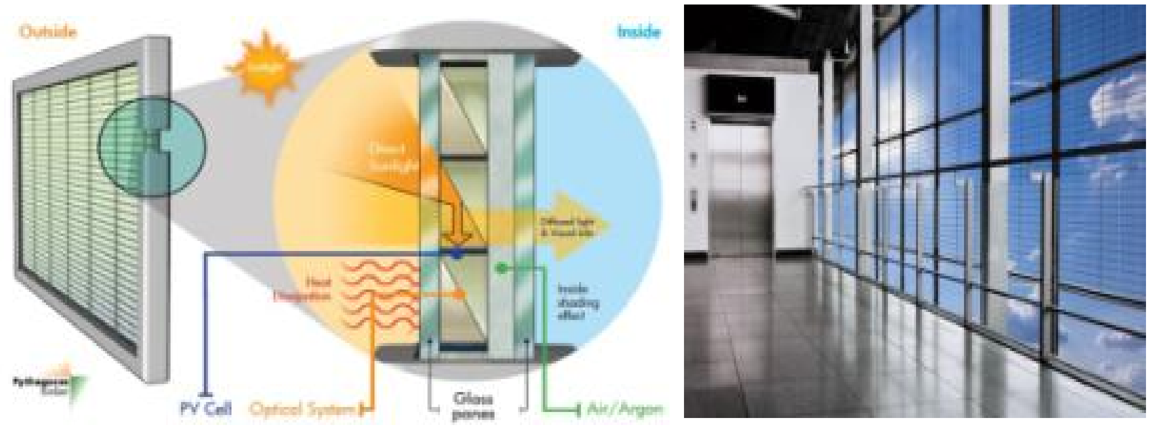


Figure 34: Pythagoras Solar

Tropiglas Technologies - is working with Edith Cowan University in Western Australia on a similar development - energy-generating clear glass panels, targeted not just at the construction sector, but also the automotive, horticulture and 'specialty' markets.

As well as harvesting solar energy, the Tropiglas panels block both infrared and ultraviolet radiation - enabling large savings in building cooling costs – and transmit visible light, helping to reduce lighting costs. The technology uses the integration of micro- and nano-engineered optical structures and materials to deliver shatterproof, extremely stable clear glass panels that not only block the UV and IR radiations, but also harvest them and convert them to electricity via PV cells placed within the window frames.

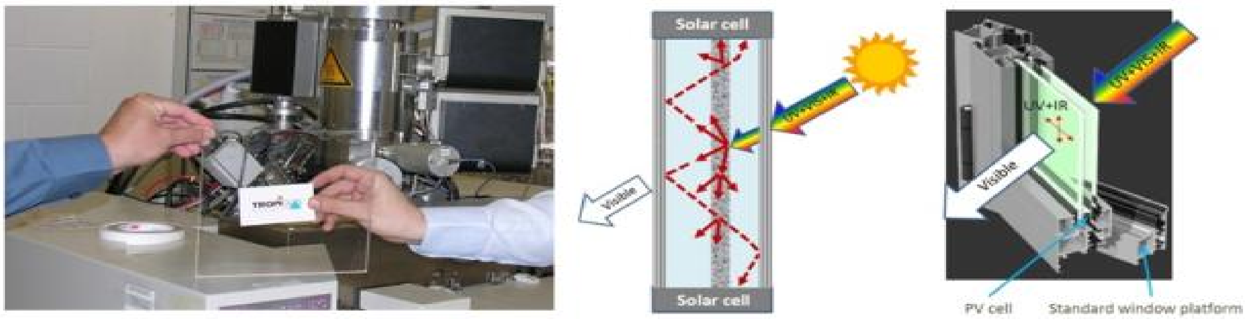


Figure 35: Tropiglass

SAF-EnergyGlass uses inorganic nanoparticles that are co-extruded with a polycarbonate interlayer, which is then laminated between two litres of 4-millimeter glass. The nanoparticles redirect components of the light spectrum to the edge of the glass, where it is collected with traditional monocrystalline solar cells.

Figure 36: SAF-EnergyGlass™

Figure 37: Schüco ProSol TF+ multi-layer a-Si translucent PV cladding materials

Mage Sunovation, as well as household names Pilkington, Schott and Sharp, also starting to develop BIPV glass. When properly sited, solar awnings can reduce a home's cooling load and supply energy at the same time. Compared to standard roof mounts, awnings allow for maximum airflow along the backside of the modules, reducing cell temperature and decreasing the efficiency hit that high ambient temperatures can take on PV performance.

Standard solar modules with opaque backsheets can be used with a racking structure to create awnings, but using glass-backed modules allows some light to pass through, which can be desirable for functional and aesthetic reasons. Sanyo's HIT Double series are "bifacial" modules, which generate electricity from both sides. Used with a reflective ground surface, they can increase energy production, Sanyo estimates, by 15% to 20% compared to standard modules. Actual energy increase from bifacial modules depends on site specifics, such as the amount of incident light reflected from the ground.

Bifacial awnings typically require a customized mounting frame to create a watertight structure, support the modules while not obscuring light transmission, and hide module wiring for better aesthetics. Several companies cater to the bifacial awning market niche, providing custom and prefabricated awning systems.

Figure 38: Sanyo HIT bifacial modules

A Kromatix™ technology produced by SwissINSO in partnership with EPFL is now able to supply PV module manufacturers with a piece of opaque, coloured glass that can be integrated into any manufacturers' modules including thin-film, crystalline and solar thermal modules without compromising on performance.

Figure 39: Kromatix™ SwissINSO

The technology is applied to glass by combining two different surface treatments. The inner side of the glass is subjected to a coloured nano-scale multi-layered treatment using a vacuum plasma process while another treatment is used to modify the glazing of the outer surface. The company explained that these treatments can prevent glare effects as well as remove the visibility of the technical components, such as the cells and wafers of PV or those in solar thermal units, which can normally be seen.

A similar approach is being followed by the Fraunhofer Institute for Applied Optics and Precision Engineering (Fraunhofer IOF). Made from paper-thin crystalline silicon wafers, simply constructed SIS (semiconductor-insulator-semiconductor) solar cell has an optically neutral protective barrier (insulator), onto which a hundred-nanometre-thick transparent conductive oxide (TCO) layer is applied to guide as many light particles as possible to the semiconductor layer below. Since TCO has a lower refractive index than silicon it also functions as an anti-reflective coating.

Different colours of the solar panels are achieved by either varying the thickness of the TCO layer or modifying its refractive index. It is possible to use the cells in conjunction with other wafer-based silicon technologies. Hence, efficient design modules can be combined with standard modules from other suppliers.

Laser-based optical welding processes allow connection of several solar cells to create a single module and accurate work at a micrometer scale without damaging the surrounding material. Researchers are also developing an inkjet printing process to deposit the conductive TCO layer on the silicon wafer. This will make manufacturing faster and allow additional degrees of flexibility in design. SIS solar cells could even be used to make large billboards that produce their own electricity such as for a building to communicate information, displaying the name of a company or even artistic pictures.

PV and glass is also being applied to roof tiles. Soltech roof, demonstrated in Sweden, use PV cells which are placed horizontally between the battens and covered by glass roof tiles and thus protected from the elements. Soltech solar thermal glass tiles air below the glass tile is heated by the sun and redirected for use by the central heating system. The system works with air-based and water-based heating systems, including, for example, a ground source heat pump, air heat pump, pellet boiler, oil boiler, or electric boiler. Initial tests showed that the system had a natural aversion to snow, given the shiny tile surface and heat reflected from an absorption fabric below the tile. The tiles are UV resistant and last longer than conventional clay or concrete roof tiles.

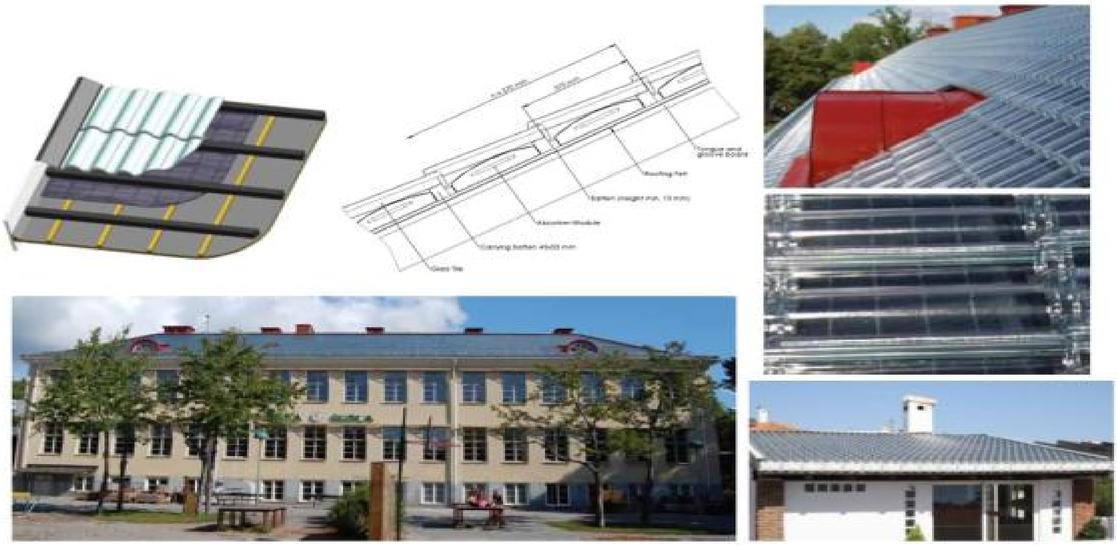


Figure 40: Soltech glass roof tiles

The conventional approach of using standardised cells encapsulated with toughened glass and changing their spacing to moderate their transparency is expected to continue to be a low risk strategy for PV glass products. The spacing of the cells can control the daylighting factor entering the building and does not necessarily compromise power output which is related to cell technology selection as represented in Figure 41.

From a building performance perspective, a balance needs to be struck between delivering power from building surfaces and allowing natural light to penetrate the inside of the building. It would be counterintuitive to design a system that shades the spaces inside the building and requires more mechanical lighting to allow the building to function appropriately. This is also important with respect to thermal tolerance. North and north-west facing façades that are thermally stressed (sun directly heats up the building) can negatively impact the performance of the cooling (HVAC) system and in office environments affect worker productivity. These factors are hard to quantify but are considerations that PV glass needs to be sensitive towards.

Figure 41: Architectural building examples of standard silicon cells encapsulated into glass

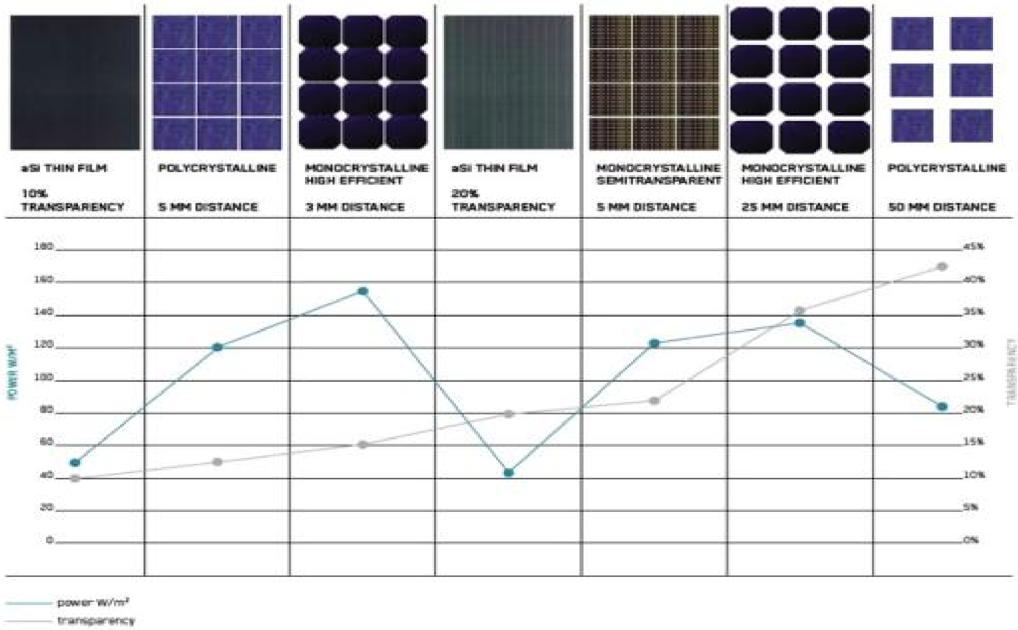


Figure 42: Possible combinations of PV glass cell types, cell distances and related performance

Figure 43: Onyx Solar architecturally appealing BIPV solutions

Further innovation for PV glass is the combination of LED lights. This was demonstrated with stunning effect the zero energy media wall, called GreenPix, at the Xicui entertainment complex in Beijing close to the site of the 2008 Olympics games. It is the largest coloured LED display at 2,000m^2 and was the first PV system integrated into a glass curtain wall in China.

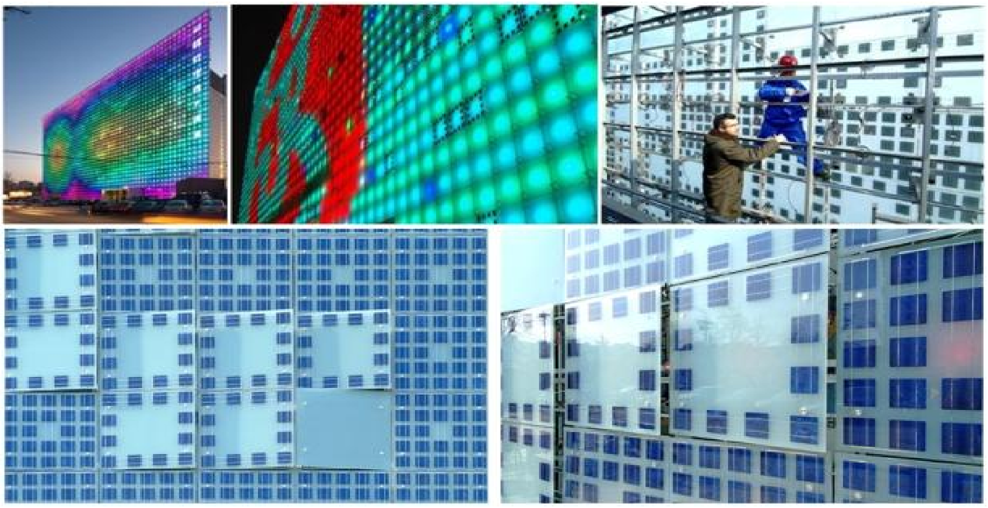


Figure 44: GreenPix LED and PV glass curtain wall, Beijing, China

Source: Simone Giostra & Partners and ARUP

Figure 45: Conventional panels cleverly integrated into a building façade

Source: ENEL, Italy

Figure 46: BIPV poly-crystalline façade La CUB – Bordeaux, France

Source: Architecte BDM

Figure 47: Perpignan SNCF Train Station

Source: L35 Arquitectos 2010

Figure 48: GDF Suez, Solal Building Dijon

Source: Philéas Atelier d'Architecture, 2011

CHALLENGES FOR PV INTEGRATED BUILDING MATERIALS

The examples of BIPV facade applications in the figures above demonstrate the ability to encapsulate conventional PV cells into building skin materials to produce innovative building architecture. Notwithstanding these outcomes, BIPV as a PV building material element has to wrestle with four key considerations, these being:

- Performance
- Safety standards
- Cost
- Aesthetics

Performance

Performance, as described in section 2, is dependent upon cell technology characteristics and how they perform under varying irradiance and ambient temperature conditions. Table 3 provides a summary of the advantages and disadvantages of the two core technologies.

Table 4: Performance characteristics of PV elements versus thin film compounds

	Crystalline Silicon elements	Thin-film semiconductor compounds
PV type	Mono and Poly	CIS, CdTe, a-Si
	Low absorption	High absorption
Product process	Ingot-Wafer-Cell-Module	Glass coating-integrated serial connection
	High temperature process	Moderate temperature process

	Advantages	**Disadvantages**
CRYSTALLINE SILICON		
Rigid BIPV	High conversion efficiency Discrete cells allows product to be laid out to simple tile dimensions	Sensitivity to silicon market and supply/demand price fluctuations
Flexible BIPV	Micro-crystalline silicon if able to be manufactured can offer high conversion efficiencies and building material flexibility	Silicon cells are typically rigid and flexible design could increase its fragility Wafer thickness is currently constrained by handling
Transparent BIPV	High efficiency, silicon cells are easy encapsulate with glass and offer a range of shapes and sizes	Assembly process is complex and hard to automate
THIN FILM-ORGANIC PV		
Rigid BIPV	Lower cost potential of thin film compared to crystalline silicon PV and can cover large areas of particular building substrates	Lower conversion efficiency. Unusual substrate shapes can be problematic
Flexible BIPV	Thin film and Organic PV is inherently flexible	Lower efficiency and challenges with encapsulation
Transparent BIPV	Automated factory production True transparency so can avoid space between cells	Difficult to make custom sizes and shapes Lower efficiency

Source: Adapted from NanoMarkets, 2012

Safety and Building Codes Compliance

BIPV (and also solar thermal combined applciations) are unique in offering a truly building skin replacement solution. This, however, presents additional challenges as it has to comply with existing building codes. Codes are in place to deal with bolt conduit to existing buildings but BIPV presents a sidewall or underside electrical integration approach. The regulatory requirements for BIPV are still to be defined. Given there is no standard exclusively dedicated to BIPV elements, although efforts internationally are progressing (EU PV Performance Project, 2009) the integration of any photovoltaic device in a building has to comply with both:

- electrotechnical requirements related to the module itself; and with
- the Building products standards as provided by the relevant national building code.

This creates barriers in complexity as it spans a number of jurisdictions through Standards Australia. Glazing has its own distinct codes and standards, as has electrical components. Whilst PV added to a building skin is well defined from a safety perspective through AS/NZ5033 installation of PV arrays, AS/NZ 3000 Electrical Wiring Rules, AS1768 Lightning Protection, AS/NZ1170.2 Wind loads and AS4777 Grid connections of energy systems via inverters.

BIPV can influence the building functions through structural integrity, mechanical rigidity, weatherproofing, thermal and daylight control, fire protection and potentially noise abatement. If as a glass element, BIPV needs to conform, for example, to laminated safety glass standards and avoidance of falling parts overhead.

It is clear that BIPV standards and compliance as a PV element is currently complex and challenging given the lack of a collective resource from which Standards Australia can make appropriate and timely responses. BIPV standards, however, do not need to be too burdensome and requires a consolidation and standardisation of existing standards that typically are separate, distinct areas of safety compliance. Without this, risk averse decisions will be made as found with DC breaker requirements, that may compromise the aesthetics and cost in delivering effective BIPV.

Cost Advantages and Disadvantages of PV Building Materials

By their very nature, PV materials are smart building elements and consequently attract a price premium. Demand for PV has significantly reduced the cost of conventional PV products to the point where the focus on reducing costs is on the balance of systems and reducing the installation costs of PV. Whilst, BIPV subsidies have been able to provide the market confidence for industry to invest in PV building applications especially in Italy and France, there is clear knowledge gap in understanding the true value proposition of BIPV. BIPV however, have the disadvantage of being at least 10% more expensive that BAPV options.

Figure 49 highlights that many BIPV building products are cost comparative with high end building materials. Work from James et. al (2011) at NREL investigated the levelised cost of BIPV compared to BAPV. Whilst BIPV faces more challenging product development issues and market acceptance than BAPV (rack mounted PV in this instance), the long term value of BIPV is far more promising. Upfront capital outlay is still a barrier for uptake, however, leasing arrangement over a longer-term plan can internalise these costs into the end building asset value. Considerations of the existing building skin will affect the payback.

From a commercial building perspective, there is the prospect of BIPV not just to deliver a cost effective zero energy building solution for new buildings, it has the ability to offer similar solutions for the retrofit market. Thermally stressed buildings can use BIPV to ameliorate these conditions, reduce the mechanical cooling and improve the overall indoor conditions that can impact on worker productivity. This is not even considering the marketing value of a green building in attracting future tenants or the value onsite power generation can assist in reducing grid network demand and consequently, defer infrastructure augmentation.

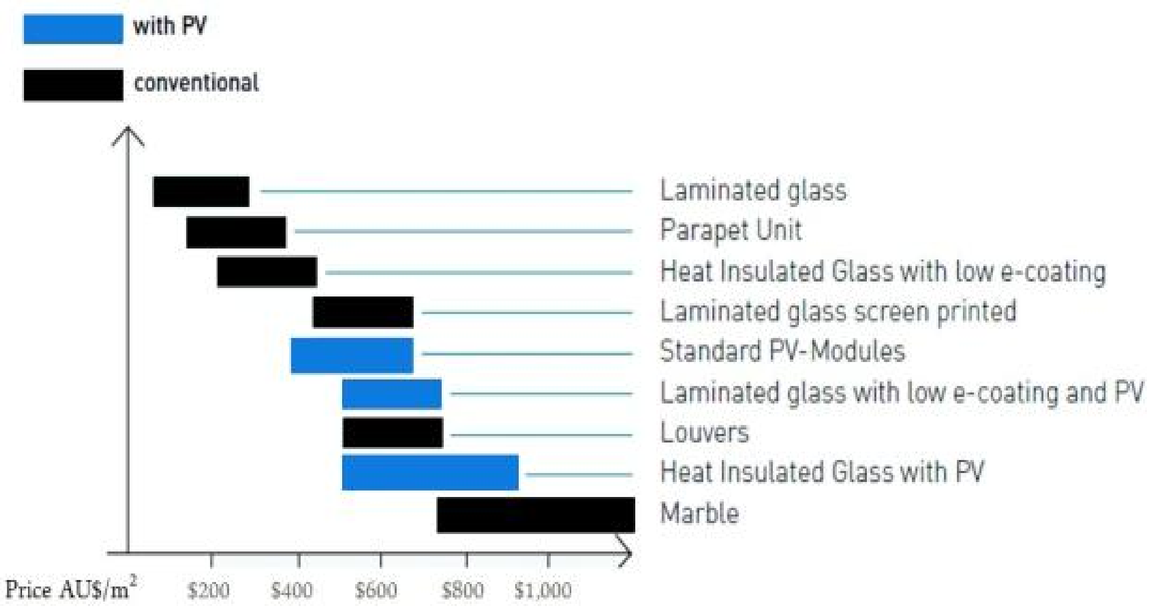


Figure 49: PV building elements versus conventional building product costs

Source: Updated 2012 and adapted from Ingo Hagemann (2007)

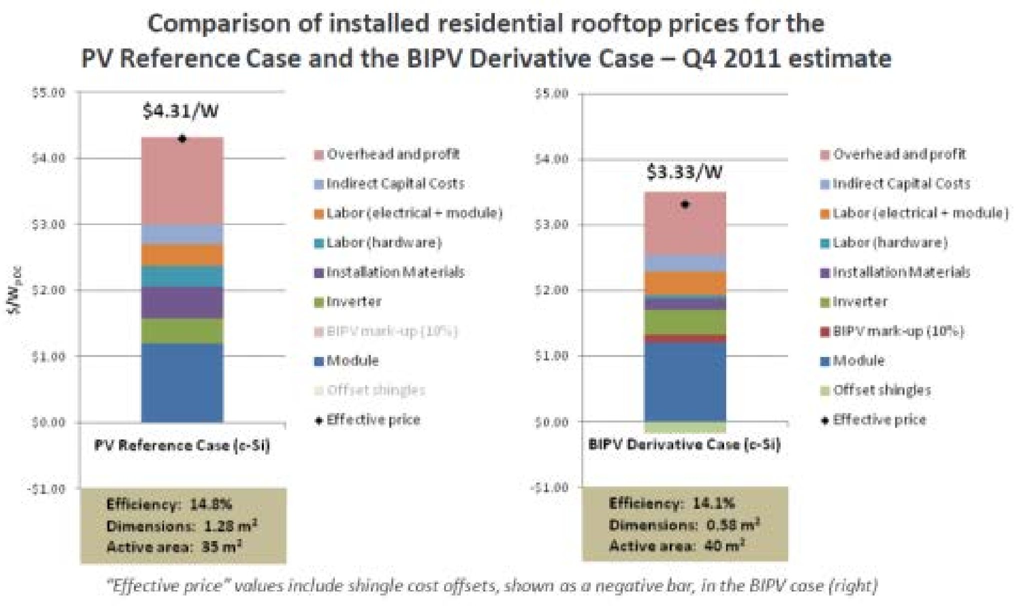


Figure 50: Levelised cost of BIPV for residential rooftops versus conventional BAPV

Source: James et. al. (2011)

Cost reductions of the simulated BIPV case are mostly from the elimination of hardware racing and associated labour costs. The possibility of reduced performance may have an impact on the levelised cost of energy but is not likely for reliable, conventional PV cell technologies.

Aesthetics

From an architectural view point, the significant formal characteristics of BIPV components are:

- Aesthetical appearance : colours, surface texture, aspect
- Dimension: shape, size and thickness of individual elements and the possibility to combine them with each other and with other material
- Flexibility and weight.

For each technology, there are specific intrinsic features that are recapped in Table 5, some of which result in limitations stemming from architectural and aesthetic considerations.

Table 5: Design aspects of different PV technologies

Type of PV cell	Maturity	Colour/surface/other	Typical area (mm)	Typical thickness (µm)	Flexibility	Operations on cells during design and manufacturing
c-Si	Highly commercially available	Blue, dark-gray, or black/smooth surface with silver grid patterns on top/cells can be coloured (gold, orange, pink, red, green, silver) by variable Si3N4 layer/decorative grid patterns possible	156 x 156	>180 to 220	Low	Bending only to a limited extent; laser cutting; heating; injection transfer moulding in plastics; lamination in plastics
m-Si	Highly commercially available	Shiny blue, dark blue/shiny grains, smooth surface with silver grid patterns on top/cells can be coloured (gold, orange, pink, red, green, silver) by variable Si3N4 layer/decorative grid patterns possible	156 x 156	>180 to 220	Low	Bending only to a limited extent; laser cutting; heating; injection transfer moulding in plastics; lamination in plastics

a-Si	Commercially available	Dark brown or black/smooth surface with light lines/cell interconnects/patterned deposition is possible	Customizable from 10 x 10 to 1000 x 2000	< 1	High	Bending; lamination in plastics; deposition on curved surfaces; cutting not possible
CIGS	Commercially available	Gray or black/smooth surface with light lines/cell interconnects/patterned screen printing is possible	Customizable from 10 x 10 to 1000 x 2000	1 to 3	High	Bending; lamination in plastics; deposition on curved surfaces; cutting not possible
CdTe	Highly commercially available	Brownish/smooth	Customizable from 10 x 10 to 1000 x 2000	1 to 3	Low	Heating
DSC	Available	Red or brown/transparent and smooth/cells can be coloured by dye molecules	Customizable	1 to 10	High	Bending; lamination in plastics
Polymer	Limited availability	Orange, red, or brown/smooth	Long strips, customizable	< 1	High	Bending; lamination in plastics

Table 6: Comparative analysis of PV technologies regarding their suitability to BIPV.

TECHNOLOGY PRODUCT	Thin Film	Crystalline Silicon
Standard in-roof systems	• Market penetration only for flat roofs	• Higher yields and higher efficiency (less area needed).
Semitransparent system (glass/glass Module)	• Design option due to different colours • Thin Films cells have uniform appearance, suitable for flush mounting • High cost and very low efficiency	• Marginal daylight elimination / capacity to play with light intake • Ideal for Skylights • Limited sizes and shapes of cells (unappealing) • Silver tabbing crosses the transparent spaces between cells
Cladding systems	• Better performance under non-ventilated facades(higher temperature) • Design option due to different colours • Better performance with indirect/diffuse light	• Futuristic/ Green building marketing • lower performance under non-ventilated facades (higher temperature) • lower performance with indirect/diffuse light
Solar Tiles and shingles	• CIGS solution to become operational	• Higher yields and higher efficiency (less area needed). • Wide range of products available
Flexible laminates	• Very low weight (suitable for weak roofs) • Easy handling and installation • No roof penetration • Curved installations possible Low efficiency (large area needed)	• No products available so far

Source: EPIA, Nanomarkets, EUPD

Within the IEA, Task 41 Solar Energy and Architecture program, the architectural integration has been carefully investigated so as to identify the main criteria of integration (IEA SHC, 2012). The functional and constructive aspects to be consider for the integration of PV in building are:

- **Formal aspects** (Aesthetics)
- **Top Cover** Glass or transparent plastic, allows light to enter the cells, while protecting the delicate cells from damage. Coated with anti reflective polymer.
- **Encapsulant** Protects the cells and holds together the top cover, PV cells and back surface. Ethyl vinyl (EVA) is common material.
- **Rear Layer** Protects the back surface of the module and prevents water, gas and dusts from entering the module.
- **Substrate** Metal conductors carry electrons out of the cells and connect cells in
- **CMOS** The modules are in series or parallel, and carry electricity out of the module.
- **Frame** To hold all components in place. Usually made of aluminium alloy.
- **Fastening** To fix the system on the building.

Table 7: Aesthetic Advantages and Disadvantages

	Advantages	Disadvantages
CRYSTALLINE SILICON		
Rigid BIPV	Cells fit well into tile-shaped packages Suitable for flush mounting Cell appearance can be attractive	Cell appearance can be considered unattractive Limited sizes and shapes of cells Silver tabbing usually required
Flexible BIPV	If it can be produced at an affordable price it offers an aesthetically pleasing solution	Standard cells too rigid and fragile for flexible BIPV Ultra-thin silicon only shown in labs with no commercial product plans known
Transparent BIPV	Custom shapes can be handled with attractive cell layouts Cell appearance can be attractive	Cell misalignment produces irregular reflections and tabbing may look unattractive Even use of prism/mirrors limits off-axis transparency
THIN FILM-ORGANIC PV		
Rigid BIPV	Clean, uniform appearance Suitable for flush mounting	More or larger panels required for same power output
Flexible BIPV	Clean, uniform appearance Curved installations possible Versatile for use on many surfaces	Additional framing is needed for some installations Versatility can lead to some undesirable installations
Transparent BIPV	Clean, factory precision appearance Some may produce transparent BIPV glass with no visible pattern	Very low efficiency limits economic appeal Custom/irregular panel shapes may have unattractive patterns

Source: Adapted from NanoMarkets, 2011

PV BUILDING MATERIAL COMPANIES PAST AND PRESENT

COMPANY	Product	Website
AGC Solar	Solar glass	www.agc-solar.com
Alwitra	Flexible thin film sheets	http://alwitra.de/en
Ascent Solar Technologies	CIGS flexible sheets	www.ascentsolar.com
Atlantis Energy	Solar glass	www.atlantisenergy.com
Bluescope	Roof thinfilm PV/Thermal	www.australiansolarinstitute.com.au/BlueScope
Cambridge Nanotech	Atomic Layer Deposition	www.cambridgenanotechald.com
CSR Monier Tile	SOLARtile	www.monier.com.au/News/Show_3.aspx
Dow Chemical	Flexible Shingles using Global Solar PV - POWERHOUSE™	http://www.dowpowerhouse.com
Dow Corning	Solar glass and sealants	www.dowcorning.com/content/publishedlit/62-1679.pdf
Dupont	BIPV roof encapsulant and PV tile	www2.dupont.com/Photovoltaics/en_US/products_services/encapsulant/pv5300_encapsulantsheets.html
Dyesol and Tata Steel	DSC organic PV roof	www.dyesol.com/partners/current-projects/tata-steel
Flexcell	Thin film R2R	www.flexcell.com
Global Solar	PowerFLEX™	www.globalsolar.com/products/integrated-solar/bipv
Guangdong Golden Glass Technologies	PV Glass	www.golden-glass.com/en/Product/Product1_5.asp
Heliatek	Organic PV glass	www.heliatek.com
Hering International	Pre-cast concrete PV	www.heringinternational.com/en/concrete/photovoltaic-4626.htm
Kalzip	a-Si roof sheet	www.kalzip.com/kalzip/uk/products/solarclad.html
Kawneer	Powershade®	www.kawneer.com/kawneer/green/en/products/1600PowerShade.asp
Koramic Soltech	KoraSun®	www.soltech.be/images/filelib/KORASUN_NL_575.pdf
Lumeta	PowerPly™	www.lumetasolar.com/Pages.aspx/Overview
Monier Group	SolarTile	www.monier.com.au/Tiles/SolarTile/Default.aspx
Onyxsolar	PV glass, façade	www.onyxsolar.com
PowerFilm Solar	Monolithically integrated silicon - PowerFilm™	www.powerfilmsolar.com
Pythagoras Solar	PVGU m-Si prismatic optics	www.pythagoras-solar.com
Schüco	Thinfilm PV glass, façades	www.schueco.com/web/ca/commercial/solarstrom_und_waerme/products/photovoltaic_systems
REC – Solar Tile Ltd	Roof tile	www.solarslate-ltd.com
Soltecture	CIS façade	www.soltecture.com
Schott	ASI THRU OPAK PV glass	www.schott.com/architecture/english/products/photovoltaics.html
Sunguard PVGU	PV glass	www.guardian.com/europe/GuardianGlass/glassproducts/SunGuardAdvancedArchitecturalGlass/AdvanceGlassingSolution/SunGuardPVGU/index.htm
Sunovation	PV glass curtain wall - LED	www.mage-sunovation.de
Sunpower	Suntile	www.rs2e.fr/documentation/sunpower/SPWR_SunTile_DS.pdf
3M and Solopower	CIGS R2R roofing	http://solopower.com/products
Technal	Suneal Brise Soleil	www.technal.co.uk/en/Products/Brise-Soleil
Tera-Barrier Films	PV coating organic PV	www.tera-barrier.com/technology.html
Trony	PV Glass	www.trony.com/html/products_bipv.php
TropiGlass	PV Glass	www.tropiglas.com
Wicona	PV Glass, curtain wall	www.wicona.ch/de/Umwelt--mehr/Powerhouse
Würth Solar and BayWa RE	CIS roof, curtain wall, façade application	http://cse.fraunhofer.org/Portals/55819/docs/BIPV-keynote-ICBEST.pdf

CONCLUDING REMARKS AND FUTURE RESEARCH CONSIDERATIONS

The market opportunities of PV as a building element are anticipated to grow significantly as zero energy building solutions drive innovation and performance outcomes underpinned by policy requirements. Whilst the industry has been highly price driven, customised PV building products that provide fabric flexibility, texture and colour without adversely compromising performance are already gaining traction.

Crystalline silicon is expected to continue to dominate market share with progress in flexible micro (paper-thin) crystalline products. Whilst CIS thin film offer promising PV building element solutions the availability of Indium is limited. On the other hand, raw materials for poly-silicons will remain in abundance. The challenge for silicon is to be able to offer sufficient supply to meet growing demand.

Given smart glass is well advanced as a sophisticated and relatively mature manufacturing process, PV can be interlaced with glass more readily. As glass is typically a large component of commercial building façades, it is likely glass encapsulated PV will corner a large market share of PV building elements. Recent research findings from Nanomarkets (2012) predict solar glass will comprise US$4.2 billion by 2015 of a predicted BIPV market value of US$7.5 billion. Around US$1.5 billion is expected from PV deposited on tiles, shingles and metal roofing materials.

Four key aspects are driving developments in PV as a building element and include performance, cost, safety/standards compliance and aesthetics. BIPV already competes on a cost perspective with high end building materials. The drive for zero energy building solutions will assist BIPV realise its full value and opportunities in the commercial sector are anticipated to grow significantly.

This review has highlighted the opportunities in the sector for clever PV building products and the flexibility in product innovation. Thin film applications, whilst they hold exciting prospects in terms of cost of manufacture, there are ongoing challenges in performance and reliability but also raw material scarcity. This present micro crystalline silicon an optimistic future if the advantages of thin film can be realised through this PV technology.

As a review of existing research and industry activities, there is a need to explore in more detail the technical performance of different PV building elements and their capacity to displace conventional building materials. Product safety codes and standards for BIPV are still poorly defined and greater clarity is required to ensure it does not inhibit future BIPV innovation.

Further suggested areas of work include:

- Review of theoretical and market potential of BIPV/Thermal applications in terms of performance benefits versus manufacturing complexities and costs;
- Stakeholder consultation with industry, compliance organisations and government to highlight the challenges and opportunities of PV-ME from a technical, market and policy perspective;
- Detailed assessment of PV-ME applications and research developments applicable to Australian conditions;
- Development of a PV-material elements (PV-ME) performance matrix and building material application; and
- Added values of PV-ME evaluation from a Zero Energy, Low Carbon Living built environment perspective.

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