PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. 2010; **18**:61–72
Published online in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/pip.920

BROADER PERSPECTIVES

BIPV: merging the photovoltaic with the construction industry

Mario Pagliaro*, Rosaria Ciriminna and Giovanni Palmisano
Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa 153, 90146 Palermo, Italy

ABSTRACT

BIPV (Building Integrated Photovoltaics) is a multifunctional technology that unifies the photovoltaic module with the overall building outer surface providing the building with several new functions while producing a portion or total building electricity usage. Increasing the aesthetic, functional and environmental value of a building at a much lower cost than in the recent past, new PV technologies will soon originate a market growth as intense as the growth of traditional PV market has been in the last 5 years. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS
BIPV; building industry

***Correspondence**
Professor Mario Pagliaro, Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa 153, 90146 Palermo, Italy.
E-mail: mario.pagliaro@ismn.cnr.it

Received 29 December 2008; Revised 12 March 2009

1. MODERN PV: NEW DESIGN ELEMENT FOR BUILDINGS

Modern photovoltaic technology transforms buildings from energy users to energy producers [1]. From the older concept of photovoltaic *installation*, namely the addition of solar panels to a building's roof, the construction technology has merged with the science and technology of photovoltaics resulting in the so called Building Integrated Photovoltaics (BIPV), the architectural, structural and aesthetic integration of photovoltaics into buildings, allowing the incorporation of energy generation into everyday structures such as homes, schools, offices, hospitals and all sort of buildings.

According to this approach, the photovoltaic modules become true construction elements structurally serving as

Copyright © 2009 John Wiley & Sons, Ltd.

Figure 1. Rated at almost a quarter of a megawatt, the Stillwell Avenue Station in New York is among the largest PV plants in the US. (Photo credit: Klingon65 on Flickr.com).

building exteriors, such as roof, façade or skylight, providing at the same time protection, aesthetic valorization and electricity generation. Figure 1, for example, shows the New York's Stillwell Avenue Station whose glass and steel structure employs a panelized construction system of thin-film photovoltaic panels combined with clear glass in custom glazing units to provide a 250 kWp (kilowatt peak performance) solar power plant the right balance among shelter, daylighting and electricity generation.

The concept is general. BIPV indeed is a multifunctional technology that is actually used for several purposes beyond electricity generation including weather protection, thermal insulation, noise protection and modulation of daylight (Figure 2) [2].

For example, roof integrated systems integrate PV modules into roof tiles; façade integrated systems act as a rain screen; and semitransparent installations can allow for some of the light to enter for daylighting or viewing.

All this has been made possible by the rapid progress of the PV technology which evolved from rigid, standardized and thick solar panels into a variety of solar modules available in rigid and flexible format, opaque or semitransparent, mate or in different colours, providing today's designers with a rich toolbox with which to expand traditional architecture and transform buildings into energy producing constructions [3].

Successful introduction of PV in the building industry requires the symbiosis of functional and aesthetic issues with financial constraints (Figure 2) [4]. When this symbiotic approach will be fully achieved as cost of PV modules fall, the enormous BIPV potential will be realized. Indeed, even at low 5% photovoltaic efficiency the 23 billion m^2 of suitable existing roofs and facades with good sunshine exposure in selected 14 countries exceeds 1000 GWp, namely the power of 1000 nuclear power plants [5]. Table I shows for example a recent EPIA estimate of the BIPV potential in Europe, US and Japan [6].

Now, as late as in 2005, Hagemann insisted that problems in solar design were mainly 'in the wide information gap between research results and knowledge applied in practice' [7]. In the intervening years, several BIPV projects have been successfully realized, demon-

Table I. Potential of BIPV (Source: D. Fraile Montoro, 2008)*.

Available Roof Surface					
	Net Available Solar Surface (Km²)	Installable PV "Potential" (GW)	Estimated Electricity production (Twh/year)	Residential Electricity consumption 2006 (TWh/year)	% of PV
Europe (75%: Germany, France, UK, Italy, Spain)	3.723	465,4 (8m²/Kwp)	511,9	859	59%
		161,9 (23m²/KWp)	178,1		20%
USA	4.563	570,4 (8m²/Kwp)	570,4	1351	42%
		198,4(23m²/KWp)	198,4		14%
Japan	1.050	131,3 (8m²/Kwp)	118,1	229	51%
		45,7 (23m²/KWp)	41,1		18%

* Facades not included.

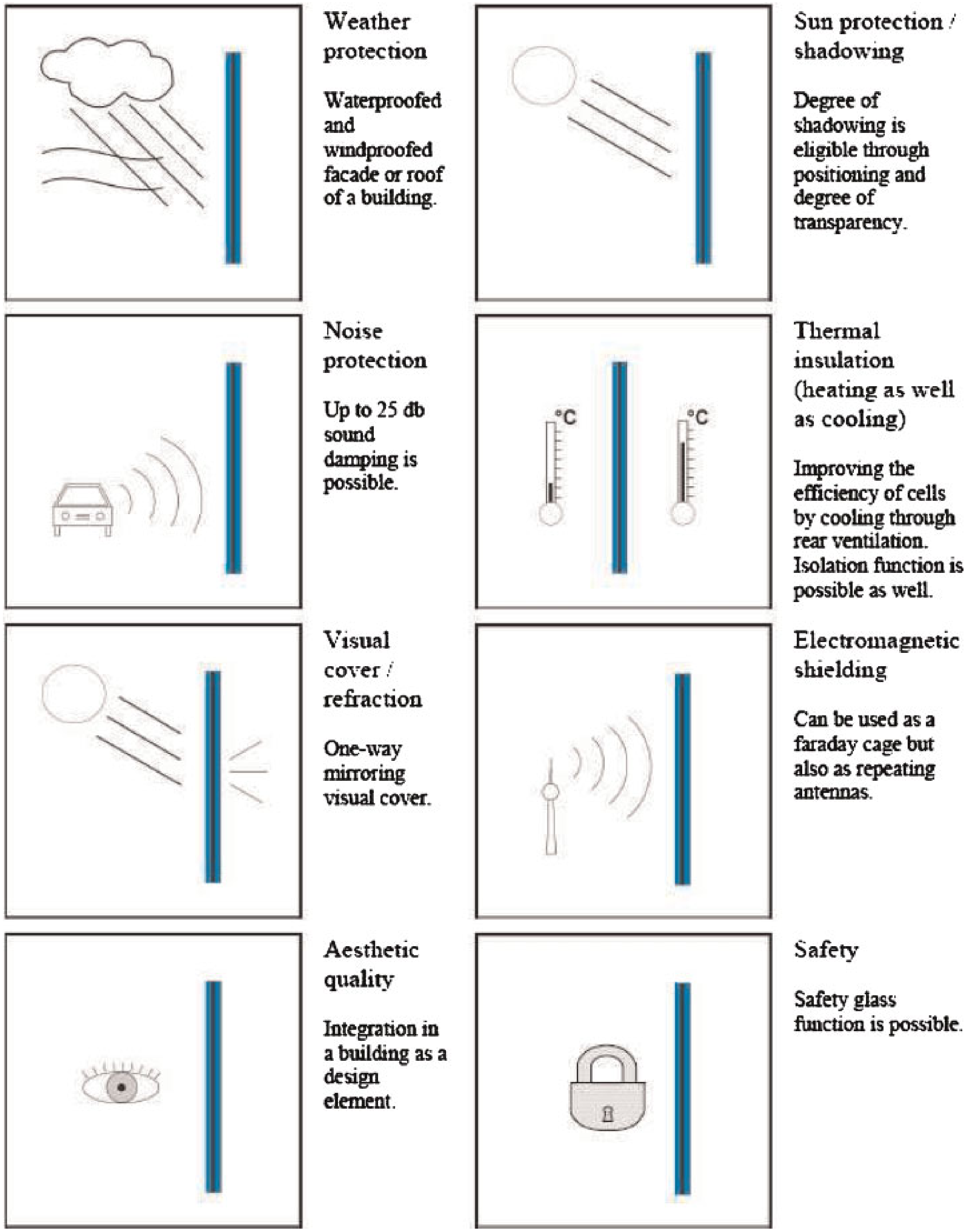

Figure 2. BIPV is a multifunctional technology (adapted from Reference 2, with permission).

strating how photovoltaic systems can be creatively integrated into buildings, and existing urban landscapes. In Europe, for instance, the 'Sunrise' project [8] was established by the EU to facilitate and accelerate the integration of PV systems in buildings by standardization and harmonization of PV components, and thus by involving all stakeholders outside the actual PV supply chain such as building companies and utilities. Written in

Prog. Photovolt: Res. Appl. 2010; **18**:61–72 © 2009 John Wiley & Sons, Ltd.
DOI: 10.1002/pip.920

this evolving context, this paper aims to further contribute to these advances by describing some of the new BIPV technologies in the context of real integration projects. We thus discuss the major challenges with BIPV technology based on an overview of the market in Europe, where the technology has been first proposed.

2. BIPV TECHNOLOGIES: DIFFERENT PRODUCTS FOR DIFFERENT APPLICATIONS

The main component of a BIPV system is the PV module, that is an array of interconnected solar cells packaged together. In general, both major types of solar cells thus far employed for BIPV relied on inorganic semiconductors, namely silicon (poly- and mono-crystalline or amorphous) and inorganic nanocrystalline salts deposited as thin films on a foreign substrate. Main thin-film (TF) solar cells, in particular, make use of amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium sulphide (CIS) and copper indium gallium diselenide (CIGS) and have the advantage that the semiconducting material is deposited on a substrate such as glass, steel or plastic, allowing for a wide range of architectural possibilities including the rigid or flexible nature of the modules [9].

So, which modules are most convenient? Or, in other words, which products are presenting greater possibilities and why? It depends on the application and on the requirements of building (old or new; orientation etc.) as well as on the customer financial and functional requirements (Figure 3) [10]. In general, first, it must be taken into account that the apparently large gap in efficiency between thin-film and crystalline polysilicon (Table II) easily leads to mistakes. For example, the standard irradiation (1000 W/m^2) and temperature (25°C) conditions under which efficiency is measured are entirely unrealistic, as the typical module temperature largely exceeds 25°C whereas the average solar irradiation at the Earth surface is 170 W/m^2. Now, the performance on crystalline Si cells rapidly decrease with rising temperature and under a cloudy sky, whereas TF solar cells generally perform far better under low irradiation and show less than half of the thermal deterioration in performance.

As a result, for example, despite the corrugation and a South–West orientation, the a-Si system integrated over the

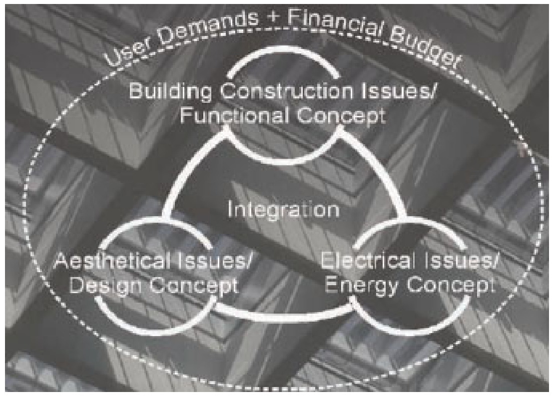

Figure 3. Successful integration of BIPV is a symbiotic Outcome. (Source: Hagemann, 2007).

Table II. Typical standard module efficiency for different technologies. (Source: D. Fraile Montoro, 2008).

Module and Cell Efficiency							
Technology	Thin Film					Crystalline Silicon	
	(a-Si)	(CdTe)	CI(G)S	a-Si/ µSi	Dye s. cells	Mono	Multi
							
Cell efficiency	4-7%	8-10%	7-11%	6-8%	2-4%	16-22%	14-16%
Module efficiency						13-19%	12-15%
Area Needed per KW (for modules)	~ 15 m²	~ 11m²	~ 10m²	~12m²		~7m²	~8m²

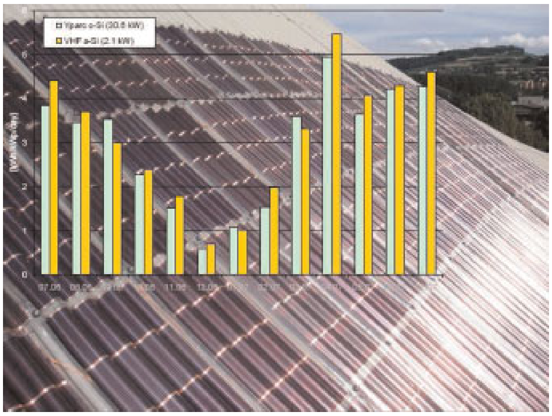

Figure 4. The a-Si system integrated over the corrugated roof of a sport plant in Switzerland produces more kWh per kWpeak installed than a c-Si system fully South oriented. (Source: Flexcell, 2008).

roof of a sport plant in Switzerland shown in Figure 4 produced more kWh per kWpeak installed than a c-Si system fully South oriented [11].

However, since thin-film technology is relatively new, the large market predominance of crystalline silicon solar cells has resulted in much faster adoption rates of crystalline Si technologies for BIPV applications. For example, in Europe the 2007 overall share of silicon was about 90%, with mono-crystalline silicon being slightly higher than that of poly-crystalline silicon due to the fact that mono crystalline technology is considered more aesthetically appealing (Figure 4) [12].

On the other hand, the thin-film technology drastically reduces the material and energy used in manufacturing and this will allow PV solar energy to become economically viable in a few years. Furthermore, thin-film has a far better outcome in architectural applications. As several new thin-film modules recently entered the market with electrical productivity rapidly approaching that of crystalline silicon (Figure 5), its market share will rapidly increase in the next few years.

One example of said new thin film BIPV product is the highly efficient and flexible CIGS-based module PowerFlex (Figure 6) recently developed for the construction industry made of copper indium gallium diselenide (CIGS) material deposited onto a thin, pliable and unbreakable plastic substrate that can be built directly into commercial, residential and public buildings. The company is able to offer these solar cells to the market through a 'roll-to-roll' manufacturing process which makes the solar cells more affordable [13].

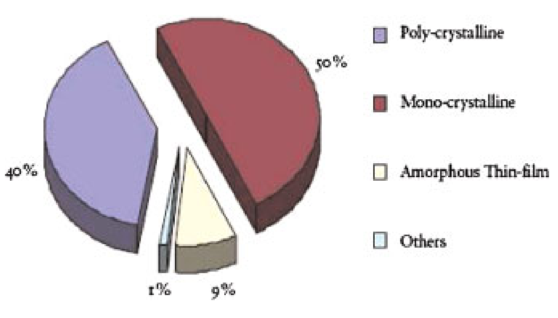

Figure 5. BIPV Market: Market Shares of Various PV Technologies (Europe), 2007. (Source: Frost & Sullivan, 2007).

Figure 6. PowerFlex (Figure 5) recently developed for the construction industry made of CIGS material deposited onto a thin, pliable and unbreakable plastic substrate that can be built directly into commercial, residential and public buildings. (Source: Global Solar Energy).

In general, different PV products based on different technologies will be used in the two main domains of the BIPV market. Standard low-cost products will be mostly used in the private housing market; whereas high-cost customized products will be used for high-rise buildings (Figure 7) [3].

However, the rate of innovation is very high also in the field of traditional crystalline Si modules that are nowadays offered in ever thinner thickness, semitransparency and tailored sizes as shown by the single household and studio of the artist Nicole Schmölzer in Pratteln, Switzerland (Figure 8) [14]. Conceived on the principle of a passive house (optimal isolation, controlled ventilation), the house/ is distinguished by an innovating integration of the photovoltaic technology in the façade.

Prog. Photovolt: Res. Appl. 2010; **18**:61–72 © 2009 John Wiley & Sons, Ltd.
DOI: 10.1002/pip.920

Figure 7. Two major classes of BIPV solutions will be developed for the real estate market. (Adapted from Hagemann, 2007).

Figure 8. The single household and studio of the artist Nicole Schmölzer in Pratteln, Switzerland. (Photo credit: Bipv.ch).

The photovoltaic installation is composed of five glass modules based on multi-crystalline Si in the parapet of the terrace, two modules are used as external sliding blinds and the other 16 modules are posed directly on the flat roof. All are directed toward south. Besides the current production, the integrated modules also serve as visual and thermal protection while those integrated like a parapet also have a safety function. The overall integrated power of 3.2 kWp ensures an annual production of 2700 kWhs of electric energy.

Figure 9. These polycrystalline, large area modules are offered in various sizes and colours for an easy integration over façades. (Photo credit: Schüco).

In general, the development of new BIPV products is being conducted directly in collaboration with construction companies. For example, Germany's Schüco and Italy's Permasteelisa, which specialize in manufacturing glass and metal façades, both opted to integrate PV solutions in their offer to the market.

Whereas the latter recently opted for DSC (dye solar cells, see below) glass façades to be manufactured soon with other partners in Italy [15], Shcüco already offers a large variety of solutions based on crystalline Si modules (both mono-and polycrystalline) whose versatility renders well the way BIPV is interfacing with current construction practices. Customers can select semitransparent or translucent modules (ProSol PV) in one of the many colours available that are easily integrated into the façade like normal filling elements (Figure 9). The new PV modules, available in non-insulated, thermally insulated and safety glass versions, are equally suitable for curtain wall facades and single-layer façades in buildings of all sizes. The combination of photovoltaic power generation and extreme thermal insulation results in unsurpassed energy efficiency.

Although the above-mentioned PV technologies based on inorganic crystalline materials will continue to make up the bulk of the market in the near future, there are other new solar cells and manufacturing technologies coming into focus as the industry tries to reduce its silicon dependence and module costs and increase manufacturing efficiencies. In particular, the new generation cell technologies being developed are organic (plastic) solar cells and dye sensitized solar cells (DSC): two emerging technologies that will rapidly find widespread application in the next 3–5 years.

For example, 3% efficient plastic solar modules recently commercialized by the US company Konarka as 'Power Plastic' have been integrated onto canopies and this technology will be installed on the rooftops of parking lots, at hotels and resorts [16]. Similarly, the first 4% efficient semitransparent orange windows consisting of DSC-based modules were used as elegant construction elements for the western façade of the Australia's CSIRO Energy Institute

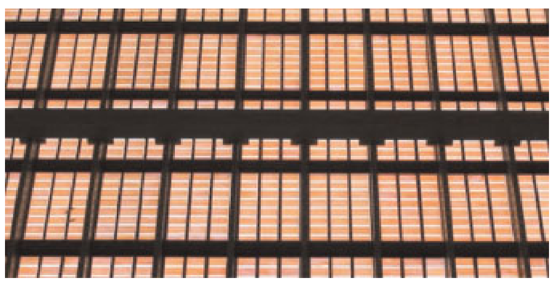

Figure 10. The first 4% efficient semitransparent orange windows consisting of DSC-based modules were used as elegant construction elements for the western façade of the Australia's CSIRO Energy Institute as late as in 2003. (Photo credit: Dyesol).

as late as in 2003 (Figure 10), as DSC do not need direct exposure to sunlight [17].

3. EXAMPLES OF ARCHITECTURAL SUCCESSFUL BIPV APPLICATIONS

Built environment allows for many kinds of PV applications to be integrated into different part of the building fabric. Most cases make use of glass as substrate that encapsulates (crystalline or thin-film) solar cells. Glass indeed is an excellent construction material that is currently experiencing a renaissance in the building industry. Glass for example can be used for almost 100% of a building's façade, including the use of self-cleaning glass that incorporated into glass-PV modules helps to keep them free of dust and thus improve the productivity of the PV cells.

3.1. Roofs

Pitched roofs can be replaced with PV shingles and flat roofs can be covered either with flexible thin film modules with no statics problems, or with new generation of silicon-based modules with no frames. For example, the first solar power plant for the Vatican right next to St. Peter's Cathedral makes use of 2394 dark solar modules covering the roof of the 'Paolo VI' audience hall with a peak total output of 221.59 KWp, enough to generate some 300 MWh of electricity in 1 year (Figure 11) [18].

The entire structure was designed, created and installed in full accordance with the original plan by architect Pier Luigi Nervi. The solar panels have replaced the 4800 degraded concrete tiles supported by different 'umbrella steel structures' on the auditorium's 5000-m^2 roof by new architectonical elements (Figure 11, top) following the rigid rules of the Italian and international Restoration Chart. The modules are optimally adapted to the fan shape of the building's challenging architectural design so that the particular undulating structure of the roof and its associated aesthetic appeal could be retained. The new roof allows the collection of solar radiation with the assistance of reflective materials ensuring optimal electricity generation. Moreover, the shade generated on the roof by the solar panels reduces the energy required for air conditioning.

Figure 11. The BIPV plant on the roof of the Vatican 'Paolo VI' hall is magnificent example of philological restoration coupled to clean electricity generation. BIPV at its best. (Photo credit: energia e ambiente Srl).

3.2. Windows and Semitransparent Façades

Semitransparent, photovoltaic-glass windows are capable to generate electricity as well as provide a abatement of the ultraviolet and infrared radiation. The windows are available with a full rage of customizable options to meet design, weather, climate and building code requirements and are generally made of glass PV laminates that can be applied to windows providing a semitransparent façade (Figure 12). The transparency is normally achieved either (i) because the PV cell can be so thin or laser grooved that it is possible to see through or (ii) because crystalline solar cells on the laminate are spaced so that partial light filters through the PV module and illuminates the room. Light effects from these panels lead to an ever-changing pattern of shades in the building itself.

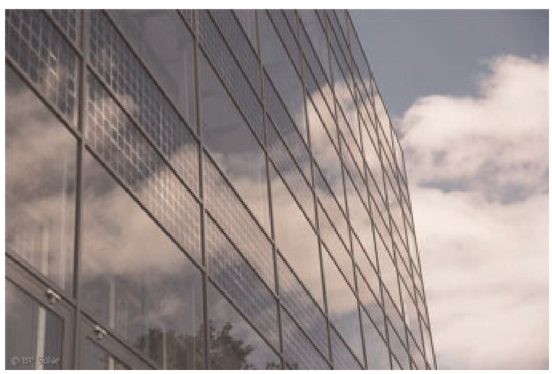

Figure 12. The glass façade including 192 m^2 of integrated PV cells at Norway's Trondheim University of Science and Technology. (Photo credit: EPIA).

Prog. Photovolt: Res. Appl. 2010; **18**:61–72 © 2009 John Wiley & Sons, Ltd.
DOI: 10.1002/pip.920

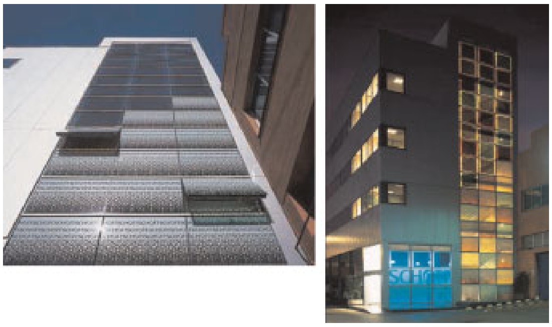

Figure 13. At Barcelona's Schott Iberica headquarter the projecting windows favour natural ventilation (left). On the right the play of light, shadow and colours on the building photovoltaic façade. (Photo credit: Technal).

Adding layers of glass to the base unit of a semitransparent PV glass module can offer for example thermal and acoustic insulation. Such PV glass modules are truly multifunctional building components. One remarkable example is the 455 m^2 double glass façade including 192 m^2 of integrated PV cells mounted on the outside of the buildinǵs existing cladding at the Trondheim University of Science and Technology (Figure 12).

Another is provided by the solar windows made of semitransparent coloured amorphous silicon solar panel at Barcelona's Schott Iberica (Figure 13). The original façade of translucent glass and lacking in casement openings caused the building to reach temperatures up to 50°C in summer. The new façade instead reduces energy consumption and increases energy efficiency by generating electricity and by shading the inner environment against entropic heating. Now, a curtain wall with projecting fastenings and windows, made up of a combination of photovoltaic modules at the top and coloured, silk-screen insulating glass at the bottom, covers the façade. This combination came about as a result of studying the insulation features of a façade which was fitted with openings that allow for natural ventilation. The building's annual heating and cooling consumption fell by 8% [19].

3.3. Façdes

The architecturally striking solar façade of the Ferdinand-Braun Institute in Berlin (Figure 14) consists of a shining black solar wall about 640 m^2 in size ($8 \times 80\,m^2$) made of thin film modules based on anthracite-coloured thin layer of copper indium sulphide (CIS) instead of the usual metallic blue silicon. The wall achieves about 39 kWp [20].

In particular, the solar power system consists of 730 active modules with an output of 45–60 W each. The typical 50 W module (Figure 15) is framed in black anodized aluminium and is 1.26 m long and 0.658 m wide but only 30 mm deep and weighs only 13.6 kg.

Figure 14. The elegantly shaped solar wall at Ferdinand-Braun Institute in Berlin costed 250 000 € for 39 kWp. (Photo credit: Sulfurcell).

3.4. Skylights and shading systems

One of the most widespread applications of BIPV is in solar skylights. They combine the advantage of light diffusion in the building while providing an unobstructed surface for the installation of PV modules or laminates. In this type of application, PV elements provide both electricity and light to the building. The PV modules and support structures used for this type of application are similar to those used in semitransparent glass façades. The structure produces fascinating light hallway walks and floors and allow a stimulating architectural design of light and shadow. The Lehrter train station in Berlin containing 180 kWp of glass–glass modules is a remarkable example (Figure 16). Since the roof of the building is curved, each of the modules had to be custom built to fit within the steel frame of the building.

Also in Germany, the town of Herne possesses one of the largest BIPV systems in the world. The project consists of an academy, hotel, library and offices all wrapped in 1000 kWp solar glass of 180 m of length, 72 m of width and 16 m of height (Figure 17 and Table III).

The inside of this wrap is not exposed to the wind or rain creating a microclimate that allows to profit from year round relaxation spaces. Glass elements with and without photovoltaic modules tilted at 5° toward South are found in

Figure 15. A typical 50 W module framed in black anodized alumium is 1.26 m long and 0.658 m wide but only 30 mm deep. (Photo credit: Sulfurcell).

Figure 16. Glass–glass photovoltaics on the Lehrter train station in Berlin. (Photo credit: jameswagner.com).

Figure 17. Academy and building multi-use Mont-Cenis, Herne, Germany. This building contains an academy, hotel, offices and library, all wrapped in glass of 180 m of length, 72 m of width and 16 m of height. (Photo credit: Bipv.ch).

Table III. Data for the BIPV plant at the Mont-Cenis Academy in Herne, Germany.

Total power	1000 kWp (925 kWp roof and 75 kWp facade)
PV elements surface	10 500 m^2 (3180 modules)
Annual production	ca. 650 000 kWh

the glass roofing. This disposition has allowed to mostly illuminate the inside atrium. The photovoltaic modules are multi-functional because they furnish shade, allow light to pass and produce electricity. The west façade is covered by 30% with mono-crystalline modules that allows light screening limiting the overheating.

The 'Flabeg Solar' modules have been used with different percentages of surface cells (from 58 to 86%). The power according to this varied percentage, respectively, is from 250 to 420 Wps. The inverters (around 600) have been inserted on the edge of the roof.

Interestingly, at the beginning of the project and for the competition of contract it was not planned to use photovoltaic modules. In the next phase of the project, when the different shading systems were discussed and the architects allowed the customer to see how much energy could be produced by the roof, the photovoltaic installation became a priority for the customer. Out of a total cost of the project of 60 €million, the photovoltaic installation costed 8 €million (this cost includes part of the roof, of the façade, the system of shading), 50% covered by Germany's State incentives to solar energy.

4. CHALLENGES WITH BIPV

The advantages of BIPV systems are clear and, once prices will fall due to rapid evolution of thin-film technology already in course, the market for building integrated PV systems will rapidly grow. BIPV systems are highly reliable in the long term (the average guarantee being 20–25 years), are almost maintenance-free and, unlike any other building materials, they produce energy and therefore allow a building owner to recover the initial cost of their investment with an average pay back time of about 10 years when State aids are in place. Afterwards, the annual return of investment is approximately 7% of the initial investment [21].

High cost (Table IV), thus, remains the major challenge with BIPV, requiring the existence of State aids (subsidies and tax incentives) to reduce prices. The average residential installation has a capacity of 3 kW so at an estimated average cost of 8 €/W, the overall cost for a customized integration is in excess of € 24 000.

For this reason, many States like France and Italy provide the highest feed-in tariffs to BIPV systems which helps those wanting to invest in BIPV in getting the bank loans.

Due to the high price of a BIPV system compared to that of a normal PV system, until recent times the only segment which opted for the costlier option than an on-roof installation are the large prestige projects, which tend to be highly customized, utilizing highly customized modules. The cost of a customized BIPV system can go up to 40 €/W is not only dictated by the cost of the solar PV module (and that of the inverter) which make up between 60% of the total system costs, but also up to 40 per by costs of installation, design, glazing, water-proofing, wiring (the so called Balance of System, or BOS) [12]. In general, however, the major part of the cost of a BIPV system goes

Table IV. BIPV Market: Average Cost per Watt of a BIPV System (Europe), 2007 (Source: Frost & Sullivan, 2007).

Company	Module (€/W)	Inverter (€/W)	Component cost (€/W)	BOS costs (% of total)	Total system cost (€/W)
Cost range	1.5–33.0	0.4–3.0	2.1–35.0	6–40.0	3–41.0
Average cost	4.3	0.7	5.0	11.0	5.55

Note. All figures are rounded; the base year is 2007. Source: Frost & Sullivan.

Prog. Photovolt: Res. Appl. 2010; **18**:61–72 © 2009 John Wiley & Sons, Ltd.
DOI: 10.1002/pip.920

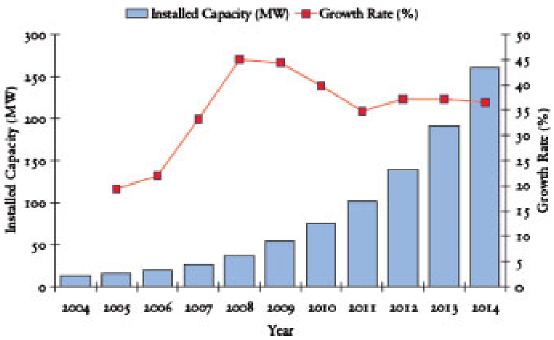

Figure 18. BIPV Market: Installed Capacity Forecasts (Europe), 2004–2014 (Source: Frost & Sullivan, 2007).

to the module and inverters (at an average of 73 and 8%, respectively) and the rest for BOS costs. This implies that the majority of the market share for BIPV goes to the module manufacturers, with a smaller share for the inverter manufacturers and the BOS suppliers.

5. BIPV MARKET TRENDS

With relatively low market size and penetration, the BIPV market holds large potential for growth in Europe and in the rest of the world. Thus far, the main driver for the BIPV market in Europe has been the feed-in tariffs for solar PV generated power in countries like Germany, Spain and Italy and more recently, France, Switzerland and Portugal.

Such feed-in tariffs provide a large incentive for consumers and companies to adopt BIPV by allowing them to sell back excessive power to the grid at a high price (3–5 times the grid price of electricity depending on the region and type of installation). In Europe, only the annual growth rate during the 2007–2014 period is expected to be 39.2% for installed capacity, with the market reaching 260.44 MW of installations and a value of €1185.9 million in 2014 (Figure 18) [12].

These figures make BIPV an attractive option for PV manufacturers looking for new avenues to renew and expand their products base. The competitive structure of the BIPV market in Figure 19 indeed reveals a lot on the overall PV business structure. There is no dominant player in the market, with even the large PV module manufacturers like Sharp and Suntech only accounting for about 8%of the market [12].

The more vertically integrated companies have had greater success in the market; but there are a few module manufacturers that concentrate on BIPV which have a niche in complete building integration installation and design based on thin-film technology providing solutions for commercial and residential applications as well.

The competitive landscape of the BIPV market reveals a multi-layered structure with a large number of players in different points in the value chain. At the top of the chain sit the manufacturers of modules and inverters, below them are the distributors, importers and suppliers, then the companies which customize modules for BIPV along with the designers of BIPV systems as well as the architects and the installers and finally the end users (Figure 20).

The solar PV value chain can be further split into polysilicon suppliers, cell manufacturers, wafer manufacturers and module manufacturers. The module manufacturers are at the bottom of this value chain and the polysilicon suppliers at the top. The further up the value chain one travels, the lesser the number of companies participating in it. This is because the knowledge and investment that is required scales up significantly in the higher part of the value chain. Therefore, there have been

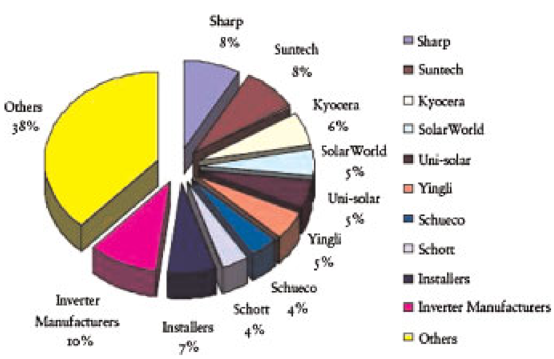

Figure 19. The competitive structure of the BIPV market. (Source: Frost & Sullivan, 2007).

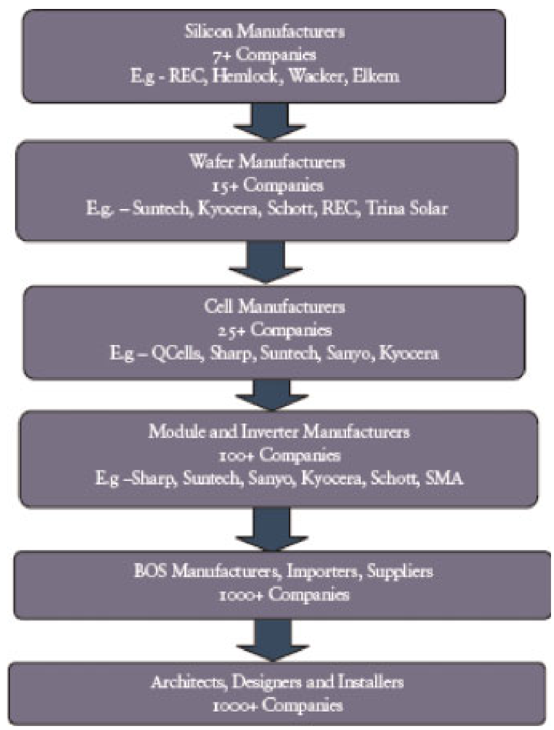

Figure 20. The competitive structure of the BIPV market. (Source: Frost & Sullivan, 2007).

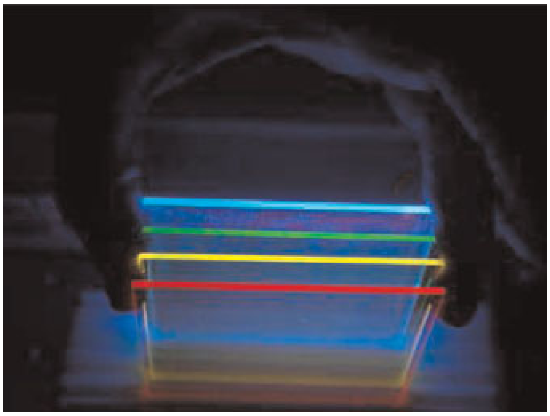

Figure 21. In future solar windows solar cells will be attached to the edges of window where light will be concentrated by the use of organic dyes reducing the cost of solar power and raising the efficiency by a factor of 40. (Photo credit: Donna Coveney).

only seven major polysilicon suppliers for solar PV industry until recently, which mainly supply electronic grade polysilicon. Similarly there are only a bit more than 15 major wafer manufacturers; about 25 major cell manufacturers; whereas the field expands vastly with module manufacturers. A lot of the major manufacturers are vertically integrated providing cell and wafer manufacture as well.

6. OUTLOOK AND CONCLUSIONS

A building needs three forms of energy: heat, cool and electricity. Eventually, all these three forms of energy will be generated by solar energy and buildings will be converted from energy users to energy producers. Solar heating façades and roofs covered with thermal solar collectors will provide heating for utilizable water and for support of heating when required; whereas BIPV systems will produce the electricity output required to the building including fresh air needed in summer. In general, a PV system can contribute significant added value to the building in terms of value and image, because all energy-related features of a building, e.g. energy consumption characteristics, play an increasing role in the value determination of a building. One of the efforts needed to remove barriers related to BIPV recently identified in the EU 'Sunrise' project was indeed the increased demonstration and awareness raising of the economic viability of investments in BIPV [22]; another was to encourage manufacturers to produce PV products that are more easily integrated into buildings.

The key opportunities for construction companies to embrace this emerging and exciting technology are clear: enhanced economic value for their buildings deriving from far better energetic and functional performance and enhanced visual aspect. The main bottleneck, emerged also during the studies conducted within said European research project, lies in the ability to communicate this enhanced value and the new possibilities to customers and thus justify the higher cost (generally an increment around 20%).

The new photovoltaic products eliminate older conflict between aesthetics and photovoltaics at such a large extent that even historical monuments can be protected and illuminated by BIPV solar technologies as demonstrated, for instance, by the EU-backed research project 'PVAccept' already in the early 2000s [23]. The examples described in this brief account and the many others available, clearly show that BIPV is a clean technology that actually offers the opportunity to design solutions that enrich the way we experience places and buildings. BIPV products capable to create solar façades, skylights, windows, roofs and walls multiply the design options of architects and act as multifunctional architectural elements providing many services beyond electricity generation.

Still, architects and construction companies need to be convinced that PV systems are a reasonable alternative in comparison with other construction materials. On the other hand, PV module manufacturers and the building sector have to collaborate in developing new products, not only for roof-top installations but primarily for building-integrated PV modules that not only generate electricity but also replace other construction materials [24].

Perhaps not surprisingly, BIPV has benefited from overwhelming political support in the EU where a 20–20–20 (per cent) overall target scheme for reducing CO_2 emissions, incentivating emission-free forms of electricity generation and raising energy efficiency has been just drafted into legislation. In the construction industry, this is being translated into new legislation frameworks which dictate radical changes in how our buildings are designed [25]. In this sense, BIPV is a strategic field of today's PV industry whose growth has to benefit society, the economy and the environment at large both in developed and developing countries. Market growth will rapidly follow the major technology and scientific advances that are being made.

For instance, low cost PV windows will harness the sun's energy concentrating light at the edges (Figure 21), with solar cells located around the edges with a 40-fold increase in the electrical power obtained from each solar cell thanks to the use of focused light [26]. Reporting on recent advances in the BIPV technology, this paper aims to contribute to such progress.

ACKNOWLEDGEMENTS

This paper is dedicated with profound affection to Roberta Gioia for the joy donated throughout all these years of friendship. We thank Engineers Giuseppe Marino (Astaldi SpA) and Mario Lanciani (Astaldi Construction Corporation) for their pioneering vision of BIPV that will soon bring many rewards to Italy's construction industry.

Prog. Photovolt: Res. Appl. 2010; **18**:61–72 © 2009 John Wiley & Sons, Ltd.
DOI: 10.1002/pip.920

REFERENCES

1. Prasad D, Snow M. (eds). Designing with Solar Power: A Source Book for Building Integrated Photovoltaics (BIPV). Earthscan Publications: London, 2005.
2. Crassard F, Rode J. The evolution of building integrated photovoltaics (BIPV) in the German and French technological innovation systems for solar cells. Master of Science Thesis in Management and Economics of Innovation. Chalmers University of Technology: Göteborg, 2007.
3. Cameron A. PV's progress: growth and potential in the BIPV industry, *Renewable Energy World*, 1 March 2007.
4. Hagemann IB. New perspectives for BIPV with dye solar cells (DSC). *2nd DSC Industrialization Conference*, St Gallen (Switzerland), 11–13 September 2007.
5. Potential for Building Integrated Photovoltaics. *Technical Report IEA- PVPS T7-4:2002*, International Energy Agency.
6. Fraile Montoro D. EPIA, Future Outlook of BIPV, *International Workshop on BIPV*, Nice, 30 October 2008.
7. Hagemann IB. Solar Design in Architecture and Urban Planning. *JSPS Symposium 'Urban Planning—Sustainable Cities'*, Tokyo, 12 September 2005.
8. See at the URL: www.pvsunrise.eu
9. Pagliaro M, Palmisano G, Ciriminna R. Flexible Solar Cells. Wiley-VCH: Weinheim, 2008.
10. Marsh G. BIPV: innovation puts spotlight on solar *Renewable Energy Focus* 2008; **9**: 62.
11. Bichsel F. Flexible photovoltaics. Building integration is our business, Flexcell, Yverdon Les Bains (CH), 2008.
12. Frost & Sullivan, European building integrated photovoltaics market. *Report (October 2008)*.
13. See at the URL: www.globalsolar.com
14. See at the URL: www.bipv.ch
15. Using technology developed at University of Rome's Tor Vergata Center for Hybrid and Organic Solar Energy (CHOSE). www.chose.it
16. See at the URL: www.konarka.com
17. Prasad DK, Snow M. Examples of successful architectural integration of PV: Australia. *Progress in Photovoltaics* 2004; **12**: 477.
18. For this project, the Vatican State, Professor L. De Santoli and Solar AG have been awarded the 2008 European Solar Prize, category Solar architecture and urban development.
19. See at the URL: www.technal.com
20. See at the URL: www.sulfurcell.com
21. Data from the EU-funded project Sunrise. See at the URL: www.pvsunrise.eu
22. Caneva S, Weiss I, PV Sunrise-Overcoming existing barriers, Fiera di Milano Rho, 27 May 2009. Accessible at the URL: http://www.aie.eu/files/PDF%20Workshops/WS_090527_02_Silvia_Caneva_Overcoming_existing_ barriers.pdf
23. Hermannsdörfer I, Rüb C. Solar Design: Photovoltaics for Old Buildings, Urban Space, Landscapes. Jovis Verlag: Berlin, 2006.
24. Henemann A. BIPV: Built-in solar energy. *Renew. Energy Focus* 2008; **9**: 14.
25. Foster N, Otto F, *et al*. Solar Energy in Architecture and Urban Planning. Prestel Verlag: München, 1996.
26. Currie MJ, Mapel JK, Heidel TD, Goffri S, Baldo MA. High-efficiency organic solar concentrators for photovoltaics. *Science* 2008; **321**: 226.