DE GRUYTER DOI 10.1515/green-2013-0020 — Green 2013; 3(2): 125–156

Expert View from Science

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Building Integrated Photovoltaics (BIPV): Review, Potentials, Barriers and Myths

Abstract: To date, none of the predictions that have been made about the emerging BIPV industry have really hit the target. The anticipated boom has so far stalled and despite developing and promoting a number of excellent systems and products, many producers around the world have been forced to quit on purely economic grounds. The authors believe that after this painful cleansing of the market, a massive counter trend will follow, enlivened and carried forward by more advanced PV technologies and ever-stricter climate policies designed to achieve energy neutrality in a cost-effective way. As a result, the need for BIPV products for use in construction will undergo first a gradual and then a massive increase. The planning of buildings with multifunctional, integrated roof and façade elements capable of fulfilling the technical and legal demands will become an essential, accepted part of the architectonic mainstream and will also contribute to an aesthetic valorisation. Until then, various barriers need to be overcome in order to facilitate and accelerate BIPV. Besides issues related to mere cost-efficiency ratio, psychological and social factors also play an evident role. The goal of energy change linked to greater use of renewables can be successfully achieved only when all aspects are taken into account and when visual appeal and energy efficiency thus no longer appear to be an oxymoron.

Keywords: solar energy, photovoltaics, Building Integrated Photovoltaics

PACS® (2010). 88.40.H-, 88.40.mr

Introduction

When renowned British architect Sir Norman Foster stated that “Solar Architecture is not about fashion, but about survival”, he condensed a highly complex phenomenon to a simple but emblematic analysis since around 40% of worldwide energy demand is consumed by buildings. Faced with limited supplies of fossil fuels and uranium, the turn toward renewable energies is unavoidable and simply vital. The decades of transition towards climate neutrality have been marked by worldwide activity in research and development, an unceasing transfer of technology, and a highly competitive market in all sectors of renewable energy commercialisation. With the massive ongoing crisis that has been seen in the photovoltaic industry since 2011, set off – amongst other factors – by price dumping and overproduction in the Far East which led to an annual drop in the price of PV modules that most recently reached levels of 20%, there was a need to make a grab for the market segment that had previously been considered to represent the supposedly luxury offspring of the sector and which had thus far scraped by only as a niche presence, despite a number of impressive

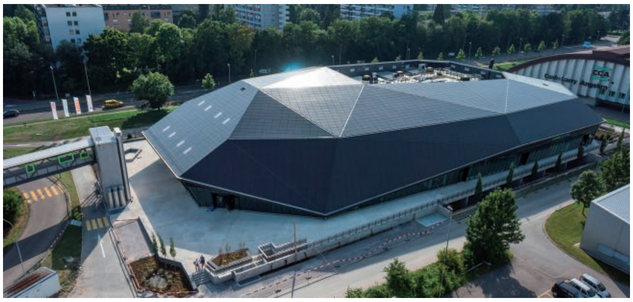

Fig. 1: Umweltarena Spreitenbach (Switzerland 2012): an example of a 203% PlusEnergy building achieved by means of a customized 750 kWp full-roof BIPV skin consisting of c-Si panels with an anti-reflective glass (Architect: René Schmid Architekten; System provider: 3-S Photovoltaics, Meyer & Burger Group; Photo: Bruno Helbling)

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improvements, namely Building Integrated Photovoltaics (BIPV).

In contrast to conventional Building Adopted Photovoltaics (BAPV), which describes the additive installation of a PV system to an already finished building envelope, BIPV is understood as an integral building component: the electricity producing modules are here both a functional unit of the finished building, and yet also a construction element of the building skin, since they replace conventional materials. This approach defines PV as an architecturally relevant component, as an active energy-producing unit that furthermore renders an aesthetic value to the whole construction. This affects new builds, as well as the economically significant retrofit segment, or refurbishment, since many architecturally attractive post-industrial, but also traditional pre- and post-war residential houses are subject to modernization.

Besides harvesting energy, well-integrated PV-modules are suitable to contribute to the comfort of the building: they serve as weather protection, heat insulation, shading modulation, noise protection, thermal isolation and electromagnetic shielding, etc. Since whole parts of the building shell are replaced by choosing this path, savings are made in terms of the costs of building materials: so PV modules are now able to replace the brickwork covering for an entire roof and at the same time deliver electricity, which is also the case for the elements used in the building façade. After an initial outlay of planning and finance costs, the multifunctionality of PV modules linked to BIPV thus has a favourable effect on the overall costs of a building project and on the amortisation of the PV system itself.

That is why the hopes of the PV sector have rested for many years on BIPV as an emerging market with “the potential to become an industry-leading, reliable, renewable and cost-effective energy source” [1]. But the increasing overcapacity issues for manufacturing during the last two years have forced many companies to exit the market [2]. BIPV-oriented manufacturers have been particularly badly hit and a number of innovative and excellent products have disappeared because of the price pressure of BAPV systems [3]. This development is completely contradictory to what even serious and thoroughly researched market reports had predicted and assumed prior to 2011 [4]. Reading through the papers that were published between 2008 and 2010, one is confronted with the phenomenon of the unpredictability of economic developments in general, and a roll call of names of producers no longer in production that were once considered to be the established Who’s Who of the BIPV business. So any kind of prognosis made today from amidst the PV crisis must be regarded with utmost restraint. That BIPV – which has been talked about for more than two decades – should suddenly, at this particular moment, provide momentum for the immediate stimulation of a groggy market, is being debated in expert circles with some controversy: on the one side, the aforementioned advantages of BIPV are clear to see, and yet on the other, there are too many inhibiting factors that still form part of the equation. Most investors, planners, architects, and builders still find the practical implementation of available BIPV solutions difficult, and there is often both a considerable lack of awareness and a persistent resistance among stakeholders towards this matter. The dedication that they show to BIPV in terms of engagement and dialogue often extends no further than the official presentation of exemplarily finished showcases at specialist symposia. Such prize exhibits are always received with applause and fill the pages of glossy trade magazines and architects’ or builders’ periodicals, but there is still the sniff of something prestigious, exceptional, expensive and almost exotic about them, despite the fact that innumerable examples of BIPV have already been built.

It is significant, in the case of Germany, for example, that alongside the many successful major projects and R&D activities, one recent journalistic approach on BIPV was published in the form of a well-intentioned, but non-committed three-page guideline aimed at architects [5]. Despite their evident advantages and the rich toolbox offered by PV products across the range from rigid to flexible, and from semi-transparent to coloured, solar-powered systems are obviously not yet considered to be a mainstream technology in building practice. Binding standards have not yet been set so far as requirements for building with PV are concerned, and the existing products and application possibilities are neither widely available, nor widely known about by private home-owners, or by many of the decision-makers in the building industry. Questions of cost tend to be cited as an obstacle, doubts are expressed over the longevity of integrated PV products and of maintenance problems. Lastly, in most cases, a conventional, non-integrated and supposedly cheaper solution is preferred to an integrated one. Here, the off-the-record opinion of a proven insider with 20 years of professional experience in the PV sector serves as a good illustration of the situation across the greater part of Europe: “Everyone is talking about BIPV, but nothing is happening”. Is this statement a true reflection of realities in the construction industry and within the built environment, or does it present a subjectively coloured distortion of circumstances that only relate to most European countries?

Review

The trend for transforming buildings from energy users to energy producers is not something that has only just appeared. Architectural, structural, and aesthetic solutions involving integrating PV into the building envelope have been sought since PV first entered the market. After the Swiss engineer Markus Real took the very first initiative ('Megawatt') of calling for 333 Zurich house owners to install PV panels on their roofs in 1986, the idea of using PV for decentralized energy harvesting through the 'smart grid' was born. This development was soon followed by considerations of how to integrate PV into the building since discussions about aesthetics had started to obstruct the course. As early as 1990, the first buildings to respect this ambitious issue at a higher level started to be erected worldwide. The Public Utilities Building of Aachen (Stadtwerke Aachen) may serve as one early example among many others: here for the first time solar cells were embedded within insulation glass to create a multi-functional, semi-transparent façade (1991) (Fig. 3). An historical examination of the term BIPV thus leads to the

Fig. 2: Typical non-integrated European PV roof-installations (1990s–today)

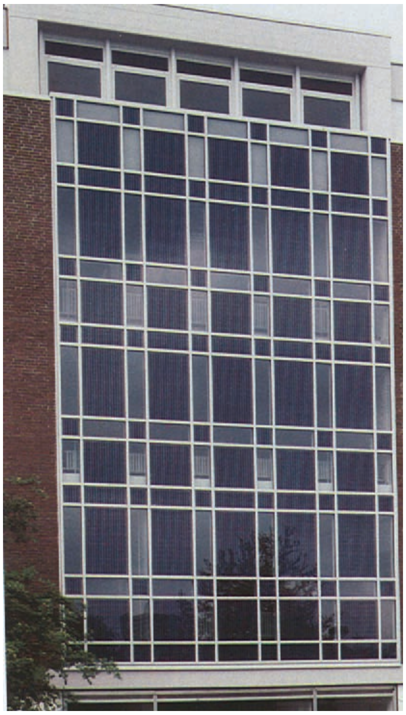


Fig. 3a: Public Utilities Building (Stadtwerke), Aachen (Germany): First façade ever (1991) embedding c-Si wafers into insulation glass (Surface: 37 m^2, Energy output: 4,2 kWp, Architect: Georg Feinhals, System Provider: Flabeg Solar; Source: Hermannsdörfer/Rüb: Solardesign, 2005)

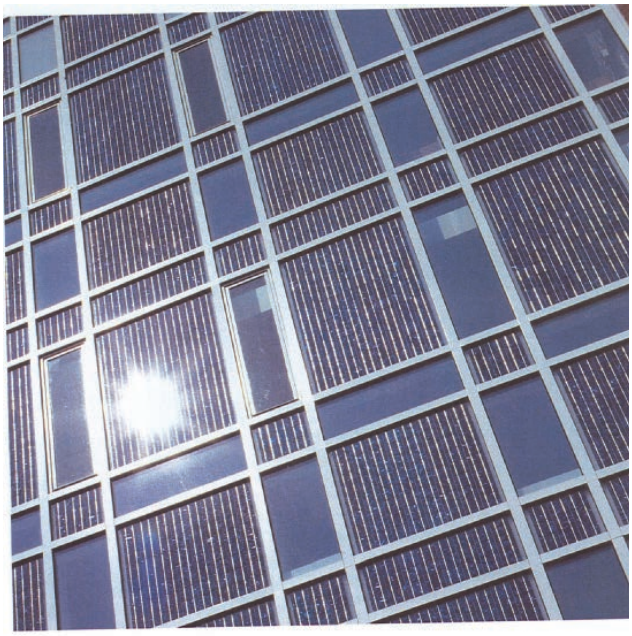


Fig. 3b: Detail

conclusion that little has substantially changed in terms of the deep-rooted objections that have been seen over the course of the decades that have followed the introduction of BIPV at the end of the 1980s. In principle, all of the technical and aesthetic possibilities of the then emergent PV technologies were fully recognised by the architects and the building industry. They were also described in detail by the very first publications on the subject. Among the first in a long history was the work published in 1993 by the Swiss authors Humm and Toggweiler [6]. It programmatically bore the integration of solar cells in building shells within its title and for a long time represented one of the few sources of inspiration within Europe. It was there that the first realisations of BIPV were introduced, which for reasons dictated by time, were mostly limited to the integration of Standard Silicon wafer based (Si) modules. Additional important impetus stemmed from the United Kingdom: one of the first expert symposia about BIPV took place in September 1996 at the University of Northumbria, in Newcastle (UK) [7]. In 1997 Task 7 in the International Energy Agency's (IEA) PV Power System Program was begun [8]. It aimed at enhancing the architectural and technical quality and the economic viability of PV systems in the built environment. This international collaborative programme was conceived as a way of linking the PV developments in Europe, the US, Japan and Australia that were related to BIPV and was completed by the end of 2001. The experts that were involved identified BIPV as an 'exciting market' and defined its technical and non-technical barriers. Market deployment strategies were also suggested, as a set of training materials for architects and system designers were developed. Within the framework of the project, a BIPV 'Demosite' was established in Lausanne. BIPV therefore came into focus for all the relevant stakeholders in the building industry and encouraged further scientific debate and practical examination.

A doctoral thesis from the Oxford Brookes School of Architecture (UK) approached the economic aspects of BIPV in 1998 [9]. In 2000, a fundamental work about the handling of BIPV was published in the USA: using the example of 16 thus far successfully realised construction projects from around the world, the variety of different possible applications and building-integrated systems were described in detail and discussed from technical and aesthetic perspectives [10]. In the Anglo-American sphere, the work stood for some time as a compendium for further ways to approach the topic and prompted the realisation of many new BIPV projects. For the German-speaking area, the 1996 publication 'Solararchitektur für Europa' [11] [Solar Architecture for Europe] brought further initiatives, which were followed by important works about the architectonic treatment of solar cells [12]. Ingo Hagemann's 2002 dissertation from the Technical University of Aachen became an important source of impetus in specialist circles and established the author's reputation as a BIPV expert [13].

Fig 4: Energiepark West, Satteins (Austria): Early and well-designed example of a 150 m^2 c-Si solar façade (Architects: heim + müller architektur zt gmbh; Photo: Christine Kees, 1996)

Around the world, successfully realised projects were reported by a large number of publications and improved technologies and systems were introduced [14]. Some focused on particular building categories, such as residential houses and commercial buildings. Investigations also took place into individual construction elements, like façades and different types of roof, while others expressly examined the multifunctional aspect of PV [15]. Just recently, a study undertaken by the National Renewable Energy Laboratory (NREL) about the prices of rooftop systems in the residential sector of the USA evidenced that the multifunctional features of BIPV systems currently available on the market offer an interesting return on the investment [16]. Among the large number of research projects, the interdisciplinary German-Italian "PV ACCEPT" project is brought out as an example. Established in 2001 at Berlin's Universität der Künste, and supported by the European Commission, the architects and students taking part revealed that a convincing PV-design constitutes a determining factor for the acceptance of PV technology in construction. With their first publication at the end of the project in 2005, they made the applications of BIPV in even listed buildings known to a wider public (Figs. 5 and 6) [17]. Further EU projects also seize on the thematic, with both the 'Sunrise' project [18] and 'Next-Buildings' [19] worthy of mention, among many others.

This rich vein of activity, presented here with reference to only a very concise and selective set of examples,

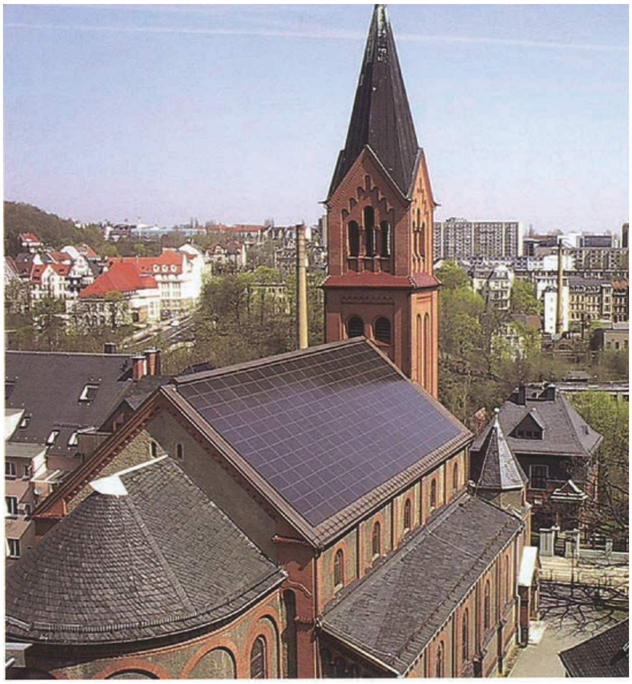


Fig. 5: Herz-Jesu church, Plauen (Germany): installation of 80 black c-Si panels with anti-reflective front glass and hidden fixings. (Surface: 160 m^2, Energy output: 24 kWp, System Provider: Solarwatt AG, 2001)

Fig. 6: Building of the Tourist Office in Alès (France): integration of three PV façades into a listed sixteenth-century building (Surface: 100 m^2, Energy output: 9,5 kWp, Architect: Jean François Rougé; System Provider: Photowatt, 2001)

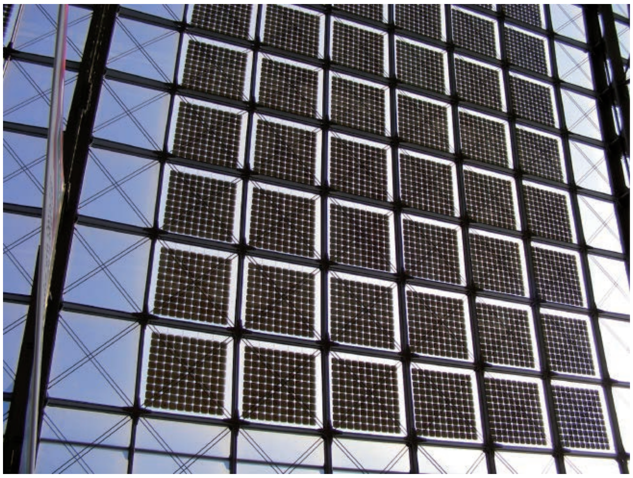
was flanked by a large number of specialist symposia: the BIPV conference in Newcastle in 1996 was followed by many more with the same intention and since about 2000, BIPV has been a fixed component of the debate at every solar conference and interdisciplinary discussion. The most advanced and important event on the subject in Europe is the 'Energy Forum on Solar Building Skins', that was established in 2006. Organized by the 'Economic Forum' (Munich-Bolzano) [20], the annual conference has in recent years taken place in Bressanone (Brixen) [21]. Invited speakers from renowned research labs around the world, as well as from within the building industry, contribute to intense discussions and updates at the highest level on just about any aspect of the subject. But smaller events elsewhere also contribute to the discussion [22] and most notably, the annual 'BIPV Summit' that has taken place in San Diego since 2008 accentuates the theme with the same level of significance. It need not be stressed that China, the biggest PV producer with its huge internal PV-markets and a booming construction economy, also took a prominent part in the debate: the 'China international BIPV Forum and exhibition' that has taken place annually in Shanghai since 2011 powerfully underlines that. Most recently in Europe, the 'Future of BIPV' symposium, staged by the IMEC Leuven (Belgium), briefly examined the status quo [23], followed overseas by the 'Building Integrated PV Symposium' at the Canadian German Chamber, Toronto (Canada) on the 23rd April 2013. The list can be added to at will and it is not possible to take everything into account here.

In addition to this multitude of worldwide activities, state incentives have proven themselves to be one of the most important motors for the expansion of BIPV: the frontrunner here was France, whose subsidy programme has successfully promoted integrated systems since 2006, along with Italy and some U.S. states. China has been catching up ground since 2009 with its 'Golden Sun Demonstration Project', while several other European countries support BIPV installations through special feed-in tariffs (FiT).

Technology trends and their influence on BIPV

Silicon wafer based crystalline cells (c-Si)

PV products based on c-Si technology are the most widespread and predominant on the market. Under ideal test conditions these inorganic semiconductors provide high module efficiencies of around 15% for multi-crystalline and up to 20% for mono-crystalline modules. Both offer a good cost-efficiency ratio and a certain variety in their visual appeal. Due to the specific material properties of the Si-solar cells, the modules available commercially are mostly rigid, opaque, and flat. Semi-transparent solutions can be obtained by a specific encapsulation, typically in



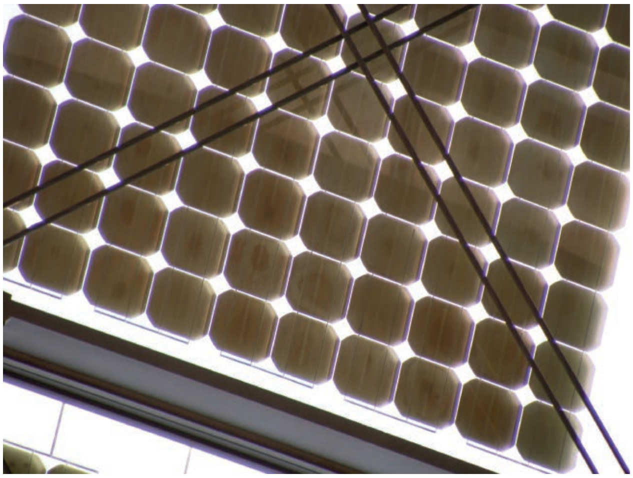


Fig. 7: Hauptbahnhof, Berlin (Germany): Detail of the 1700 m^2 curved roof surface covered with 780 semi-transparent c-Si panels, each customized, comprising 78’000 c-Si wafers overall (Energy output: 180 kWp, Architect: Meinhard von Gerkan; System provider: Optisol, 2003)

Fig. 8: ECN, building 42 (Petten, The Netherlands): Semi-transparent and curved c-Si-skylight roof (Bear Architecten, 2001)

Fig. 9: Albasolar Head Office, Alba (Italy): the exterior of the building consists of an amorphous photovoltaic ventilated façade (System provider: Albasolar, 2012)

glass-glass laminates or by perforating the wafer. Transparency is produced by means of a particular distance set between the array of solar cells, which allows the transmission of light (Fig. 7). There is also a range of coloured crystalline solar cells on the market. Homogeneity can be obtained by using a backsheet of a color similar to the solar cell, as encapsulant, which makes the dominant solar cell structure more discrete. Back-contacted solar cells are often used for BIPV because of their hidden contact busbars. C-Si modules are offered with aluminium frames or as a frameless device. Both have been used in BIPV since the start of the 1990s, with a preference for their use as in-roof solutions, opaque or semi-transparent façade elements, or as semi-transparent PV skylights.

But despite their wide-ranging possibilities, the field of standard c-Si applications in the building envelop is limited by several technical constraints. One disadvantage of this technology is known to be the loss of performance as a consequence of high temperatures and of shading caused by the surrounding buildings, their chimneys, or other kinds of obstacles: even one single partly shaded c-Si module will thus lead to a significant loss of power, not only in that particular module, but in all the others connected in series within the same circuit. They will all be affected and reduced to the same reduced power output as the one that is shaded, and as a consequence, the whole system could suffer a ‘cutout’. This significant issue has to be taken into account when planning with c-Si technology. Here the recent emergence of microinverters associated to each individual modules can partially solve the problem and could provide a new impetus for integration of c-Si technologies. Another option of

Table 1: Market share of the various PV technologies in the BIPV market in 2009 (Source: Nanomarkets, EPIA analysis)

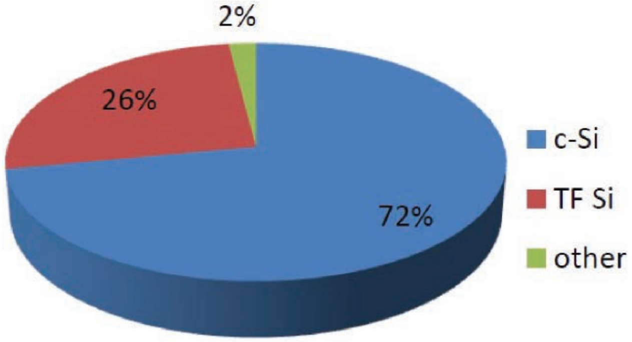


Table 2: Conversion efficiencies and temperature coefficients of Pmax of the various PV technologies

Technology	Module Efficiency [%]	Temperature Coefficient P_{max} [%/°C] (±0.03)
Mono-crystalline silicon (mono c-Si)	15–20	−0.45
Poly-crystalline silicon (poly c-Si)	11–15	−0.45
Copper Indium Gallium Selenide (CIGS)	10–13	−0.34
Cadmium Telluride (CdTe)	9–12	−0.25
Amorphous Silicon (a-Si)	5–7	−0.21
Micromorph Silicon (a-Si/μc-Si)	8–10	−0.27
Heterojunction (HIT)	18–20	−0.30
Dye sensitized Cell (DSC)	2–5	−0.005
Organic Photovoltaics (OPV)	4–5	−0.43

choice is the use of modules made on the basis of thin-film technology which are usually less affected by partial shading.

In Si-technology, irrespective of ever improving records for efficiency, there are no special new trends to identify that are about to lead to completely new BIPV features, despite the solar cells becoming increasingly thinner. Semi-transparent solar cells (with multiple openings created directly in the cells) that were developed ten years ago failed to succeed on the market on account of their high levels of efficiency losses.

Thin-films: Amorphous (a-Si) and micromorph (μm-Si), CIGS, OPV, DSC

Amorphous (a-Si) and micromorph (μm-Si)

Despite all the positive prognoses that were seen as recently as 2010 [24] and the anticipation of an expected increased market share for thin-film technologies, things have since fallen so far that some of these technologies have now even being declared ‘dead’ by the media and some competing industries. This is mainly due to the strong increase in production capacity (learning curve effect) and to the falling price of poly-silicon [25], the raw material that had previously made the competing wafer technology considerably more expensive than silicon based thin-film, where only very small quantities of abundant and non-toxic materials are used. Another factor that has displaced promising TF technologies even further toward the edge of the market is the overriding focus on cell-efficiencies, regarded as a fetish by most parts of the public: efficiencies of 6% for brownish amorphous and 10% for black micromorph PV modules – with realistic options pushing towards 11–12% [26] – do not seem to be competitive figures at first sight, with c-Si and silicon heterojunction (HIT, see below) showing efficiencies up to 20%. This is both a clear misunderstanding and false conclusion for several reasons since official cell and module efficiency rates are exclusively assessed under ideal lab conditions and have no significance for the annual energy production under real weather conditions within a certain region. In other word the performance ratio (PR) of BIPV systems can be better for thin-films, thereby limiting the impact. It does not take into account the lowest cost/m^2 of thin-film technologies either, which is often a neglected factor in BIPV, as it can replace building elements which come in the same price range. We develop here below on some of these advantages of thin-film over wafer-based crystalline Si-technology.

Firstly, compared with c-Si, the efficiency decrease in silicon thin-film cells is less affected by high temperatures and there are less significant losses of performance under conditions of indirect and hence lower sun irradiation caused by cloudy weather conditions and shading by trees, other buildings, or chimneys. The annual energy output of PV modules based on thin-films provides a demonstrably higher energy output than common standard screen printed c-Si technology. It is clear that these facts have not been properly communicated to a wider public by the TF industry. On many façades in heavily built urban spaces, or on partially shaded roofs where the aspect of homogenous and uniform appearance plays a role, black micromorph Si-TF units are therefore still a product of choice with the promises of a higher annual energy harvesting.

Secondly, when calculated per square meter, Si-TF modules, for example, still have a decisive price advantage over Si-wafer modules due to the drastic reduction of their semi-conductive layers and manufacturing process.

Fig. 10: Baoding (China): Detail of an a-Si façade. The active PV panel in the middle to the right is surrounded by metal façade elements of the same colour (Courtesy: Tianwei Solar Films; Photo: P. Heinstein)

They currently cost only around 40 Euros per m^2, compared with 120–200 Euros for crystalline-Si products. Even if around 30–40% more surface area is required to produce the same level of electricity as is the case with high-end c-Si modules, Si thin-film is still more economical in terms of price per square meter, providing it substitutes a building element. The surface dependency indeed constitutes one of the limiting factors for the expected emergence of a-si and µm-si TF in the building envelope. Ideal for façade applications, their employment in small and well-oriented roofs is less attractive. In these cases, c-Si technologies will lead to a higher energy output.

Thirdly, through a process of laser scribing (see section about 'semi-transparency' below), it is easy to manufacture transluscent and semi-transparent modules with an absolutely homogenous appeal. By adding encapsulated polymer of whatever colour or interferential coating, the variety is unlimited. Flexible Si-TF-laminates are also available, but their increasing market significance for BIPV must remain in doubt, due to a quite limited field of application in the traditional built environment. As a composite with, for example, zinc standing seam panels (Fig. 13), they already played – and should continue to play – an important role in the industrial and commercial building segment. There are also market niches in perspective of lightweight solutions for ephemeral or inflatable constructions (Fig. 14).

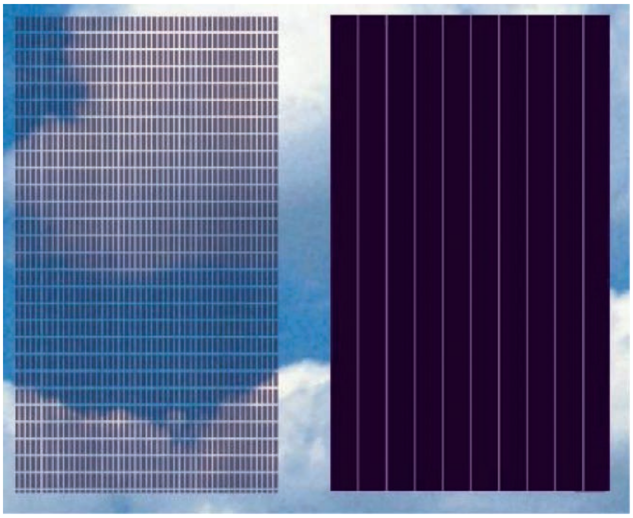


Fig. 11: A semi-transparent and an opaque a-Si thin-film module (Source: Schott Solar 2009)

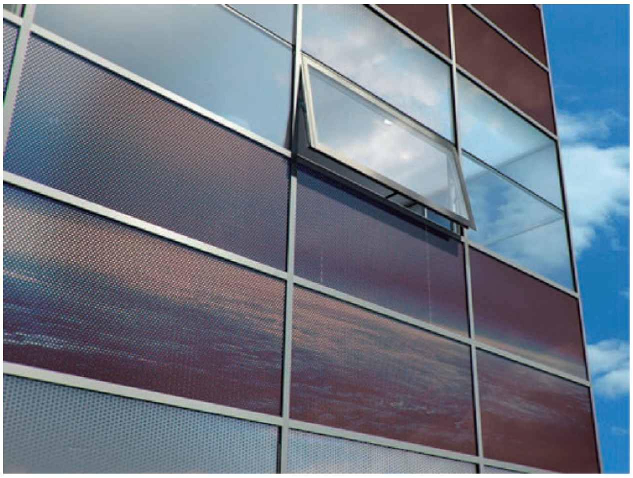


Fig. 12: Semi-transparent a-Si façade

CIGS (also 'CIS')

This alternative thin-film technology offers high laboratory cell efficiencies of over 20% under lab conditions and recently, modules with efficiencies up to 13.4% have been available. The name derives from copper, indium, gallium, sulphur, and selenium, which are employed to make quaternary alloy, with semiconductor properties. A limiting factor to mass production might be set by the use of indium, which is a scarce raw material. Since health issues arise from the use and exposure to gallium, sulphur and especially selenium, CIGS technology is connoted by many experts and potential clients as a technology with

Fig. 13: PV applied on zinc standing seam panels

Fig. 14: Transparent light-weight solution

only a minor ‘green’ aspect, even though it can be assumed to be stable in a module. Like nearly all TF products, CIGS allows cell deposition on flexible substrates and semi-transparent solutions can also easily be achieved. Some industrialized products are already available, and there have been achieved interesting results by installing CIGS panels with black and antireflective rendering (Fig. 15). Noticeably though its temperature coefficient (typically 0.3–0.4%/°C) is more favourable than the one of standard crystalline silicon, and CIGS module tend to exhibit an efficiency increase in the first time of use, leading to favourable system performance ratio.

Fig. 15: Ferdinand-Braun-Institute, Berlin: 732 dark CIS modules designed as a curved façade (Surface: 640 m^2, Energy output 39 kWp, System Provider: Sulfurcell Solartechnik GmbH, 2007)

OPV

Organic Photovoltaics (OPV) – the darling child of the popular press whose name already has something of ‘the green touch’ about it – has recently been talked about on account of its ever improving world records, and after more than ten years of research it is beginning to come out of the shadows of other PV technologies. With current rates of cell efficiency under laboratory conditions of 11.5% and with rates of 15% being sought in the foreseeable future, this technology, with its interesting material properties ranging from flexible (Fig. 16) to semi-transparent and the reasonable manufacturing costs

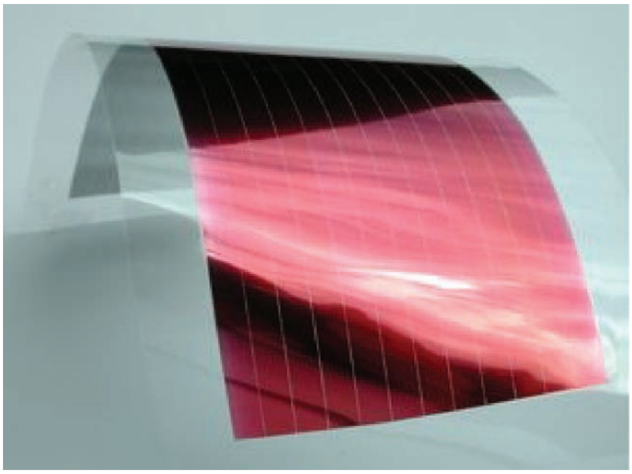


Fig. 16: OPV on a flexible substrate

made possible by roll-to-roll production techniques will perhaps come to play a more defined role in BIPV in a couple of years [27]. The current limiting factors for OPV are its still low levels of module efficiency and the absence of products with long lifetime guarantees. Both count against its broader BIPV application in the very near future.

DSC

Another technology, that of so-called Dye-sensitized Cells (DSC or Grätzel cell) can also be added to the Folio of existing BIPV examples. Based on a photochemical system, the current relatively low level of efficiency of around 5–6% at module level is offset by other properties, such as, for example, the potential to be produced in various colours on flexible, rigid, or semi-transparent substrates in a cost-efficient way [28]. To date a couple of BIPV projects have been realised with DSC (Fig. 17), mostly in the Far East, the US and Australia, where one of the biggest industrial DSC producers is settled who came up with coloured and semi-transparent windows worthy of note [29]. Other solutions like recently announced DSC-applications on metal substrates await their critical evaluation [30]. Neither OPV nor DSC has managed to gain the predicted increase in market share in the short term of a couple of years. One of the main inhibiting factors to its wide acceptance, however, is that even after more than 20 years of research, the product stability is still very limited and does not meet with high standard build requirements that are demanding 20 plus years of functionality and much more. Current and very intense DSC-research activities may result in more promising BIPV products emerging in the long run of the next ten years.

Fig. 17: Façade with dye sensitized cell (DSC) technology (System provider: Konarka, 2011)

HIT cells (Heterojunction with intrinsic thin layer)

The hope among wide parts of the branch lies with modules based on crystalline heterojunction solar cells, an area where intense research activities can be observed, and where Sanyo/Panasonic is already delivering high quality product. To oversimplify matters, this technology is about a combination of c-Si wafers and TF-technology, since a thin semi-conductive layer is deposited on a mono-crystalline Si wafer. HIT cells achieving efficacy rates under lab conditions of around 24.7% and at module level of around 18–19% have recently been grabbing attention. Two specificities of HIT technology are power temperature coefficients below –0.3%/°C, in the range of amorphous and micromorph silicon, the quasi perfect low-illumination behaviour, and the potential to come close in production costs to standard crystalline c-Si technologies [31]. Distributed mostly as typical wafer-based panels, they are currently being recommended for both roofs and façades less on account of their visual appeal but more because of their performance: on a surface of around 6 m^2 with optimal alignment, it is currently possible to generate 1 kWp. A module surface of only 28 m^2 would thus cover the average electricity requirements of a Middle-European household if installed under ideal conditions (see thin-film section above). In terms of price per square meter, however, HIT modules now belong amongst the most expensive modules ones on the market and still cost around 200 Euros per square meter. The efficiency potentials in HIT-cells of probably up to 20–22% at module level and the falling prices that are to be expected as a benefit of new mass production technologies would then probably lead to a gradual replacement of traditional mono-crystalline and poly-crystalline Si-wafer based technology in the future. Beside its notably increased efficiency, however, HIT-technology opens no genuinely new or breath-taking architectural or visual aspect for BIPV: the rendering is almost identical to the common bluish or black c-Si wafer modules and the problem of shading remains the same.

A short overview of the main categories for BIPV applications [32]

Roof systems

Roofs are so far considered to be the ideal field for BIPV applications since pitched roofs of a certain angle (i.e. within Central Europe: 30°) provide the best energy harvesting. Standard in-roof systems figure among the most

Fig. 18: Typical framed in-roof installation, Sumiswald (Switzerland): the installation achieves a homogeneous appeal through the fact that both, the frame and the modules, share the same colour.

Fig. 19: Framed in-roof system: less homogenous appeal due to the contrast of the aluminium frame and the PV panels.

Fig. 20a: Frameless c-Si in-roof installation, Ins (Switzerland): 32 modules (Surface: 35 m^2, Energy output: 5.12 kWp, System provider: 3-S Photovoltaics, Meyer & Burger Group, 2011; Courtesy: Derk Bätzner, Photo: P. Heinstein)

Fig. 20b: Detail

Fig. 21: Full-roof installation with c-Si panels (System provider: 3-S Photovoltaics, Meyer & Burger Group)

common BIPV approaches: here the PV modules simply replace the tiles. A well-integrated system is characterized by an installation that is flush-mountable with the surrounding roof tiles, and a frameless module design. Water tightness has to be guaranteed, for instance, by means of a specific under construction of vertical rails, a horizontal module overlapping and an impermeable interlayer underneath. Framed modules are an alternative solution. Architects view them as less attractive, however, on account of the frame being used as an additional visible material. Besides in-roof installations that cover only a part of the roof, a full-roof covering of PV modules is regarded as a more economic and more elegant alternative choice: maximum surface area guarantees both maximum energy

Fig. 22: Frameless c-Si full-roof BIPV installation on a 19th century Swiss farmhouse in Uettligen (System provider: 3-S Photovoltaics, Meyer & Burger Group)

Fig. 23: In-roof installation combined with cement fibre panels (Courtesy: 3-S Photovoltaics, Swisspearl)

harvesting and a very appealing homogenous rendering, especially when an anti-glazing front glass is applied.

Both crystalline silicon and thin-film technologies are available for BIPV roof-solutions. The former comfortably dominates the market, whereas the latter is used where shading by chimneys, trees, or neighbouring buildings would otherwise lower the efficiency of a classical crystalline silicon installation to a tremendous extent.

The use of thin-film technology in flexible laminates generally plays a minor role in the building sector [33] and is only applied where crystalline modules are excluded on account of their rigidity or weight, especially when modules need to be attached to flat or curved zinc roofs. Typical bluish or black c-Si solar cell patterns are the most widespread among roof-installed PV modules. Semi-transparent, wafer-based solutions used as skylights have also become more and more common since the early 1990s, especially for bigger roofs on public, commercial or industrial buildings.

Fig. 24: Middle European solar tiles (System provider: Panotron)

Fig. 25: Solar shingles: ideal for shale roofs (System provider: Solar Century)

Solar tiles and solar shingles offer an alternative constructive and aesthetic approach on account of their likeness to ordinary roof tiles, but their use involves some disadvantages (Figs. 24 and 25). The first obvious idea from the tile industry proved to be a poor investment: the ‘solar-tiles’ that were born as a result, that is to say normal roof tiles with PV modules applied on to them, are completely uneconomical and require every tile to have its own cabling. With several hundreds tiles per roof this means the same number of electrical plug-in connections, each of which presents a certain technical susceptibility to the ingress of water and humidity, etc. Very few of these products were therefore able to establish itself on the market. The tile producers then turned to bigger, more

Fig. 26: Residential estate, Allington (England): solar shingles seamlessly inserted replacing conventional tiles (Surface: 9, 6 m², Energy output: 1 kWp; System provider: Solar Century, 2003; Source: Hermannsdörfer/Rüb 2005)

Fig. 27: Solar tiles solution in Italy to meet with Mediterranean roof tradition (System provider: Tegola Solare)

cost-effective units. A horizontal tile segment of about two meters, for example, is thus completely replaced by a suitable PV module in the tiled roof. This sits on a plastic or metal housing for support, which shows the same lateral, sideways geometry as the adjacent tiles and therefore integrates perfectly with the roof. It thus provides all the properties of an ordinary tile, such as water tightness, etc. (Figs. 25 and 26). The disadvantage of this otherwise interesting approach is that due to the multitude of existing different tile types and the geometric variations that can exist even within a single country, these BIPV products are exclusively linked to the particular tile producer, and to just one type of tile from his assortment. This lack of compatibility means a great disadvantage to the client and

Fig. 28a: Solution by vertical installation of PV panels on Mediterranean roofs (System provider: Hemera)

Fig. 28b: Detail

forces him to purchase tiles and PV tiles from one and the same producer. It is mostly only the market leaders in the tile industry that can expect to sell enough profitable quantities of such a BIPV product to make them worth designing and offering at a competitive price. In the United Kingdom, where the roof tiles and most notably roof shingles are significantly more uniform in comparison with continental Europe, one manufacturer has been breaking through with success on the internal market. Outside the UK, with so many varied forms of roof coverings, it will scarcely be possible to replicate a similar success. Local market leaders in Central Europe therefore recently came up with very similar products matching with their own tiles.

Façades

The second major field of BIPV application is that of façades where solar panels of all technologies can be integrated as a conventional cladding system for curtain walls and single layer façades.

Fig. 29: Building of the Chamber of Commerce, Vienna (Austria): mono-c-Si façade (Surface: 447 m^2, Energy output of 55 kWp, (Architect: Eduard Neversal Ziviltechniker GmbH; System provider: Ertex-Solar, 2008)

Current development is aimed at developing more advanced applications like adaptive modular PV façades and intelligent ways of balancing daylighting and shading. Defining the 'ideal' dynamic thermal and visual properties of the building envelope is another important issue [34]. By combining PV and thermal insulation, versatile applications are emerging that can produce an ideal rendering of the way in which BIPV has to interface with traditional building and construction practice.

PV façades are despite their widely known, iconic importance in the field of architecture not yet widely distrib-

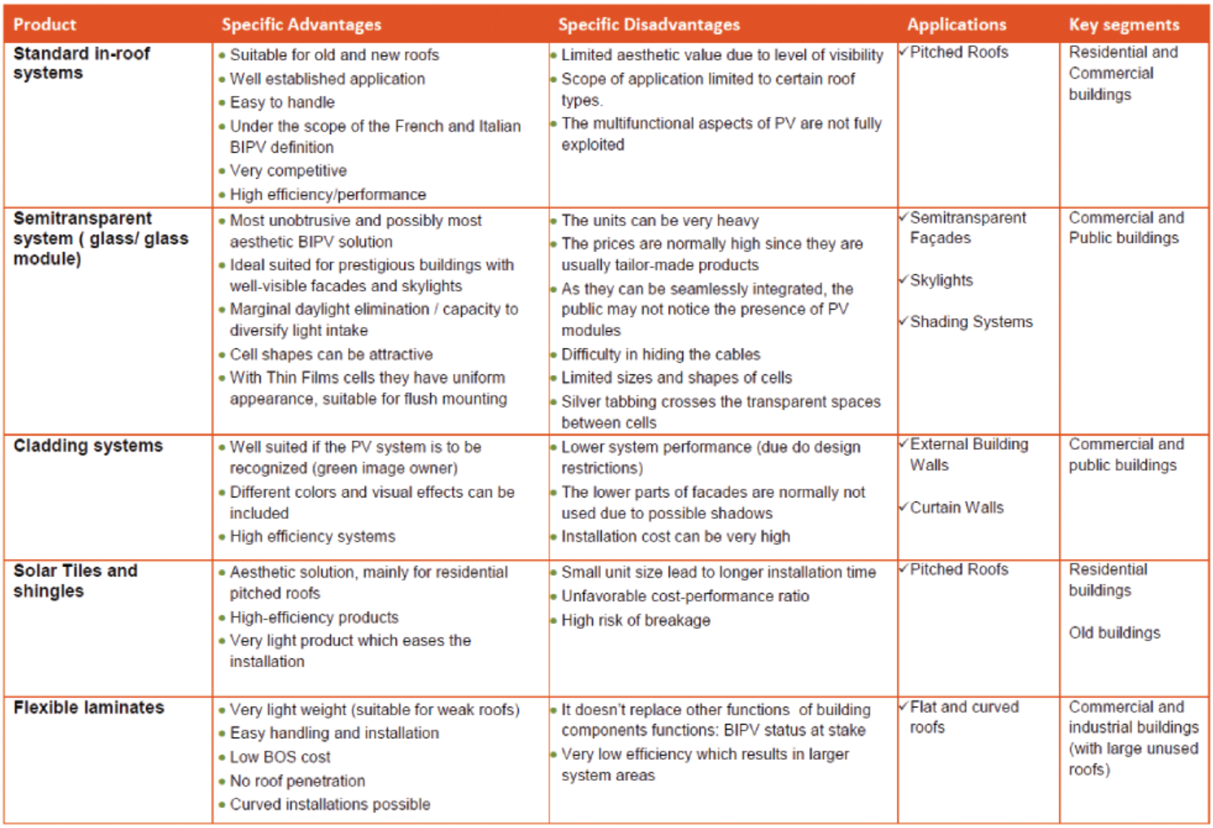
Fig. 30: Juwi Head Office, Bolanden (Germany): ideal façade inclination with large-scale PV modules to harvest a maximum of solar energy (Surface: 70 m^2, Energy output: 7.2 kWp, System provider: Schüco International KG, 2004)

Fig. 31: Kulturhaus Milbertshofen (Germany): façade with black micromorph and semi-transparent thin-film modules (Energy output: 3 kWp), RPM-Architekten, System provider: Voltarlux, 2008)

uted. They belong to the sector of high-rise and commercial buildings, where investors are looking for a quick profit instead of calculating with the added value of lower building operation costs. Therefore solar façades have not been accepted by most stakeholders in this very investment-orientated business. On the other hand, the attitude of only desiring the highest efficiencies pushes façades within the building skin into the second tier, since conventional crystalline Si-panels have an energy yield loss of 20–40% when installed vertically, depending on the location. Thin-film offers better results here, due to the improved low illumination performance/and or improved temperature coefficient.

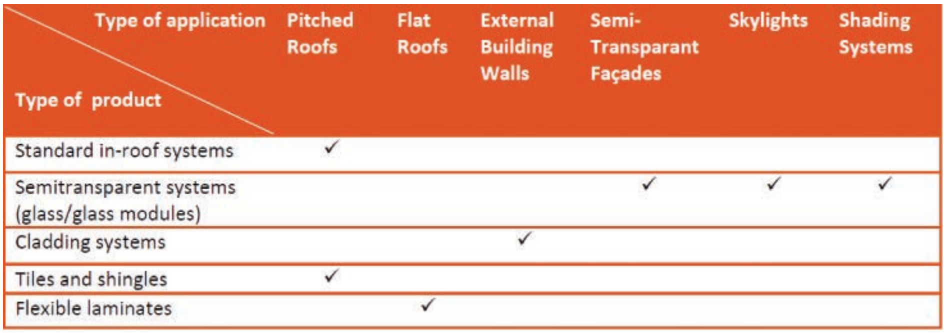
PV façades require complex planning and compliance with a great many physical properties. However, a multifunctional design also makes it possible to fulfil a lot of these demands. Current research is moving in the direction of using PV façades as a dynamic building envelope and a climate-adaptive building shell [35]. Among many others, the Fraunhofer Institute for Solar Energy Systems ISE (Freiburg, Germany) also puts an ambitious emphasis on the subject (Table 3) [36].

Table 3: Comparative analysis of different BIPV solutions (Source: EPIA)



Product	Specific Advantages	Specific Disadvantages	Applications	Key segments
Standard in-roof systems	• Suitable for old and new roofs • Well established application • Easy to handle • Under the scope of the French and Italian BIPV definition • Very competitive • High efficiency/performance	• Limited aesthetic value due to level of visibility • Scope of application limited to certain roof types. • The multifunctional aspects of PV are not fully exploited	✓Pitched Roofs	Residential and Commercial buildings
Semitransparent system (glass/ glass module)	• Most unobtrusive and possibly most aesthetic BIPV solution • Ideal suited for prestigious buildings with well-visible facades and skylights • Marginal daylight elimination / capacity to diversify light intake • Cell shapes can be attractive • With Thin Films cells they have uniform appearance, suitable for flush mounting	• The units can be very heavy • The prices are normally high since they are usually tailor-made products • As they can be seamlessly integrated, the public may not notice the presence of PV modules • Difficulty in hiding the cables • Limited sizes and shapes of cells • Silver tabbing crosses the transparent spaces between cells	✓Semitransparent Façades ✓Skylights ✓Shading Systems	Commercial and Public buildings
Cladding systems	• Well suited if the PV system is to be recognized (green image owner) • Different colors and visual effects can be included • High efficiency systems	• Lower system performance (due do design restrictions) • The lower parts of facades are normally not used due to possible shadows • Installation cost can be very high	✓External Building Walls ✓Curtain Walls	Commercial and public buildings
Solar Tiles and shingles	• Aesthetic solution, mainly for residential pitched roofs • High-efficiency products • Very light product which eases the installation	• Small unit size lead to longer installation time • Unfavorable cost-performance ratio • High risk of breakage	✓Pitched Roofs	Residential buildings Old buildings
Flexible laminates	• Very light weight (suitable for weak roofs) • Easy handling and installation • Low BOS cost • No roof penetration • Curved installations possible	• It doesn't replace other functions of building components functions: BIPV status at stake • Very low efficiency which results in larger system areas	✓Flat and curved roofs	Commercial and industrial buildings (with large unused roofs)

Table 4: Overview of BIPV solutions and their fields of application



Type of application / Type of product	Pitched Roofs	Flat Roofs	External Building Walls	Semi-Transparant Façades	Skylights	Shading Systems
Standard in-roof systems	✓					
Semitransparent systems (glass/glass modules)				✓	✓	✓
Cladding systems			✓			
Tiles and shingles	✓					
Flexible laminates		✓				

Barriers and sources of momentum for the diffusion of BIPV

Because of the still limited markets, several pioneer companies in BIPV products either stopped or abandoned development in the field. Possibly at the wrong time. BIPV is now on the minds of decision-makers in the building industry, and of scientists, politicians, investors, and private homeowners. As a vital part of both the PV industry and the building industry, it already plays a certain but not yet well or commonly defined role. The extent to which BIPV will contribute to the highly expected pick-up of the PV market in 2014 cannot be accurately predicted and it depends on a multitude of factors: there are technical, legal, administrative, and market barriers to be considered, and all of this is accompanied by disputes on aesthetics, and above all on calculations of cost-efficiency. However, compared to 10 years ago, the impressive cost reductions achieved by all PV-technologies, opens in principle infinite possibilities for low cost solar electricity produced by BIPV systems. To promote, foster and establish BIPV in the near future, the following aspects seem to be of considerable importance.

BAPV versus BIPV: underestimated market volume and cost

One of the most repeated and most widely circulated misjudgements is that the market volume for BIPV is limited in comparison with that of BAPV. This is explained to some extent by the fact that in the area of residential housing, only a smaller percentage of the building stock undergoes a complete roof renovation, and it's only when renovation is required that the full or partial replacement of roofing with PV modules appears economically attractive. BAPV on the other hand can potentially be put to use on any roof on which the sun shines, and so speaks to the other 98% of the building stock. However, it is worth taking a proper look at the figures: in fact it is still the case that up to 2% of existing roofs across middle Europe are completely renovated each year and in this process, old tiles are replaced by new ones [37]. Up to 18.2 million existing residential buildings in Germany would represent a figure of around 360,000 roofs that need replacing every year, not including new builds [38]. By ignoring the relatively small section of flat roofs from the 1960s and 1970s and calculating on the basis of all roofs being well aligned in relation to the sun, the sums make interesting reading: if all 360,000 German roofs that annually require complete renovation were equipped with BIPV compatible systems instead of tiles, there would be – assuming simplified initial costs of 10,000 Euros per PV system – an annual market volume for BIPV roof systems alone of over 3 billion Euros. Additional forecasts go even further and identify 3000 km^2 of building surface suitable for BIPV: 300 GW could be installed on this surface. The total turnover for these installations, including façades, is estimated at some 800 billion Euros only for the German solar and construction industry [39]. The market perspective concerning 14 leading industrial countries, with their 23 billion square meters of well-exposed roofs and façades is proven to exceed an energy production of 1000 GWp, which represents the peak output of 1000 nuclear power stations [40]. This now long obsolete calculation from 2002 was based on the use of 5% efficiency modules. In view of today's efficiencies of 10–20%, the figures could be multiplied by two or three. The expected turnover for BIPV and building industry can only be estimated.

The complex symbiosis of manufacturers, planners and architects and the lack of specialised BIPV consultancies and trained roofers

BIPV does not represent any standardised, hard-defined industrial product. It describes the whole range of potential applications of PV in construction, based on the integration of a multifunctional PV element in the building envelope. The full integration of PV therefore demands a complex and tight interlocking of all stakeholders, including those responsible for products and product develop-

Fig. 32: Solarhaus Darmstadt (Germany): prize-winning pilot project from the Technische Universität Darmstadt with a 200% PlusEnergy gain. The façade is covered with black CIS thin-film modules (System provider: Würth-Solar, 2009)

ment, marketing, planners, developers, architects and installers. Such an holistic approach requires a multitude of building codes to meet with electro-technical codes in order to provide access to the electricity grid. The variety of partners that take part in BIPV planning and the individual character of each building construction determined, for example, by different specifications and national building standards, place BIPV in a very demanding context. Adopting individual BIPV solutions according to the demands of a particular construction project accordingly means providing a complex architectonic service, which from the side of the PV provider needs to be on the basis of a well thought-out business model. Without the close networking of project developers, architects, and the construction industry, it is impossible to imagine a successful market presence. On top of that, BIPV developments in the building sector are often very localised, and serve, for example, only a certain domestic market. This leads to a great deal of confusion about existing products and uncertainty in the minds of planners and architects.

The complexity of integrating BIPV in the planning process requires expert knowledge that makes certain demands of the individual house-owner and architect: the market appears to be confusing, and providers of BIPV that are still operating successfully suddenly switch their activities because of the difficult state of the market, etc. All this unsettles not only the private individual, but also the architects and project developers. It would be so much better to have an easily accessed and independent information forum (see next chapter). So to date it has been incumbent on architects and project planners to step in on behalf of BIPV in construction, mostly in the face of resistance from the investors, who from their side fear the rise in building costs right across the board. So it is known, if not statistically proven, that a great number of architects generally find PV to be aesthetically problematic, something that complicates the planning process and limits their creative possibilities. This is a misconception and will be subject to compulsory and fundamental change in the foreseeable future in almost every industrialised nation as the result of rules that have been established about the promotion of renewable energies. The architect will then see himself forced to coming into terms with this technology and to recognise more strongly the potentials of BIPV.

Focusing on the residential market, a network of trained BIPV installers is another crucial factor. The practice shows that the relevant training is only available to a few of them. If they are not already under contract with a manufacturer of BIPV-compatible products, they will of course recommend to the owner the conventional BAPV products that they already know. Since the installers are courted by many manufacturers at the same time, they will ultimately recommend those PV products that promise the most profit from the smallest investment of labour. However, because the planning effort in the installation of a BIPV system is usually higher and more demanding and requires close cooperation with the architects, the installer or roofer soon reaches back towards conventional BAPV products. The setting up of a well-trained network of PV installers is therefore indispensable for the expansion of BIPV in the classical residential sector, a network of professionals who will recognise that the installation of such systems represents the economic surplus yield for their own business.

With respect to the market confusion it is to be hoped, moreover, that for more complex fields of application like BIPV façades on high-rise or commercial buildings, a branch of BIPV consultancies could be established. Specialist offices of this kind would come to occupy a key position in proceedings: on the basis of an accurate knowledge of the market, the best-suited PV product for the particular building project would be selected in close collaboration with architects and developers, and suitably installed by the PV provider. For reasons of costs, the proportion of standardised elements for roofs and façades would have to be as high as possible and the amount of customised components with divergent geometry such as triangles and other polygon surfaces would need to be minimised. At the moment, an independent BIPV service manager would perhaps still be seen as unwanted competition from the side of the construction industry. In the authors opinion, however, there would be a positive synergy effect: the PV industry, construction industry, property owners, project developers, architects and craftsmen would only profit and PV would be threaded into the planning process under optimum conditions from the very start of the planning process and not afterwards. In this way solar energy can be set up whilst ensuring the highest technical and aesthetic standards. This kind of cooperation would equally enliven the private residential as well as the commercial buildings sector. In the latter, the common aim of investors looking to make a fast profit by cutting out investments in renewables, regarded now as an avoidable element of expenditure, will need to undergo a complete correction: future cost calculations on buildings will have to implicate BIPV as a constant. Attracting and luring potential buyers with low building costs by excluding this aspect should become unthinkable. It will be standard practice to solicit business by calculating the advantage of low energy operating costs as an asset. Purblindness and focusing on a short refinancing period by neglecting the complete life-cycle costs of builds will be followed by a rude awakening for any customer and buyer. According to the English saying: ‘The bitterness of poor quality remains long after the sweetness of a low price is forgotten’ [41].

The ambiguous role of the building industry

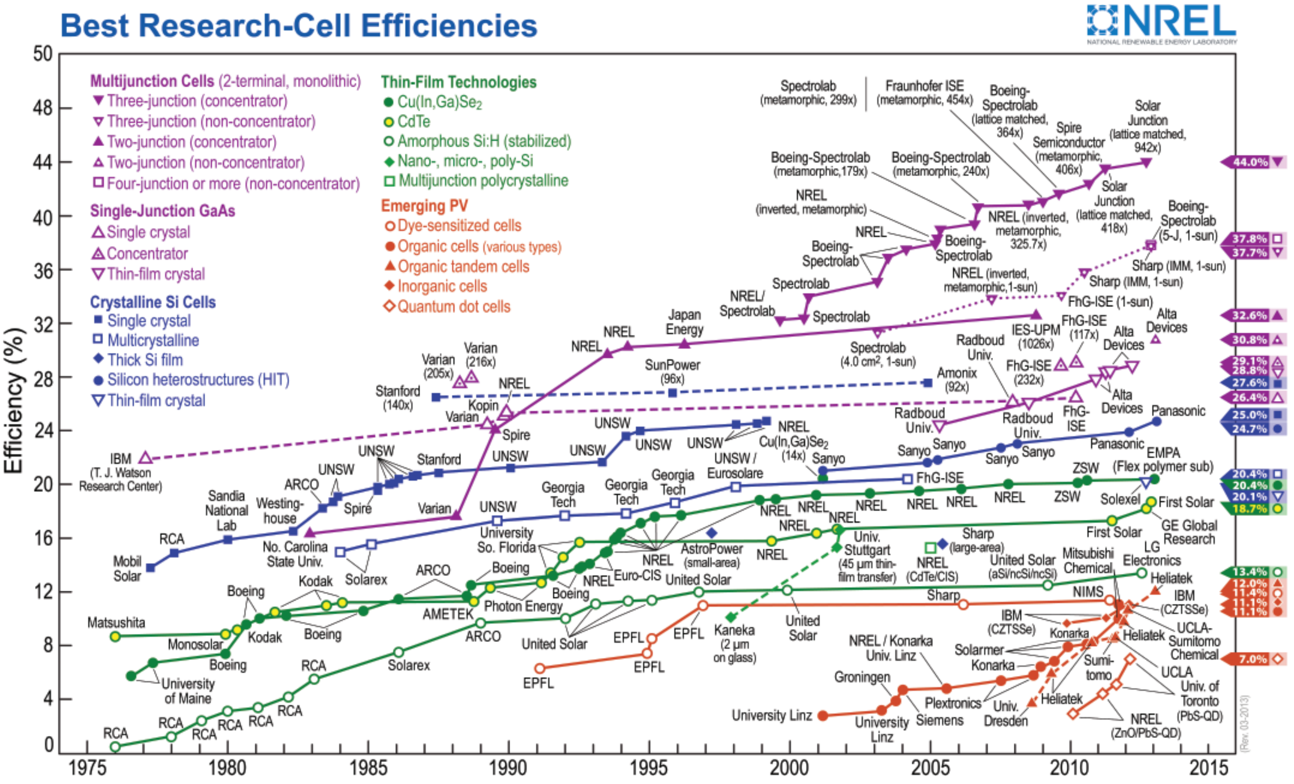
On the side of the building industry, for obvious reasons, there is a need to determine the most successful initiatives for the expansion of BIPV. The branch has a vital economic interest in being involved in the future development of the market in low-energy housing, BIPV curtain walls and PV roof applications. So in Germany, for instance, the Bundesverband Bausysteme e.V formed a group of experts in BIPV, one of the few nationwide operating platforms dedicated to the subject, and at the same time, one of the most important interfaces between the construction industry and the solar industry in this country.

But parts of the industry also sometimes stand in the way of development in order not to lose their own market share of traditional products. So it is evident that the manufacturers and distributors of roof tiles, for example, have no great initial interest in roofs currently under construction or renovation being completely covered with PV panels instead of traditional roof tiles. Naturally, this branch of industry has for a long time recognised the sign of the times and has reacted by producing its own PV products distributed as PV roof tiles. But, as mentioned before, installing hundreds of tiny, tile-shaped solar units each applied on a traditional tile inevitably has to turn out to be a dead-end job, and more compact intermediate solutions like roof-shingle units compatible with different types of tiles are far more promising and cost effective.

The fetish for cell efficiency % rates and the neglect of ‘grey energy’ calculations

Among scientists and more recently in general usage, the data for stating cell-efficiency as a percentage has been the catchiest formula defining progress in the PV sector. As mentioned above in the ‘thin-film’ chapter, cell efficiency shows significant discrepancies between performance under lab conditions and performance in installed, operational PV modules: Standard crystalline cells currently reach almost 17–19% in the lab and 15–16% at module level. With low sun irradiation, fog and a cloudy sky, it will even decrease. Decision-makers in the construction industry have taken note, however, of figures of around

Table 5: Improvement of research cell efficiencies in existing PV technologies since the 1970’s (Source: NREL, 2013)



25% that have appeared in the press, and reports of cell-efficiencies of over 40% for as yet non-industrialized high-end concentrator cells developed by various laboratories. Such simplifications and eye-catching figures might encourage the development of unrealistic expectations over existing products and prevent a lot of potential BIPV clients from installing, while they simply wait for systems capable of even higher performance. It should be pointed out, therefore, that even in the high performing HIT-field, genuine values are not yet available for levels of module performance that clearly exceed 21%. Enhancements on a scale of 1% could take years of intense research. So instead of waiting ten years in anticipation of a probable improvement of around 3%, the time for installation is now, for an immediate start to enjoying the profits of harvesting whatever the efficiency is.

On the other hand, the nominal kiloWatt-Peak (kWp) value of a systems determined for testing conditions at 25 °C for 1000 W/m^2 of light radiation (with a given AM1.5g spectrum), says little about the actual harvesting of energy in a specific place, i.e. the number of kwh/kWp that can be harvested. This can lead to uncertainty in architects and owners, since it lacks a binding common measurement, and also in light of the fact that in construction, this is measured in terms of price per square or cubic meter. For architects and house owners, it is significantly more interesting to find out, that today, given optimal inclination and sun alignment, a module surface of about 30 m^2 is already sufficient to cover a household's average yearly use of electricity at around 4400 kWh [42]. Covering the whole roof with BIPV would result in much more energy production. For the BIPV sector in general, it is essential to reach the point where the added value of a multifunctional building component is included in the calculation, which is barely yet the case.

Moreover, Kilowatt-Peak and cell efficiency take no notice at all of 'grey energy', that is the energy expended in the supply, transport and installation of a PV-module (or system), or in its recycling. For central Europe, the grey energy invested for an average crystalline Si system will be paid back at the end of 3–4 years, and for a thin-film glass/glass module the calculation can come down to about 1.5–2 years. On the side of the thin-film manufacturer, constantly disadvantaged in the competition for record-beating cell-efficiency, the 'levelized costs of electricity' (LCOE) are promoted to be a more appropriated ratio [43]. This is the price at which electricity can be produced over the lifetime of the project. This economic assessment of the overall cost of the energy-generating system includes all the costs incurred over its lifetime: initial investment less the savings made possible by the PV panel on building or roofing element, operations and maintenance, cost of fuel, cost of capital, etc. This balance could fall better for the thin-film branch than it does for the Si-branch. While traditional PV is driven by cost reductions and high volumes, BIPV is driven by the constantly increasing demand for energy-efficient buildings due to national and international energy standards. It is a common mistake to compare BAPV and BIPV only according to the aspects of price per square meter or installed Watt-Peaks without taking into account the material and cost savings generated by BIPV, which represents a considerable factor in the calculation. In the long-term view, BIPV could then be equal or even more cost effective than traditional building-applied PV (BAPV).

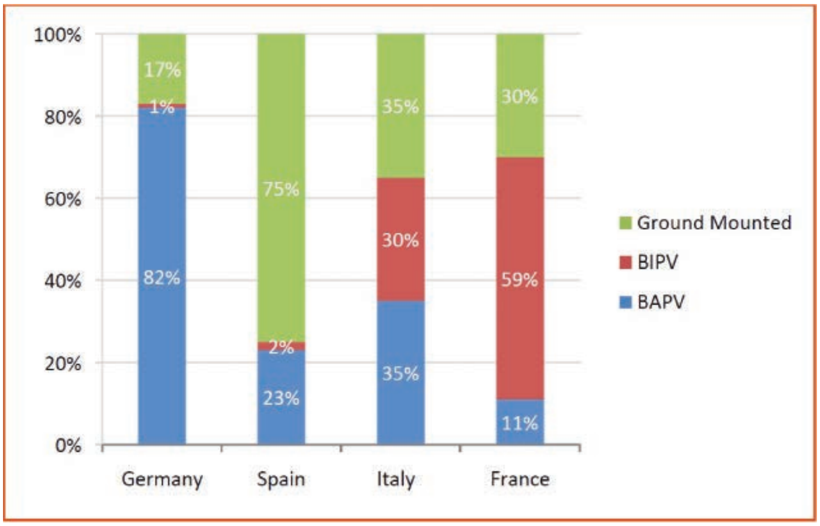
The case of France and Switzerland: strict building approval and modest BIPV incentives created a demand for innovative products

All the market studies and numbers confirm that in the first place, state promotional programmes have a quite decisive influence on the expansion and acceptance of BIPV, since it is often still more expensive in the short term than a simple BAPV solution. The examples of Germany and France serve as a good illustration. France has not established any general subsidies on PV, but the government has instead focused on massively fostering the diffusion of BIPV through the pursuit of ambitious policies [44]. So it is not surprising that BIPV installations are disproportionately more widespread there than elsewhere in the world. If this policy has given rise to significantly less PV systems in terms of numbers, at least these are brought about through good integration: 59% of all French PV systems are integrated, whereas in Italy, where similar subsidies have been established, it stands at 30%.

In Germany, generous subsidies have supported the spread of PV in general, BIPV installations there were completely neglected by the energy legislation before 2010: in-roof systems have been disadvantaged in terms of tax depreciation, since the part of the building which is liable to tax is not assessed as 'independent movable economic property subject to wear and tear'. Since 2010, however, this disadvantage has been abolished and in-roof installations are now equated as being the same as on-roof installations and are subject to the same allowances for deduction on the grounds of depreciation.

The comparative numbers for BIPV in Germany are food for thought: the 1.3 million systems in this country

Table 6: Market share for the four key European PV markets in 2009 (Source: EuPD Research)



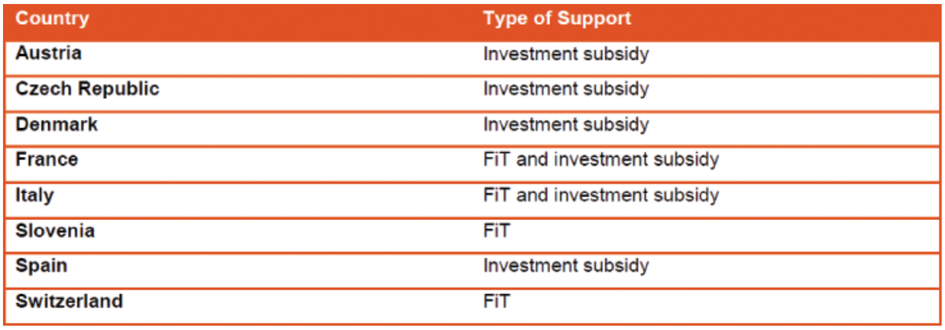
make available the biggest PV density in the world and as the world's greatest adopter of Photovoltaic systems, the country's PV systems produce some 33 gigawatts of electricity per year. However, since BIPV issues have been neglected in the national energy programme, only around 1% of all PV installations are integrated according to common BIPV standards. In Austria, modest BIPV incentives led to a market share of BIPV of probably around 4% [45].

The interplay between ambitious demands in terms of legal building approval, legal incentives and the availability of an innovative product promoted by successful marketing is well illustrated by the case of Switzerland. According to the latest estimates (May 2012), about 25,000 PV systems have been installed in Switzerland with a total capacity of 400 MWp. Although, for other reasons, photovoltaics currently only constitutes 0.7% (Germany 5.5%) of the total national electricity production, BIPV contributes to at least an astonishing 30% (estimated) of all installed PV systems in Switzerland [46].

How can this significant difference be explained given the background of very similar economic and social conditions? The country's legal status as a neutral one with its strictly executed Customs Act does not sufficiently explain the disproportionately widespread use of BIPV there, compared, for instance, with Austria or Germany. And there is surely no greater willingness on the part of individual Swiss homeowners to invest in a well-integrated premium in-roof system.

Swiss industrial traditions in terms of setting high standards for quality, deriving among others from the traditional watchmakers industry, have also led to a demanding attitude towards the built environment and the country's characteristic landscape. Federal laws were enacted that set high BIPV standards in order to comply with legal requirements. Switzerland also offers modest incentives for BIPV installations through a 10% higher feed-in tariff (FiT) to the grid. Both factors created a domestic demand for high-end products with a direct impact on domestic PV

Table 7: Various support schemes overview targetting BIPV in European countries (Source: EPIA, DENA)



Country	Type of Support
Austria	Investment subsidy
Czech Republic	Investment subsidy
Denmark	Investment subsidy
France	FiT and investment subsidy
Italy	FiT and investment subsidy
Slovenia	FiT
Spain	Investment subsidy
Switzerland	FiT

industry. It appears in fact, that in Switzerland, around 2000 installed installations with a combined capacity of around 20 MWp [47] are allotted to a single Swiss-based provider of roof-integrated frameless Si-modules. This corresponds to around 8.5% of all Swiss installed PV systems, to nearly 40% of all Swiss-installed BIPV, and to 5% of the currently installed MWp in the country as a whole.

It can be assumed that this figure may be explained by the interaction between strict building approval regulations, the 10% extra-FiT and the associated demand for an innovative BIPV product to perfectly meet the legal standards. From the aesthetic point of view, the frameless black Si-modules with a matt front glass finish that are offered by the aforementioned provider are among the convincing BIPV compatible products on the traditional market for residential pitched roofs, and they stand out because of their discreet, homogenous black rendering and a fairly simple mounting system. Additionally, the provider offers customized solutions to guarantee a 100% full-roof covering. Because of price, they may not really be mass compatible, and even in Switzerland they still qualify as a high-end premium product.

In neighbouring Germany, the same product has scarcely made an appearance due to less demanding levels of building approval and the aforementioned disadvantage of BIPV in tax legislation: the application of common mass produced and less costly BAPV installations with standard crystalline modules on top of existing roofs is therefore common and stands at 99%. At least it has been possible in the meantime for German officials responsible for the protection of historic monuments to get the message across with a short statement used in a concentrated campaign explaining how, if certain guidelines were observed, PV could also be considered for use on listed buildings, especially when essential BIPV criteria were taken into account [48]. Some Federal Monument Offices (*Landesdenkmalämter*), such as those of Bavaria, Baden-Württemberg and the Rhineland prepared picture instruction brochures containing case studies.

Apart from in France and Italy, BIPV was thus only able to eke out a meagre existence and even conventional in-roof applications in the private residential sector rank as complete exceptions. This lack is eclipsed by some major architectonic projects, with the semi-transparent solar roof of the Berlin Hauptbahnhof worthy of mention. Here, it is often a case of prestigious, publicly-financed projects, or the headquarters of global players who have the necessary funds: the developer is keen to make his relationship with renewable energy clearly demonstrable through his use of BIPV and expects that his core business will receive a boost in terms of a good image and positive influence. Corporate identity activities of this kind are to be expressly welcomed and bring imitation projects in their wake into the small, medium-sized, and private sectors.

Financial, social and psychological aspects: the importance of personal communication and dialogue

The falling costs of PV have not directly resulted in a higher incidence of subsequently installed PV façades and integrated roof systems, since their ‘bankability’ is not a given: as an integral part of the building that cannot be dismantled in case of insolvency, the banks do not usually agree to give a mortgage for investing in such systems. New concepts like ‘contracting’ have also shown promising results in PV roof-installations in the US and Switzerland: the installation is provided by a PV supplier who remains the owner of the system and carries out all technical maintenance until the system is fully paid by all the parties that benefit from it, which includes both house owners and tenants. This offer and course of action aims to cope with the general dilemma that any kind of investment in the building is normally only related to the house owner, but not to the tenant who might also wish to participate. This has led to a massive investment backlog in renewables, and hence in the use of PV worldwide.

All market analyses provide evidence that it is not only costs, legal barriers, discussions on cell efficiencies, aesthetics and the other issues being mentioned here that figure as inhibiting factors on the distribution and acceptance of PV and BIPV. Social and psychological aspects and even irrationalism also play a crucial role. This has been revealed and proven by several market observations and studies in the US and elsewhere:

Very ambitious activities led by energy suppliers hoping to recruit a maximum number of households to participate in their cleverly conceived and fair renewable energy programmes have led to modest results: only 0.1% of all US households that were addressed ended up joining the programme. 99.9% refused, despite the split-investment on offer, a positive cash flow as the result of paying lower monthly electricity rates than before, and even zero asset costs [49]. This seems to represent irrational behaviour since there were no hidden disadvantages at all. But when similar activities were started by local urban authorities addressing the people of a certain district (i.e. Boston, USA), quarter or neighbourhood, the positive response rate immediately leapt to 10%. By involving the local city councillor and several private associations (church, sports etc.), the rate of people agreeing to participate in the proposed new energy programme was raised to an astonishing 40–80% [50]. Sustainable communication has thus led to the wide acceptance of sustainable energy.

To illustrate the impact of social behaviour as an additional important driver in the promotion of renewables and BIPV, the annually awarded *Schweizer Solarpreise* (Swiss Solar Award) is worthy of mention. Since its jury pays particular attention to integrated systems, the laureates become widely known by the media. This attention might have encouraged other homeowners to ‘keep up’ with their neighbours by installing the same prestigious systems. This widely known social phenomenon of ‘imitative instinct’ has not therefore led to the purchase of a bigger car or lawnmower, but to better integrated solar energy systems. So even if BIPV does become more affordable and mainstream in the years to come, the effect of lifting one’s social standard and image by purchasing a better PV product won’t lose its impact: whoever has then missed out on investing in a BIPV installation might face a certain social pressure and will be pushed into keeping up in order to be part of the mainstream and to have a greater personal sense of being “integrated”.

Psychological aspects in terms of reliability issues of solar panels

Typical PV modules can exhibit a power loss due to degradation in the range of 0.5% per year, a figure that represents a 12.5% loss after 25 years. R & D activities worldwide are aiming to minimize this natural degradation rate. Moreover, BIPV installations are technically even more exigent compared with standard PV sites on account of the complex interface between the PV module and the building envelope. Some technologies like DSC, OPV and CIGS might show higher moisture sensitivity than others such as a-Si and c-Si and therefore required particularly watertight sealings. The reinforcement of the International Electrotechnical Commission’s (IEC) requirements in the 1990s has already led to a massive improvement in PV module reliability.

A decisive psychological barrier to the expansion of BIPV is the official warranty on the life cycle of PV modules: the currently guaranteed span of 20 or 25 years still represents good value but in no way describes the maximum performance time, which despite the aforementioned rates of degradation stands at over 30 years without any need for complex technical maintenance. The average life cycle of a traditionally tiled roof is estimated at between 25 and more than 50 years. But there are countless examples of old buildings that can proudly show a fully intact roof that has seen 100 or more years of service. A guaranteed life cycle of 25 years for BIPV modules hence produces the fear in the homeowner that even in the course of his own lifespan, the system will still need to be completely replaced. The same homeowner often won’t hesitate, however, to buy a new car that is three times more expensive and only has a guarantee of two years! In industrialized economies there is still an obvious concentration of priorities in favour of other, technically less doubted industrial products than those made available through BIPV. With the increasing need for renewable energy those priorities will dramatically change: energy production will be more vital than mobility. For the installers of PV installations to start granting warranties of 50 years is hardly likely to meet with the legal realities or with international standards, but psychologically, it would very much help with sales if the life cycle of PV modules could be raised on a voluntary basis to exceed the legal norms and stretch to a duration of 40 or 50 years. Many research laboratories are under great pressure as they continue to work on this issue by enhancing the material properties, optimizing the encapsulation processes and finding new composites and substrates. Industry must not fail to invest in these developments and to commercialize these products. For BIPV, accurate field pre-testing is key for assessing all of the reliability issues that are linked to the technology. Very often in BIPV, it is issues that are related to the installation and to other components – the so called Balance of System (BOS) – rather than the actual PV cell or module that tend to be underestimated: a failure in the fixings, shading from nearby buildings, soiling and water stagnation, fragility of connectors and cables, mechanical stress due to wind exposure, etc. are all issues that have to be taken into account.

Some critical remarks on shape and colour as a potential driver of BIPV

Questions relating to the shape and size of PV modules stir up a sensitive and much discussed field. It can be clearly stated that there is no important market demand at all for any kind of fancy polygon, or curved module outline (Fig. 33). Keeping within the common rectangular formats may fulfil the current requirements of the building industry, but it has in fact proven to be very unfortunate for BIPV that nearly every manufacturer of PV modules offers his own format to protect his own market share. Given that

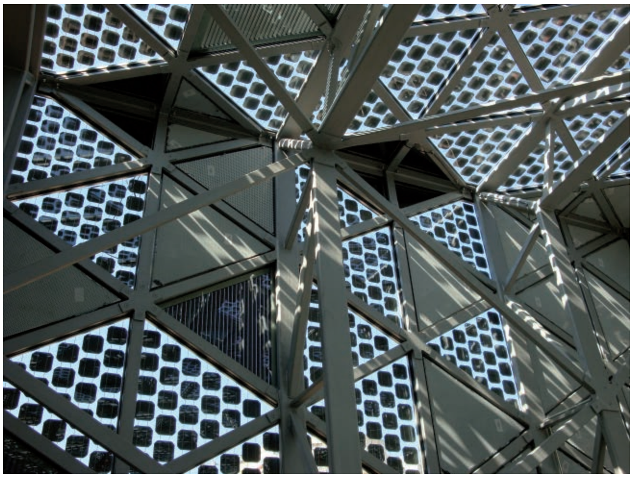


Fig. 33: Cité du Design, St. Etienne (France): one of the very few examples of customized triangular c-Si modules as skylight solution (Architects Finn Geipel, Giulia Andi, LIN Berlin, 2009)

Fig. 34: Rhône-Alpes area (France): PV façade with micromorph thin-film PV panels of 1.10 × 1,30 m each (ou bien: 1.4 m^2) (Surface: 130 m^2; Energy output: 738 kWh; System provider: Pramac; Façade: Face InTec, 2011)

one size never fits all, the availability of any kind of customizing features will be one of the main future issues for sections of the PV industry looking to grab new grounds in the BIPV sector. The manufacturing process in traditional wafer-based Si-modules quite easily makes it possible to finish individual, customised modules in different sizes. This has contributed to some extent in them becoming the leading technology in PV and hence BIPV so far. In the Si thin-film technologies that mostly deal with rigid glass/glass substrates, customized solutions are much more difficult to create, since the assembly lines are only set up for a certain module size. A change in the once predetermined format would be bound up with disproportionate costs, to an extent nowadays of several tens millions of dollars if the full manufacturing equipment needs to be redesigned, which in the face of the predictable turnover figures would make them absolutely uneconomical. One example should be picked out to illustrate the issue:

Si-TF glass modules produced by one of the leading production line manufacturers have an external mass of 1.3 m × 1.1 m, measurements that derive, ironically, from TV screen production standards of the 1980s. Such an arbitrary, not even fully square shape neither fulfils the building industry's demands, where mostly rectangular formats dominate façade constructions according to ceiling-height units of round about 3 m, nor the aesthetic demand of most architects. How will the still promising Si thin-film technology survive – a technology that is in certain dimensions so highly recommended for building façades – if the product is insufficiently compatible with the architectonic traditions and aesthetic views of the mainstream? The option of variability is hence a crucial aspect to be scheduled into the engineering and design of future production plants. It would be much to be desired, if Si thin-film production lines were differently conceived and allowed for a certain range of formats to all run on one and the same line to prevent architects from having to plan their buildings according to a given and restrictive module size. In this respect large size amorphous Si modules of around m^2 each produced by some companies could at least offer after post processing to different sizes, interesting options for BIPV.

The developers and manufacturers of standard PV modules, that is to say mostly physicists, chemists and engineers, often present the idea that an expansion in the range of colours in which the PV modules are available will effortlessly help to open up new markets. But for many years, Si-wafers have been available in different colours and thin-film also offers that possibility by using a coloured front glass, polymers or substrates. To date, however, practice shows that these products continue to remain largely ignored and scarcely find application in the field of BIPV.

It would need a cultural-historical essay dependent on representative questionnaires to properly discuss the issue of acceptance of the use of colour in construction, among architects for example, and then this would again need to be specified according to diverse geographical regions, cultural circles and mere personal preference. Even then the results might be so disparate that it wouldn't be possible to draw any sensible, general conclusions about the acceptance of colour in BIPV. Some related studies prove that the possibility of choice would be generally welcomed by architects, but this has not yet been reflected in building practice [51]. It is shown by trend that the colours offered by the PV industry are often regarded within expert circles in the construction business as being superficial, or even as interfering 'messing about'. Building tradition remains quite dominant since the possibility of colour has been connoted as 'unclassical' and to some extent artificial by those 'architects of the Modern' who have set the tone in terms of the styles that continue to persist. The material itself should speak through its own properties and texture: concrete, tinted or untinted glass and surface-finished steel and aluminium have determined the image of large cities since the 1920s. It was not until the postmodernists of the 1980s that form and colour were again subject to a greater sense of play. Yet after this intermission, there has been a regressive tendency towards a reduction in the use of colour amidst greater complexity in the geometrics of buildings and a bias for 'using materials as they are'. In Asiatic metropolitan centres there is a greater readiness for colour, yet even here, attempts to produce spectacular accents of colour are targeted less by means of fully coloured glass-façades than they are by expressive nocturnal lighting. The extent to which this material purism – based on what are now almost 100 year-old Bauhaus traditions – seems to be so common among architects probably also derives from a unilateral and not always profoundly reflected opinion of what 'honest' and 'pure' building material is all about, and a general fear of ornament. This ambiguous issue is best illustrated with an example: concrete gets its light-grey natural colour as the result of adding the traditional cement component. Since grey is by chance associated with neutrality in the psychology of human perception, light concrete grey counts among most architects as the neutral and acceptable natural colour of this material. The possibility that exists today of adding colour to concrete is seen by most purist architects as a suspicious manipulation of the basic material and as an expensive gimmick or game playing. By contrast, working the same concrete in the direction of a semi-transparent building material, already state of the art, is followed with great interest and good will by the very same architects. In both cases, the original material, the grey concrete, undergoes a complete optical transformation and yet only one of the two transformations is seen by the architects as being something interesting, while the other is more of a useless frippery. The reason for this apparent contradiction is at hand: while the dying is interpreted as simple colouration and suspicious decoration that is heading in the direction of an ornamental no-go area, working the material in a semi-transparent direction appears to promise an additional advantage for the property, something to help brighten the interior, whilst sticking to a certain neutrality of materials.

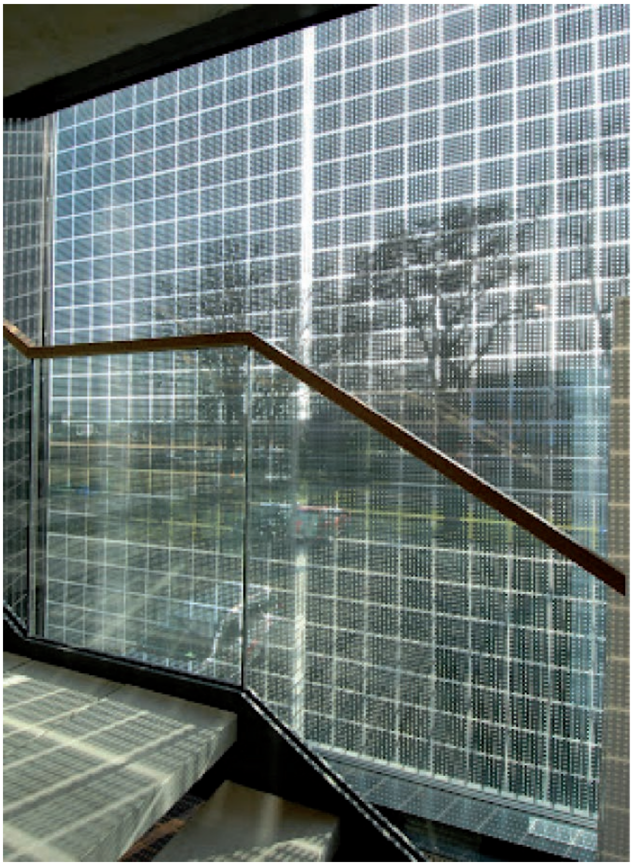


Fig. 35: The Energiewürfel (Energy Cube), the customer centre for Stadtwerke Konstanz GmbH (Germany): semi-transparent c-Si solar cells with an overall transparency level of 22% provided by the perforated c-Si wafers and the space between them (Architect: Arnold Wild, Stadtwerke Konstanz GmbH; System provider: Sunways, 2011, Photo: Ian Collins)

What does this ambivalence from the majority of architects in their judgement of one and the same building material mean for the acceptance of coloured BIPV-compatible solar panels of a particular size? It means that architects are more ready to accept colour (or its absence) when it is linked to a particular added benefit and value. Material properties such as transparency and translucency are much more sought after: windows that are also PV modules, skylights, shading elements, PV combined with insulation that provokes new light transmission effects, etc. (Fig. 35). This does not mean that all R&D efforts addressing coloured PV modules have to be switched, on the contrary. But a 'colourful' module colour alone will not be the decisive motor that will drive BIPV forward in the foreseeable future, so great is the desire for colour neutrality in the area of transparent, black, white and grey. Most Western architects will continue to prefer tinted or partly mirrored glass façades, in which atmosphere and surroundings are reflected and coloured accents are set as

Fig. 36: Pfizer-University of Granada-Junta de Andalucía Center for Genomics and Oncological Research (Spain): the ventilated solar façade combines PV elements (2,5 × 1 m each) with serigraphic glass, both specially customized for this project (System provider: Onyx Solar, 2010)

Fig. 37: The Thyssen-Krupp Steel building, Duisburg (Germany): Colourful rendering obtained by coloured steel façade elements (Product: ReflectionsOne) and vertically integrated common Si-solar panels (Surface: 1000 m^2; Energy output: 51 kWp; Colour Design: Friedrich Ernst v. Garnier, Studio für Farbentwürfe; Architects: Czerny-Gunia, Essen; System provider: ThyssenKrupp Solartec, 2002)

if by themselves, and less by colourful PV elements. Black, white and light grey are more accepted due to their neutrality and by combining them with simple coloured glass or metal panels an interesting building design can be perfectly achieved (Figs. 36 and 37). Furthermore, translucency and transparency are in demand, but there is also a need for discrete interferential coloured glass coatings to provide homogenous building shells. Those filters are in most cases still angle dependent and the colour changes from different point of views. Most architects and planners will thus continue to be critical so far as coloured PV modules are concerned and will generally reject them. One driving factor with the potential to advance the cause of BIPV will be the addition of extra properties to the PV element, such as insulation features.

So far as roofing in the private housing sector is concerned, it seems that black and terracotta are the only options suited for affordable mass production, both of which are the result of a rejection of colour based on centuries-old traditions. In addition, neutral grey may have a certain justification in the area of new builds. Moreover, in a sloping roof installation, the colour effect is largely lost on account of the sky being reflected in the front glass of the PV module, and even with the use of an anti-reflective glass, the surface of the module itself can still have the appearance of a glaring windowpane at high light grazing incidence. Following the Swiss research project ‘Archinsolar’, it has been possible to develop a terracotta-like and very homogenous a-Si module at the IMT Neuchâtel, which matches the traditional colour of clay tiles and is recommended for use in historic and landscape-sensitive zones (Figs. 38 and 39) [52]. As part of the same project, glass coating with coloured filters has been provided and has shown very promising initial results (Fig. 40). In general, further R&D activity is required to reach fully acceptable optical effects based on anti-reflective glass coatings, surface microstructure and interferencial filters.

Material and surface properties: Flexibility, homogeneity and transparency

As already discussed, various material properties and features of advanced multi-functionality will probably determine the future development of BIPV to a much greater extent than the mere use of a countless variety of colours. Solar cells (a-Si; µm-Si, DSC, OPV, CIGS) on a flexible metal or plastic substrate, manufactured mostly in roll-to-roll techniques, have long been seen as a particular candidate for use in BIPV with a promising market potential [53]. Their advantage lies in their simple, custom-produced finishing and a certain freedom for design so far as their use in curved building parts is concerned, but the manufacturers still have to struggle both with quite low efficiencies and the limited field of application. Meanwhile, flexible CIS-based cells (Copper, Indium, Selenium) are available with efficiencies of around 10%. Another persistent competitor in terms of curved solutions is c-Si embedded wafer-technology, also available in curved, rigid plastic substrates.

It is generally worth noting with flexible cells that their flexibility for use in the building envelope, which is propagated as their outstanding design advantage, is a

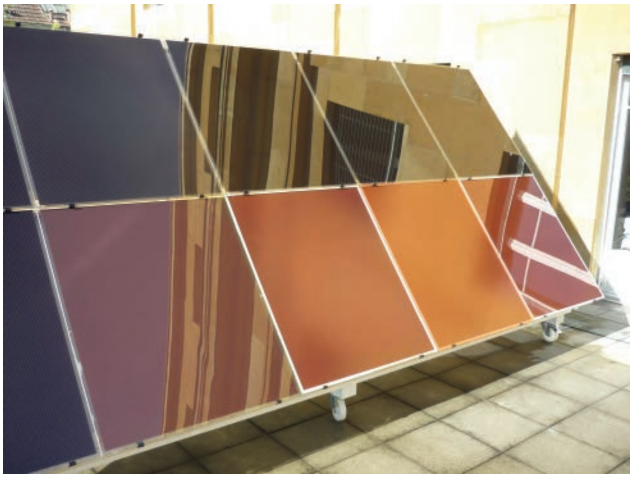


Fig. 38: Archinsolar PV-module: the first ever fully homogenous teracotta-like a-Si thin-film PV module, developed by IMT Neuchâtel (Switzerland), using a textured anti-reflective front glass (Photo: P. Heinstein).

Fig. 39: Archinsolar PV module installed for testing on a traditional roof (Photo: P. Heinstein).

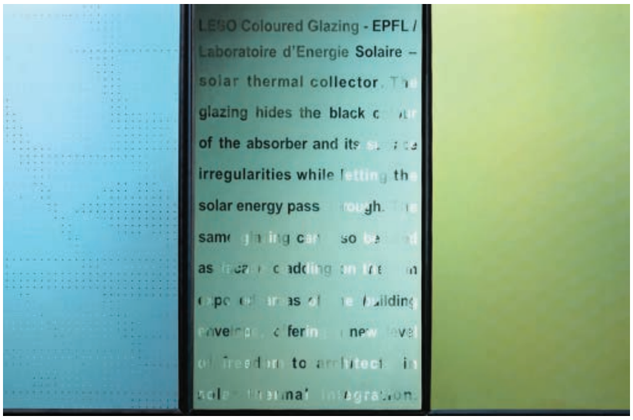


Fig. 40: Glass with interferential filters (System provider: SwissInso, Switzerland)

benefit that is scarcely ever reaped: tightly curved façade surfaces are an exception in architectonic design, where bigger radii and right-angles will continue to dominate. Hence, providing modules on rigid glass or metal substrates still appear has the most promising way to conquer notable sections of the market in the building sector. The welding-on of flexible PV runways on curved or flat industry roofs might still be a market that could be revived, including in places where the widespread use of wooden or lightweight construction methods calls for lighter roof modules.

The homogeneity of PV modules is a particular and oft-quoted reason for employing them in the building envelope. Façades that dazzle from poly-crystalline Si-solar cells in every imaginable kaleidoscopic colour and even more homogenous mono-crystalline Si modules may have their appeal (Fig. 41), but for most architects, however, they are far too overpowering and are an expression of an aesthetic handed-down from the early 1990s. Si-modules fulfil this requirement of homogeneity by having a dark backsheet applied behind the wafer pattern and thin-film modules already show a homogeneous rendering as a characteristic feature of their production process.

As mentioned several times before, translucidity and transparency are much sought after material properties in construction, since a comfortably bright building interior figures among the main demands made of living and working conditions. Gaining optimized daylighting in buildings is a basic feature for all kinds of builds. Dynamic façades with easy handling and automatic shading strategies prevent an overdose of sunlight and overheating. So, providing energy harvesting through the use of transparent or semi-transparent building elements and shading devices seems to be the most self-evident consideration in terms of BIPV (Fig. 42). Nearly all of the common PV technologies offer such properties as a highly demanded architectural feature, including c-Si, CIGS, a-Si and µm-Si, the latter by nature of the thin-film technology and most notably by different forms of laser scribing. Si-technology

Fig. 41a: Building at Quai de Valmy 179, Paris (France): seven storey façade covered with 130 customized emerald-green multicrystalline Si panels (Surface: 173,6 m^2; Energy output: 17 kWp; Architects: Emmanuel Saadi and Jean-Louis Rey, System provider: Sunways AG, 2011)

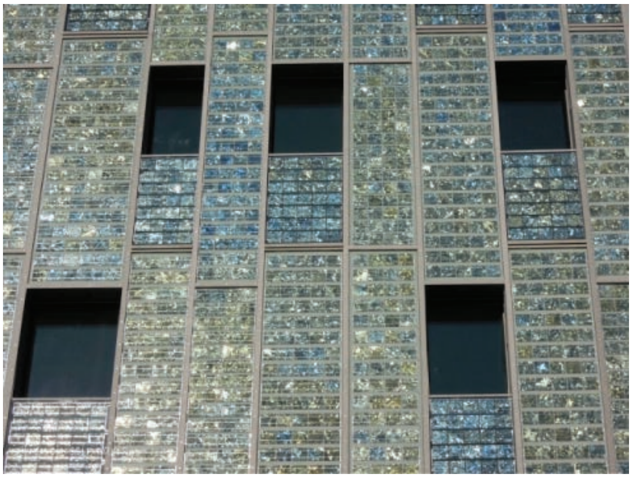


Fig. 41b: Detail

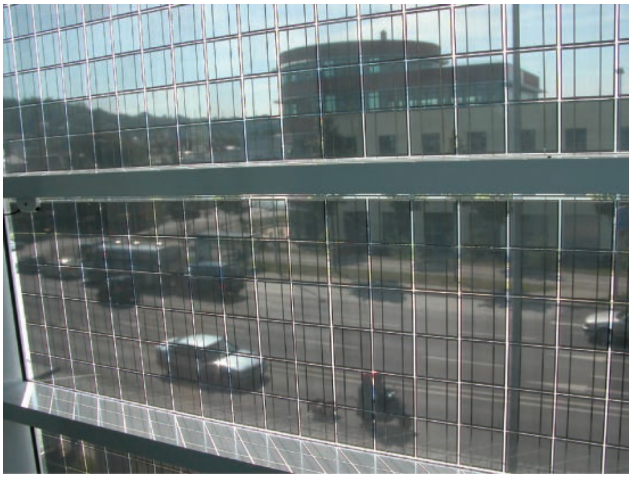


Fig. 42: Solar parking deck Bahnstadt P 7, Ravensburg (Germany): PV facade with perforated c-Si wafers (System provider: Sunways, 2005)

offers transparent solutions by encapsulating Si-wafers on transparent substrates (glass; plastic). Respecting a gap of a certain dimension between the non-transparent wafers thus allows daylight to be transmitted. But this also leads to an ever-changing pattern of shades in the interior of the building, which is sometimes rated as being disturbing. From an aesthetic point of view, most architects consider glass/glass laminated semitransparent crystalline modules with their characteristic and dominant wafer-pattern to be a less attractive and more old-fashioned architectural emblem of the very first approach towards renewables. Despite the expected decreasing thickness of silicon wafers, there is no considerable change in their visual appearance on the horizon. The PV-industry launched ambitious attempts with perforated semi-transparent Si-wafers as early as ten years ago (Fig. 43). None of these excellent products survived due to high production costs, the very limited demand at that time and the considerable loss of efficiency that came along with perforation. And exactly this points out the disadvantage inherent in any transparent or translucent PV solution: the more transparent the cell or the module, the higher the loss of efficiency. As yet, there is no solution in sight to successfully mediate between the constant demand for ever-higher cell-efficiencies and other desired features such as semi-transparency. A choice will have to be taken, since there is no silver bullet in this field. In the nearer future, a new generation of thin-film based BIPV could probably provide a wider and more differentiated range of semi-transparent applications, despite its lower cell efficiencies.

PV research activities towards ‘Luminescent Solar Concentrators’ have been discussed for many years now and might one day lead to promising, transparent BIPV windows [54]. Conventional semiconductors are here replaced by lumiphores (dots) like phosphor in order to absorb sunlight of a certain wavelength. Visually, the

Fig. 43: Boading (China 2012) semi-transparent a-Si modules with coloured polymers (Courtesy: Tianwei Solar Films; Photo: P. Heinstein)

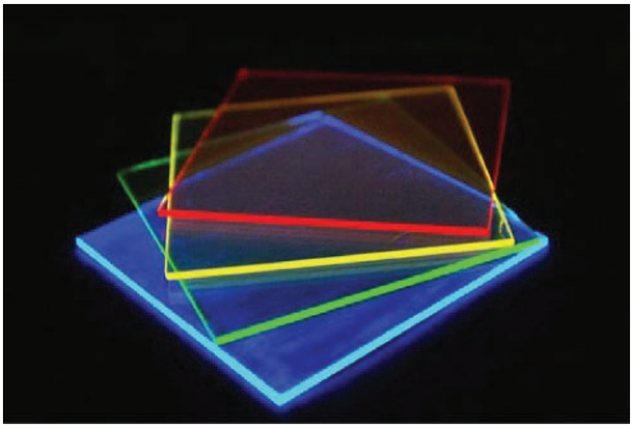


Fig. 44: Several glass panes each serving as a luminiscent solar concentrator for light of a specific wavelength.

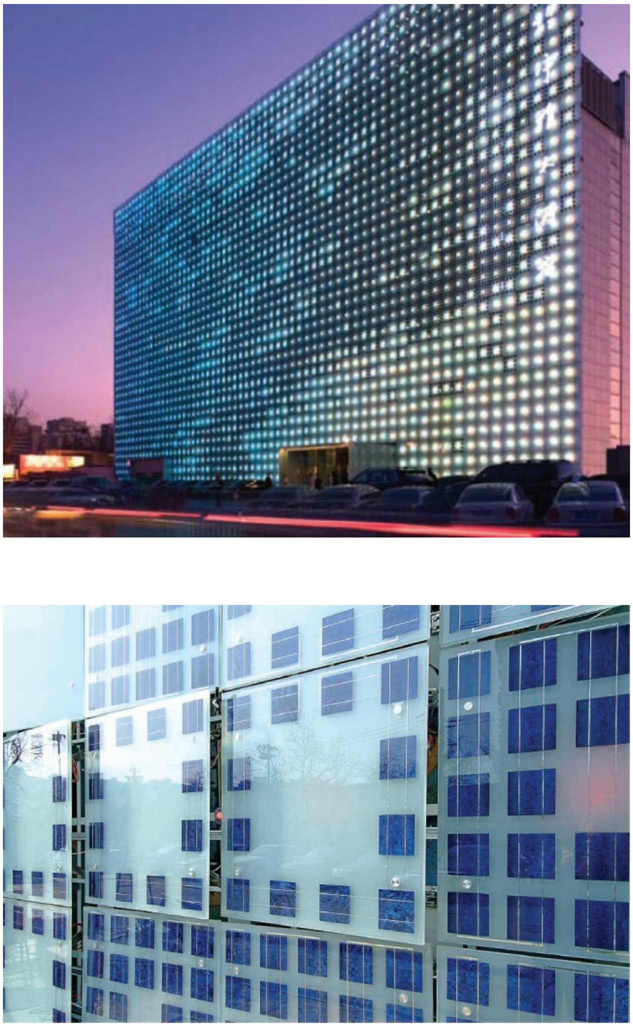


Fig. 45: Media Wall at Xicui entertainment complex, Beijing (China): combining sustainable and digital media technology, featuring the world's largest colour LED (2008)

glass screen is completely homogenous where the absorbed light is led to its edges by the lumiphores and captured by solar cells attached to the glass edges, but with a reduction in the total transmittance of the glass (Fig. 44).

Probably the "SolarWindow" project, which just has entered into the second phase of its cooperative research and development agreement between New Energy Technologies Inc. (Columbia, Maryland, USA) with the NREL will lead to promising results by advancing the development of a technology, capable of generating electricity from "homogenous" glass panels.

Solutions to combine BIPV and LED are already known since a couple of years but represent no real market share (Fig. 45). It has to be doubted if it makes sense to harvest energy to be wasted at the same time by a huge LED display.

Outlook

The increasing number of even global players that are ending their engagement with PV and BIPV shows the difficulty that there is in successfully merging photovoltaics with the construction industry. After the painful “market corrections”, new attempts and new efforts will have to be made in order to identify the aforementioned traps and to eliminate inhibiting factors. The market potential for BIPV is enormous, but there are still too many restricting factors at play. As the examples of France and Italy show, incentives still play an indispensable role in stimulating the BIPV market for residential, commercial, and public buildings. Short-term growth could be expected in the residential sector where stricter energy requirements will serve as a very powerful driver. Ever stricter national and international legal energy standards will inevitably lead to an increasing demand in BIPV products. The EU’s 20-20-20 goals (20% increase in energy efficiency, 20% reduction of CO2 emissions, and 20% renewables by 2020) all depend on the re-configuration of the European electricity grid into a ‘smart grid’. These legal conditions are fundamental for any renewable energy expansion in this economic area. Therefore, in the EU, integrated solutions will definitely but gradually contribute to the acceptance of PV, with increasing importance from 2020 on, after which no new builds are allowed to be erected without the inclusion of PV in the planning, and as of 2050, every building will have to fulfil the set standards of energy neutrality. This will push project developers, investors and architects into coming to terms with BIPV. PV will then have to be taken into account in the building planning and will replace other materials like roof tiles and passive façade elements. But this won’t lead to a perceivable breakthrough on the market before 2020: it is only when the restrictive renewable energy laws of 2021 literally force all stakeholders to change their attitude towards renewables, that the European BIPV market, now discretely on the verge of expanding, will finally emerge and boom. Other countries will follow the example of the EU. In the USA, the ambitious development of PV and BIPV underlined by the NREL-paper on ‘Net Zero Energy building’ (NZEB) will depend, besides legal directives, on the further influence of the still very powerful oil, gas and atomic industries. Psychologically, widespread activity aimed at exploiting new gas fields through hydraulic fracturing represents an inhibiting factor to the promotion of renewables in the States.

Given their specific physical properties, current PV technologies will recommend themselves for being incorporated as BIPV products in the building envelope, but it cannot yet be foreseen in exactly which direction the market will expand. A completely unexpected technological breakthrough in PV research is not yet in sight. Conditions are not yet in place for fostering BIPV, since existing and still improving technologies still need to be brought together with conventional building materials to serve as an intelligent, multifunctional composite. Different building demands and building cultures, such as construction in steel and wood, for example, will justify the parallel existence of different PV technologies and BIPV systems on the market.

A major issue for the PV industry will be to offer customised products at a competitive price that will suit the individual dimensions of any building operations. Those BIPV systems, now connoted as premium product will hence become an individually adopted mainstream: as low-cost customized roof systems in the private residential sector and high-cost customized systems for commercial and high-rise buildings, where an advanced BIPV façade technology with insulation and other properties is urgently required. The technical solutions are already there as the example of the nearly finished building of the Foundation Pierre Arnaud at Crans-Montana (Switzerland) proves (inauguration in 2013).

Mere aesthetics will also be of importance, but are not expected to be the sole driver to promote BIPV: For reasons of architectural traditions in Europe and the USA, the colour and flexibility of PV modules will continue to stand somewhat in the background, but will gain importance in China, which is culturally more open-minded towards these issues. Moreover, the surface textures and material properties of BIPV-compatible products, such as translucence and transparency will again come to the fore in façade and window construction as a result of intense cooperation between PV research and the glass/module industry. Cell efficiencies have to be improved in this segment but the generally lower efficiencies that result from semi-transparent solar units will also have to be accepted by the customer as a simple law of physics. Since the radiation angle of the sun and local climate conditions have to be taken into account individually, zones with potentially high-power energy harvesting and others with a lower expected output will be used, instead of searching for the silver bullet solution related to a single, solitary system. This new path of dual BIPV applications will then no longer be accompanied by one-dimensional and to some extent bemusing discussions on competing rates of cell efficiency and will instead open ways by which to optimize and complement the overall energy performance of a building. By this correction of traditional perspectives and mentalities products that are about to be sacrificed on the altar of efficiency records will also find their way back to the market, such as semi-transparent solar windows with lower efficiencies, or thin-film devices to cover shaded zones. Wafer based modules will be reserved for non-shaded zones with maximum sun irradiation in the same building. A uniform rendering of different PV technologies can easily be provided by the same glass coating of all those different units and so the building design remains absolutely homogenous. A lower efficiency will then no longer be the cause of 'technological embarrassment'. Second best will turn out to be best, according to the more intelligent and diversified application of each PV technology based on its physical eligibility. So a mentality of 'either X . . . or Y' will simply have to be replaced by a mentality of 'X *and* Y'.

The certification and standardization of products will also play an important role in the transition process to take BIPV from a niche to a broadly accepted application. This development has to be fostered by a better network of trained architects and installers and the increased awareness of all participants about existing products. New formal training like BIPV consultancy could play a role, but will require excellent professional training in a highly complex interdisciplinary sphere. In the traditional housing sector for in-roof installations, suppliers' success will not depend on complex and sophisticated marketing strategies, but on direct communication within the living quarters and neighbourhoods. Here, social interaction has turned out to be the main driver for PV and BIPV.

New financing concepts will be launched by energy suppliers, such as 'Energy Performance Contracting', 'On-bill-financing' (also 'Pay as you save' PAYS) and 'split incentives' that will promote the broad acceptance of renewables. The future market will be dominated by those companies who have not missed out on investing in the BIPV sector at the right time, or those who have managed to resist and survive the on-going crisis. However, there is always the chance for newcomers with a good business plan and direct marketing strategies to commercialize the innovative systems that are now being developed in labs around the world [55].

Acknowledgements: The authors acknowledge financial support of SIG-NER, CCEM-CH, Swiss Federal Office for Energy and Swiss Electric Research.

Received: May 6, 2013. Accepted: May 16, 2013.

References

[1] Energy Design Resources: Design brief building integrated photovoltaics (prepared by Architectural Energy Corporation, Boulder, California), 2004, p. 2.

[2] David Owen, Photovoltaics International, February 2013, p. 1.

[3] One example to point out here, among many others, would be the complete withdrawal of the German window manufacturer, Schüco, which offered very promising thin-film BIPV-compatible solutions.

[4] See Frost & Sullivan, 'European building integrated photovoltaics market', Report (October 2008); GTM-Research Report, August 2010; Pagliaro, M. et al: BIPV: merging the photovoltaic with the construction industry, in: *Progress in Photovoltaics*, 2010, 18: 61–72.

[5] Schwarzer, Steffen: 'Bauteil integrierte Photovoltaik: BIPV – ein Leitfaden', in Deutsche Bauzeitschrift, 59 (2011), 6, pp. 50–52.

[6] Humm, Othmar; Toggweiler, Peter, 'Photovoltaik und Architektur – Die Integration von Solarzellen in Gebäudehüllen', Ed. Bundesamt für Energiewirtschaft (BEW) und Bundesamt für Konjunkturfragen (BfK), Basel 1993.

[7] Building integrated photovoltaic systems: conference C68 of the Solar Energy Society, the University of Northumbria, 9–10 September 2006; proceedings: Pearsall, Nicola. – Machnylleth, Powys: Solar Energy Society, 1996.

[8] T. Schoen, D. Prassad, D. Ruoss, P. Eiffert, H. Sorensen: Task 7 of the IEA PV Power Systems Programme – Achievement and Outlook. 17th European Photovoltaic Solar Conference, Munich 2001.

[9] Eiffert, Patrina (1998), 'An Economic Assessment of Building Integrated Photovoltaics', PhD Dissertation, Oxford Brookes School of Architecture, 1998.

[10] Eiffert, Patrina; Kiss, Gregory J. (2000), *Building-Integrated Photovoltaic Designs for Commercial and Institutional Structures: A Source Book for Architects* (National Renewable Energy Laboratory), Golden (CO) 2000.

[11] Edited by Astrid Schneider, with a foreword by Hermann Scheer, Basel, Boston, Berlin 1996.

[12] Rexroth, Susanne (Ed.): *Gestalten mit Solarzellen. Photovoltaik in der Gebäudehülle*, Heidelberg 2002.

[13] Hagemann, Ingo B.: 'Gebäudeintegrierte Photovoltaik – architektonische Integration von Photovoltaik in die Gebäudehülle', Köln 2002.

[14] To give a selected choice: Abbate, Cinzia (Ed.): L'integrazione archittetonica del fotovoltaico; experienze compiute. Progetti dal Case Studies del Task 7, International Energy Agency, Roma 2002; Prasad, Deo Snow, Mark: Designing with Solar Power: A Source Book for Building Integrated Photovoltaics (BiPV). London 2005; 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; Cameron, A. PV's Progress: growth and potential in the BIPV industry. In: Renewable Energy World, 1 March 2007; Paolo Bosisio, Vincenzo di Dio, Alessandra Scognamiglio: Fotovoltaico negli edifici. Dimensionamento, progettazione e gestione degli impiantiMilano 2009; Mario Pagliaro, Giovanni Palmisano, Rosaria Ciriminna: BIPV. Il fotovoltaico integrato nell'edilizia.

Palermo 2009; Simon Roberts, Nicolò Guariento: *Building Integrated Photovoltaics. A Handbook.* (German title: Gebäudeintegrierte Photovoltaik, Ein Handbuch) Basel 2009; Tamasi Moyra: Panua, Rajsekhar: Building Integrated Photovoltaic (BIPV) system, Saarbrücken 2012; Jesse Russel, Ronald Cohn: Building-integrated photovoltaics, Miami 2013 (print on demand); Frederic P. Miller, Agnes F. Vandome, John McBrewster: Building-Integrated Photovoltaics. (print on demand).

[15] Bendel, Christian; Hullmann, Heinz et al: ‘Multifunktionale Nutzung photovoltaischer Anlagen’, in FSV Forschungs Verband Solarenergie, FVS Themen, 2003.

[16] ‘Building-Integrated Photovoltaics (BIPV) in the Residential Sector: an Analysis of Installed Rooftop System Prices’, Ed. National Renewable Energy Laboratory (NREL), USA, 2012.

[17] Hermannsdörfer, Ingrid; Rüb, Christine: ‘Solar Design: Photovoltaics for Old Buildings, Urban Space, Landscapes’. Photovoltaik für Altbau, Stadtraum, Landschaft. Berlin 2005.

[18] See the URL: www.pvsunrise.eu. During the Hamburg workshop in Sept. 2009, ‘The increasing role of building integrated photovoltaics’ was also discussed.

[19] See the URL: www.next-buildings.com.

[20] See Url: www.economic-forum.eu.

[21] See the 2012 and 2013 programme under the URL: www.energy-forum.com

[22] For example, the ‘JSPS Symposium Urban Planning-Sustainable Cities’, Tokyo, 12. September 2005, with a presentation by Ingo Hagemann about ‘Solar Design in Architecture and Urban Planning’. See also the ‘International Workshop on BIPV’, Nice, 30. October 2008. In addition, the ‘Fifth User Forum Thin Film Photovoltaics’ from January 2009 in Würzburg, with its own BIPV section.

[23] It took place on 7th March 2013 and presented speakers from the building industry, PV research institutes and experts from internationally operating PV consultancies.

[24] M. Pagliaro et al. 2010, p. 65.

[25] The price has fallen from 500 US Dollar in 2008 to around 20 Dollar in 2012.

[26] 21% for p-type mono-Si wafers and 23% for n-type mono-Si wafers are expected. This will lead to efficiencies at the module-level of still less than 20%, see A. G. Aberle et al., Industrial Silicon Wafer Solar Cells – Status and Trends; Green 2012; 2(c): 135–148.

[27] Peter Erk, ‘Organic based Photovoltaics. Aesthetics meets Integration’, in ‘Energy Forum Solar Building Skin’, proceedings 2012, pp. 39–41.

[28] Hagemann, Ingo B.: ‘New perspectives for BIPV with dye solar cells’ (DSC. 2nd DSC Industrialization Conference, St. Gallen (Switzerland), 11–13 September 2007.

[29] One of the best-known examples is the building of Australia’s CSIRO Energy Institute, with its orange-brown semi-transparent DSC windows.

[30] Interview with Richard Caldwell, chairman of Dyesol Ltd, PV Magazine, 28. March 2013. See the URL: www.pv-magazine.com/news/details/beitrag/dyesol-on-new-investment--grid-competitiveness-and-why-silicons-limitations-have-been-exposed_100010718/#axzz2UOv3kyBh

[31] S. De Wolf, A. Descoeudres, Z. Holman, Christophe Ballif: High-efficiency Silicon Heterojunction Solar Cells: A Review. Green, 2, 2012, 7–24.

[32] See also the report of the Euroean Photovoltaic Industry Association (EPIA) on that subject: ‘Building integrated photovoltaics. An overview of the existing products and their fields of application’; Authors Daniel Fraile Montoro; Pieterjan Vanbuggenhout, Joanna Ciesielska, Brussels 2009.

[33] At the exception of rolls of thin-film silicon modules as produced by Unisolar, and combined with TPO roofing membranes.

[34] See the talk by Bart de Boer from TNO (Netherlands Organisation for Applied Scientific Research) about that very subject during the 7th Energy Forum on Solar Skins at Bressanone (Italy) on Dec. 6th 2012.

[35] See Maria Konstantoglou: ‘Dynamic building envelopes’, Energy Forum Solar Building Skins, proceedings 2012, pp. 9–13; Bart de Boer, ‘Climate adaptive building shells’, ibid, pp. 15–19; Bart Janssens: ‘Flexibility options for building skin design’, ibid, pp. 21–25; Tilman E. Kuhn: New building-integrated solar façade components, ibid, pp. 27–31.

[36] Tilman E. Kuhn: ‘New building-integrated solar façade components’, Energy Forum Solar Building Skins, proceedings 2012, pp. 27–31.

[37] For Austria in 2001, this was around 2% of the building stock, including extensions and loft conversions. Source: Statistik Austria 2001. All figures regarding Austria are taken from the paper ‘GIPV in Österreich, heutige Barrieren und Rahmenbedingungen’, by Franz Tragner, (Sustainable Projects). The paper was presented on 19th Oct. 2012 at the 10th. Austrian Photovoltaic Seminar in Laxenburg, see URL: www.energiesystemederzukunft.at/edz_pdf/events/20121019_pvtagung_10_tragner.pdf

[38] http://de.statista.com/statistik/daten/studie/70094/umfrage/wohngebaeude-bestand-in-deutschland-seit-1994/

[39] See ‘Positionspapier Bauwerkintegrierte Photovoltaik Systeme’ (February 2012), from the Bundesverbandes Bausysteme e. V.

[40] Potential for Building Integrated Photovoltaics. Technical Report International Energy Agency (IEA), PVPS T7-4: 2002.

[41] See the explanations on that subject by Andreas Karweger: ‘Markt Solarfassaden. Neue Ansätze können Wende am Markt bringen’, in ‘Sonne, Wind und Wärme’, 16/2011, 26–30, here p. 27.

[42] Wirth, Harry Aktuelle Fakten zur Photovoltaik in Deutschland. Fraunhofer ISE; current data see under the URL: www.pv-fakten.de

[43] Interview with Richard Caldwell, chairman of Dyesol Ltd, PV Magazine, 28. March 2013. See the URL: www.pv-magazine.com/news/details/beitrag/dyesol-on-new-investment--grid-competitiveness-and-why-silicons-limitations-have-been-exposed_100010718/#axzz2UOv3kyBh

[44] Rode, Johannes, ‘The evolution of BIPV in Germany and France. Building integrated photovoltaics in the German and French technological innovation systems for solar cells’, Köln 2009.

[45] In 2011 BIPV installations had a share of 6.7% of all PV installation made that year. In Spain it was at 2%. These are divided into 4.6% with roof-integrated and 2.1% façade integrated systems. 83.4% of all new installations each year fall to conventional BAPV roof-installations. See, ‘GIPV in Österreich, heutige Barrieren und Rahmenbedingungen’, by Franz Tragner, (Tatwort, nachhaltige Projekte). The speech was delivered on the 19th October 2012 in Laxenburg, Austria, at the 10th Austrian PV symposium, See URL:

www.energiesystemederzukunft.at/edz_pdf/events/20121019_pvtagung_10_tragner.pdf

[46] Informal notice from David Stickelberger, Swissolar, Zürich. There are only estimates available for the numbers of BIPV systems in Switzerland, the official figures were only published after going to print in June 2013. At the end of 2011 there were only around 14.000 systems with a capacity of 188 MWp, see Schweizerische Gesamtenergiestatistik 2011, URL: www.solarch.ch/main/Show$Id=313.html

[47] Informal notice from 3-S Photovoltaics, Mayer & Burger Group, Thun, Switzerland.

[48] 'Arbeitsblatt 37, Solaranlagen und Denkmalschutz', Vereinigung der Landesdenkmalpfleger in der Bundesrepublik Deutschland, (spring 2010).

[49] Ibid.

[50] Ibid.

[51] Christina Munari-Probst: Architectural integration and design of solar thermal systems. PhD Thesis, Lausanne 2011.

[52] See the CCEM Annual Activity Report 2012, pp. 59–61.

[53] Pagliaro, M., Palmisiano, G, Ciriminna, R., 'Flexible Solar Cells', Weinheim 2008; Marsh, G: 'Innovation puts spotlight on solar', in 'Renewable Energy Focus 2008'; 9: 62; Bichsel, F.: 'Flexible photovoltaics. Building integration is our business', Flexcell, Yverdon Les Bains (CH) 2008.

[54] See, for example, the papers of Dick K. G. de Boer et al. from Philips Research, Eindhoven, the Netherlands, on the subject, e.g., 'Progress in phosphors and filters for luminescent solar concentrators', Optics Express, Vol. 20, Issue S3, pp. A395–A405 (2012); also the research of Sue Carter, University of California, Santa Cruz.

[55] In Switzerland some of the key institutions on PV and BIPV are the PV-lab (part of IMT Neuchâtel) of the Ecole Polytechnique Fédéral de Lausanne (EPFL) and the newly established CSEM PV-center, both located on a single campus in Neuchâtel and directed by Prof. Christophe Ballif. Pioneering activities in BIPV took place at the LESO laboratory of EPFL in Lausanne (Prof. Jean-Louis Scartezzini).

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