BUILDING INTEGRATED PHOTOVOLTAICS
Technology Status

by

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Building integrated photovoltaics modules provide a high degree of design possibilities and additional functionalities in combination with the plain electricity generation well known for standard photovoltaic installations. Consequently, the specialized know-how to understand building integrated photovoltaics, properly design and manufacture them requires much more than the electrical knowledge developed and applied in standard photovoltaic systems. Expertise of building physics and building regulations are also required on a high level. As building integrated photovoltaics modules are usually custom designed, typical electrical design and simulationols cannot be used without modifications, while deeper insight of complex shading influences and specialized overall system design are advantageous. Authors of this publication were involved in well over 1000 building integrated photovoltaics system designs and developments, and their experiences are shared. Recurring questions, issues and mistakes of various building integrated photovoltaics projects are touched, whereas special emphasis is provided on building integrated photovoltaics engineering procedures, system design complexity, as well as shading issues and differentiation of shading according to their origin.

Key words: *building integrated photovoltaics, building envelope/skin, façade shading, colors*

Introduction

Thirty years after the invention and introduction of the first solar photovoltaic (PV) cell by US Bell Labs, first PV modules were pioneered in 1982 by Herzog, who integrated them into the building skin. Since then vast number of projects worldwide have been equipped with, so called, building integrated photovoltaic (BIPV) modules. In October 2016 even the dedicated European standard – EN 50583 – *Photovoltaics in buildings* was introduced that provided guidance on which building regulations should be considered when designing, planning, manufacturing and installing BIPV modules in one of the various possible locations of the building envelope. Nevertheless, BIPV elements are still considered to be relatively expensive and complicated.

In case of BIPV systems, a building envelope itself acts as a support structure for solar PV modules, and at the same time, PV modules can be an integral part of the building skin. Costs can be shaved from PV installations not only by tying them into the utility power grid, but also by means of design features that lower construction costs. Additionally, BIPV elements

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provide aesthetics and a significant marketing value. Using the PV system as the building's weathering skin, such as glazing, eliminates the need for an additional façade, windows or roof, thus displacing conventional building materials and labor costs. Photovoltaics is playing a significant role in todays and the future built environment.

Due to integration of state-of-the-art technology, modern glass façades can undertake various functions. Building façades are on one side regulating inside climate or air-conditioning, as well as considerably reducing the buildings' energy requirements. On the other hand, building envelope integrated PV elements can perform onsite green energy generation.

The planning and construction of innovative buildings is today decisively determined by the requirement of maximum energy efficiency. The European Parliament Directive recommends that all new buildings will have to be *nearly net zero energy* by 2022. In this regard the focus is on the development of architecturally attractive buildings, which combine minimum primary energy requirements with maximum user benefits and convenience, as well as onsite energy generation. Great flexibility along with the highest degree of energy efficiency is provided by glass façades of the newest generation. In addition their weather-proof characteristics, these multifunctional façades also assume the functions of energy generation, heating, and cooling. The BIPV systems clearly have great potential for building applications, because they can be installed on a wide range of exterior surfaces and be integrated into variety of roofs and façades. Combining energy production with other functions of the building envelope, such as Sun shading, thermal and acoustic insulation, and weatherproofing, makes PV systems more attractive. Cost savings achieved through these combined functions can be substantial. Using buildings to generate electricity makes sense, as high value land can perform the additional function of generating electricity at the point of use, avoiding transmission and distribution losses. The BIPV systems are the ideal solution uniting both criteria, while offering a variety of new approaches.

Approximately 75% of the energy used in developed world is consumed in cities, and up to 40% of that energy is used in buildings. Today's buildings should not be used just for housing. Homes and offices have traditionally had very little built-in intelligence. However, new advanced systems and devices are increasingly being added. A general agreement is arising that tighter controls are needed on the effects on our environment and that people should use more energy efficient systems. The electrical demand of a large office building usually exceeds the production of a solar power system installed on it, meaning that all solar electricity produced can be used within the building. In this way, the solar power system reduces the building's external energy demand and thus reduce operations costs since the solar generated electricity is cheaper than the electricity provided by the utility. Commercial buildings are a very attractive application for PV [1]. Solar modules lend themselves to various uses, where they can replace more expensive building surfaces – and even offer additional benefits. For example, in façades they can easily be substituted for mirrored or stained glass, while at the same time generating electricity. In addition, they could even perform additional functions, such as providing shading and insulation. In BIPV applications, the cost per unit area of the solar power elements is of great importance, since PV materials can act as a substitute for other building materials. The effective additional cost per unit area of the BIPV elements is the difference between the price of PV modules and the material they could replace. A solar electric grid-connected system cost could be comparable per square meter to high end façade materials, such as marble. In suitable cases, where the two material costs are roughly the same, the added bonus of BIPV is that the solar electricity comes free of charge. Demands are being placed on architects and the construction industry to develop more environmentally sustainable buildings with better energy efficiency. On the other hand, people want to live and work in attractive surroundings. The BIPV systems are the ideal solution uniting both criteria, while offering a variety of new approaches. From an architectural, technical and financial point of view, PV in buildings today:

- does not require any extra land area and can be utilized also in densely populated areas,
- does not require any additional infrastructure installations,
- can provide electricity during peak times and thus reduce the utility's peak delivery requirements,
- may reduce transmission and distribution losses,
- may cover all or a significant part of the electricity consumption of the corresponding building,
- may replace conventional building materials and thus serve dual role, which enhances faster pay-back,
- can provide an improved aesthetic appearance in an innovative way,
- can be integrated with the maintenance, control and operation of the other systems in the building, and
- can provide reduced planning costs.

The BIPV integration techniques

The imagination of architects and BIPV system designers is the only limitation on how some of the BIPV products, that exist on the market today, could be integrated into the building envelope [2]. Numerous building integration techniques could be utilized for a seamless BIPV module incorporation targeting various building skin locations, fig. 1.

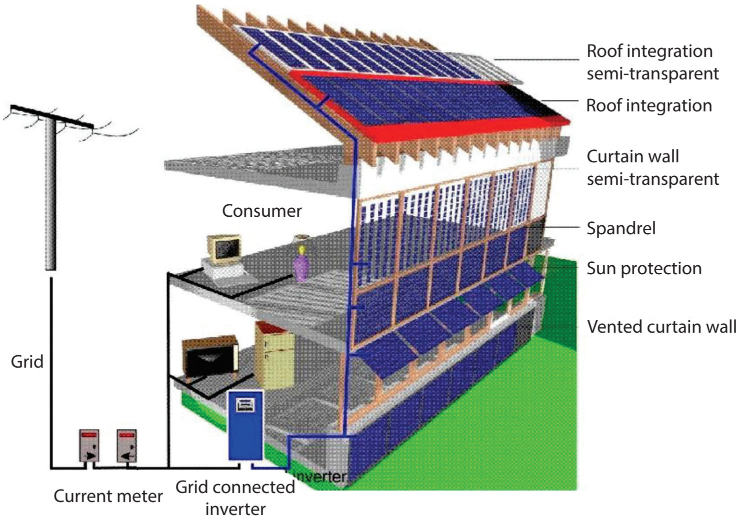

Figure 1. Possible BIPV module locations in the building envelope

The solar industry has long envisioned the integration of solar modules into building design (PV cladding) as an elegant way to deliver electrical energy to buildings, fig. 2. The appeal of integrating PV into building materials is that the structure itself becomes an energy producer, providing some or all of the building's electrical energy requirements. When PV power generation is combined with high performance building products and conservation strategies, fully sustainable building energy designs become possible**.** In addition production of electricity for buildings, the PV modules can serve as the roof, or exterior cladding of the façade. They can also be used as sunshades, combining electricity production and Sun protection, or together with conventional glazing to blend electricity production with heat insulation or noise protection [3].

Figure 2. The PV in buildings

Sloped or pitched roofs are often the preferred location for BIPV modules for three reasons. First, incident solar radiation is greatest on south-facing sloped roofs (or North facing in the Southern Hemisphere). Second, roofs are usually relatively free of obstructions, so that large areas of PV modules can be easily installed without custom shaped panels. Finally, the PV modules can replace the conventional roofing system, thereby saving roofing costs. Whether with slate, clay or polymer tiles, fig. 3, a roof can be covered in the conventional way. The crucial difference, however, is that the regular tiles with their special adoption slots, are prepared for the direct integration of the matching PV modules. The main advantage of these PV tiles is that a separate supporting structure is not required for the PV modules, and the roof becomes a solar power station.

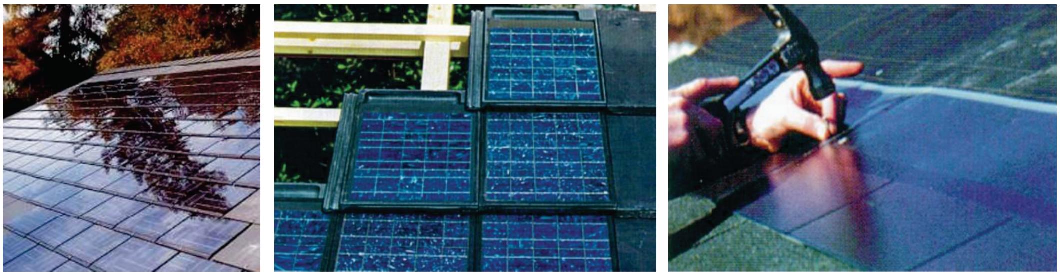

Figure 3. Slate, clay, and polymer PV roofing elements

Façade glazed cladding is today's most interesting PV building integration alternative, fig. 4. The trend in PV modules production is to replace the regular glazed wall construction elements with BIPV modules, which will at the same time generate power. Another application of PV building integration is a curtain wall. While the vertical curtain wall is not optimized for energy production, it offers one of the most attractive opportunities for PV utilization. Most commercial buildings today use curtain wall construction for the exterior envelope. They consist of a wall framing system that is attached to the building structure. The framing system is modular with both vision (transparent) and spandrel (opaque) panels. The BIPV modules can be seamlessly integrated in standard commercial building curtain wall construction. Architects can specify the color and pattern of solar cells, as well as of the back-sheet glass. It is also possible to integrate BIPV laminates into the double-glazed units. Wiring for the BIPV elements can be easily run through the curtain wall mullions.

The PV modules may provide energy benefits beyond the electricity they generate by providing passive solar heating or cooling load reduction and solar/light control [4]. Opaque PV modules installed as window awnings, or partial PV skylight enclosures and sunshades will shade interior spaces from direct sunlight while simultaneously harnessing

Figure 4. The BIPV façade cladding

sun power, fig. 5. Most of windows need some method of solar/light control. Often this is done with interior drapes or blinds. The disadvantage of these shading devices is that the solar gains still end up in the space and the view to the outdoors is restricted or eliminated. A glazed awning containing a BIPV system is a very viable alternative. The awning can be sloped for maximum solar collection and can provide a filtered light similar to the atria glazing to the interior. A variety of PV materials can be mounted on a façade in aesthetic manner to serve as awnings. Similarly, BIPV elements can serve as a window overhang (instead of awnings) or as a cover over entranceways or walkways [5].

Figure 5. The BIPV Sun shading and light control elements

The BIPV glass element that provides different degrees of shading can be designed to enhance indoor thermal comfort, as well as daylighting. The BIPV modules can be either solid, used where no light transmission is required, or semi-transparent, used as a light screening material where some solar transmission is desired, such as in atria, reducing cooling loads and the need for interior shades [6].

The PV light shelves can shield direct Sun while providing diffuse, indirect light to the interior of buildings. The portion of these light shelves which are exposed to sunlight would be PV and the portion in shade could be any reflective material. The modules surface would bounce light on the ceiling inside the building [7]. Another PV device with some passive solar benefits is the semi-transparent PV module, or PV window, designed to admit a specific amount of light and/or view to a space, fig. 6. Some amorphous silicon thin-film PV devices are inherently semi-transparent if produced with clear conductive coatings on glass substrates. Alternately, opaque PV devices may be rendered effectively transparent by the creation of a pattern of clear areas where the opaque materials have been removed [8]. With a less active PV area, the solar performance of these semi-transparent modules will be less than opaque PV elements, but the passive benefits and vision which is produced in some cases will outweigh the reduction in efficiency.

Figure 6. The PV windows

The immediate future for building integrated PV looks very promising. There are also some innovative PV systems integrated with other *built forms* such as PV systems integrated with sound barriers along highways, fig. 7. The integration of PV and noise protection elements, in order to achieve a structure of harmonic façade character, require novel design for noise protection barriers. Customized PV elements have to be developed to adopt a double function for both electricity generation and noise protection.

Figure 7. The PV sound barriers

The roof tops and façades of buildings are highly suited for incorporation of solar PV elements. However, building façades must be attractive as well as functional, therefore, offering product in a range of colors and styles will assist in the widespread adoption of the technology by architects and designers. Colored solar cells and modules are not the limiting factor for PV applications any more [9]. Figure 8 shows colored BIPV elements which incorporate crystalline silicon (c-Si) solar PV cells.

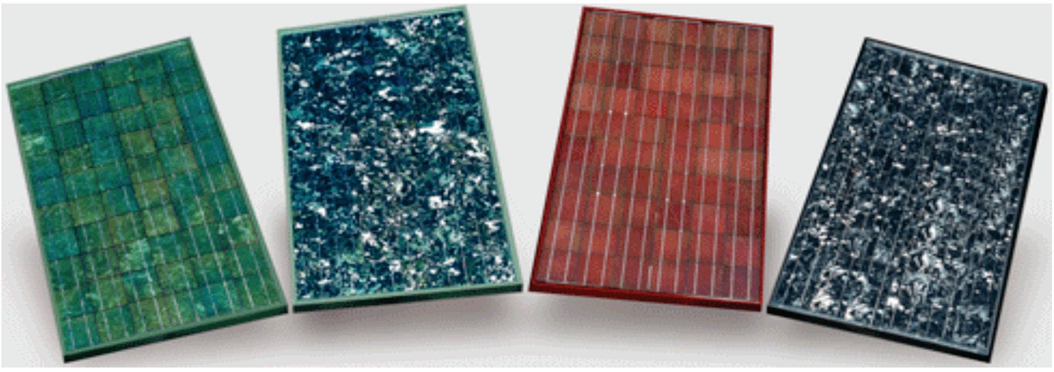

Figure 8. Colored crystalline silicon BIPV modules

Similarly, thin-film BIPV elements are also achievable in various colors and patterns, fig. 9.

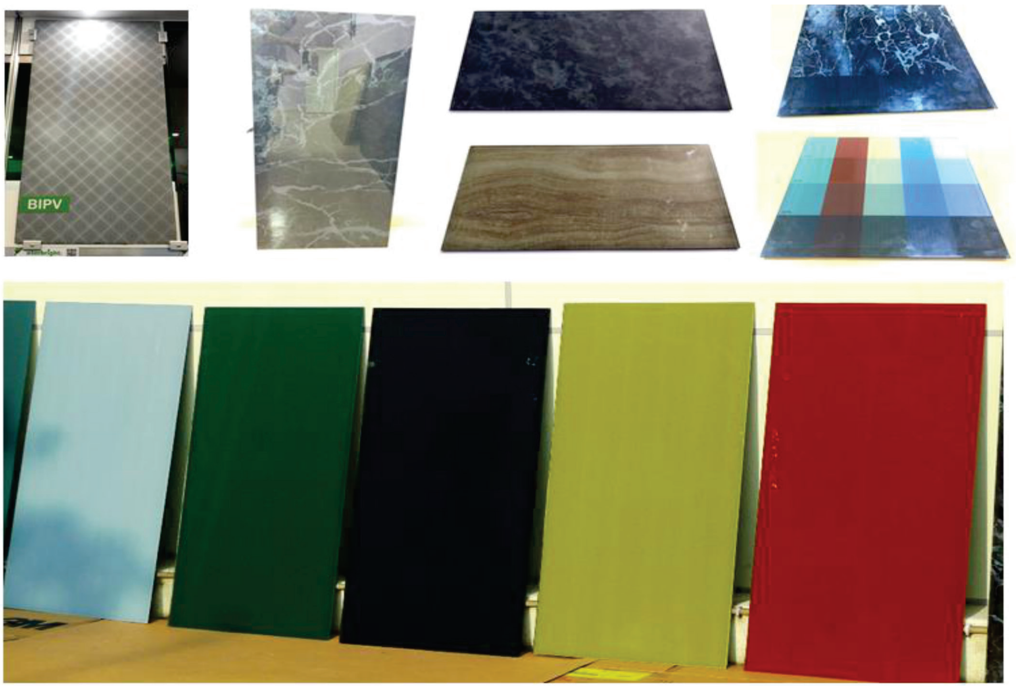

Figure 9. Colored thin-film BIPV modules

Customized BIPV system engineering

A PV system total generated power involves two-components: the product of irradiance multiplied by its nominal performance, and various loss factors which alter the mentioned product (the proportion between the generated power and the estimated maximum power). Some of the loss factors are: irradiance, shading, reflection, temperature, radiation spectrum, dirt, dispersion or mismatch, wiring and connections. The PV systems are affected with different intensity by these factors.

The procedure of systems engineering in standard PV systems is highly predefined by specified products – PV modules, inverter and mounting structure. The objective is commonly not to achieve the highest energy yield, but rather to achieve highest revenue at given boundary conditions [10]. Typical boundary conditions are:

- specified budget,
- given area,
- products that are preset to be utilized,
- availability of required product, and
- legal regulations, such as feed-in-tariff, minimum or maximum system size*, etc.*

Thus, the standard PV system engineering contains mainly the choice and combination of predefined standard products that cannot be modified. In contrast, system engineering of BIPV installations is usually customized iteration type of process where BIPV products are designed to provide the multi-functionality that is either required to provide a specific functionality or performance of the building. In addition, the BIPV products are often predefined by the envisioned design of the architect. Depending on the specific building design the required BIPV element might be significantly different from module to module even within particular system [11].

Figure 10. The BIPV system comprising of 28 different BIPV modules

As an example of a complex BIPV system set-up, fig. 10 provides illustration of the BIPV system with extremely diverse design of BIPV elements within specific installation. The particular system consists of 28 completely different units. The customized BIPV modules are mounted in four slightly different orientations. Seven BIPV modules are set-up as double-glazing units conventionally linearly mounted on a skylight substructure. Three BIPV modules comprise of a combination of double-glazing and laminated set-up. The double-glazing part of these three BIPV modules is linearly mounted whereas the cantilevering part is mounted using special bolting system. The remaining 18 BIPV modules are glass laminates, which are also mounted using different bolting system. The architects design required the following:

- solar cell alignment in both directions regardless of the BIPV modules tilting angle,
- continuation of the solar cell pattern regardless of the distance between BIPV modules,
- full area coverage of the BIPV glass using cut to fit inactive solar cells,
- specialized BIPV glazing bolting, as well as at the sloped glass edges, and
- maximization of the active solar cell coverage due to relatively restrictive available system space,

The customized system engineering of this particular example BIPV system is an iteration loop of some of the following steps:

- mechanical glass lites dimensioning,
- distinctive definition of the bolting placement to minimize mechanical loads in order to reduce the glass thicknesses,
- specifying the location of the active solar cell coverage,
- definition of the electrical interconnections within and between the BIPV elements,
- determination of g- and U-value, as well as shading coefficient of the double-glazing surface, and the cantilevering of laminated glass area, and
- calculation of the annual energy yield.

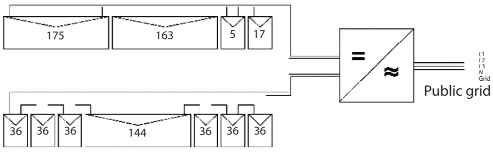

Figure 11. Example of an advanced BIPV system lay-out comprising of BIPV modules with different number of solar cells per module [12]

In contrast to the assumption that the mechanical or design premises would be very complicated, it turned out that the electrical design was the most complicated part. The reason behind is that there are no electrical system design tools available in which BIPV modules with different electrical properties could be combined. In the design software for standard PV systems only PV modules of identical electrical set-up can be connected in series. A system design or simulation of a BIPV system with non-conventional set-up shown in fig. 11 is not possible with conventional PV simulationols, which are commonly provided by an inverter manufacturer.

Additionally, in conventional electrical design software the PV module temperature is commonly assumed to be constant throughout the entire PV array. This BIPV system created with BIPV elements contains – even within single BIPV module – significantly different module temperatures due to their glass set-up being laminated or double-glazed.

As a consequence, completely custom BIPV electrical array design tool has been developed. In this tool up to 25 BIPV modules of different sizes and electrical characteristics can be freely combined. The resulting voltage – current (I-V) curves are graphically combined with the I-V operation range of a suitable and locally available inverter. The developed primary level electrical design is based on the verification of the three crucial design criteria in BIPV systems which are the following:

- is the BIPV system voltage open-circuit voltage (V_{OC}) at the lowest design temperature T_{MIN} of the BIPV system, lower than the highest permissive inverter input voltage (this argument is illustrated in blue in fig. 12),
- is the system maximum power point voltage (V_{MPP}) at the highest design temperature T_{MAX} of the BIPV system, higher than the lowest permissive inverter input voltage? (this argument is illustrated in yellow in fig. 12), and
- is the system maximum power point current (I_{MPP}) at the standard test conditions (STC) of the BIPV system, lower than the permissive inverter current at V_{MPP} (this argument is illustrated in red in fig. 12),

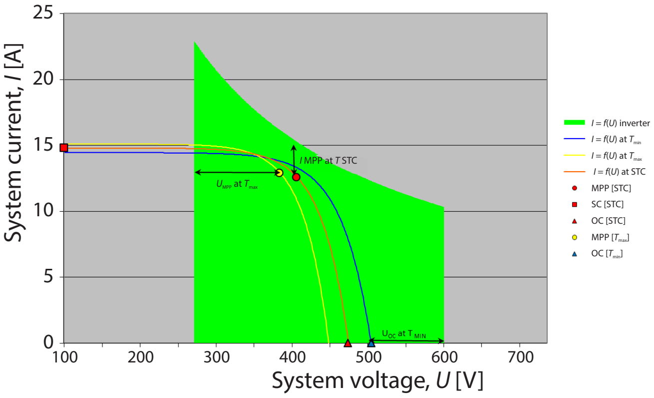

Figure 12. Superposition of the BIPV system operating range (three lines: yellow at T_{MIN}, red at STC, blue at T_{MAX}) and inverter operating range (area in green) with characteristic design criteria points V_{OC} at T_{MAX}, U_{MPP} at T_{MIN} and I_{MPP} at STC

This higher-level electrical design then considers mismatch effects resulting from a non-identical BIPV module orientation, as well as BIPV module temperatures in correlation with onsite irradiation distribution, possible shading due to adjacent buildings*, etc.*

Shading of BIPV modules

The BIPV systems are in comparison roof-top or ground mounted PV systems much more likely to encounter shading for the simple reason that conventional PV systems are exclusively designed in the way that their electrical performance and cost effectiveness are prevailing [13]. Hence, anything possible is done to omit any potential shading. The shading conditions that BIPV systems possibly encounter is differentiated according to their origin, figs. 13-22:

- micro-shading – shading of the PV module is caused by components of the PV module itself,
- mezzo-shading – shading is caused by components of the PV system or the building, and
- macro-shading – shading is caused by external objects, such as trees or adjacent buildings.

Figure 13 shows the detail of a BIPV module that contains two electrically separated cell arrays, – left and right sections. The inter-cell distance throughout the entire solar cell area, and between the two sections, is 2 mm, while string interconnector has 5 mm space gap. As the 2 mm cell distance is too small, the electrical connector from two adjacent strings had to be placed in front of the solar cell. As a consequence, the connector causes permanent shading of approximately 5% on the solar cells, which has in this specific case dimensions of 100 x 100 mm. The annual energy loss is just due to this specific design issue 5% lower than a non-shaded BIPV module could supply.

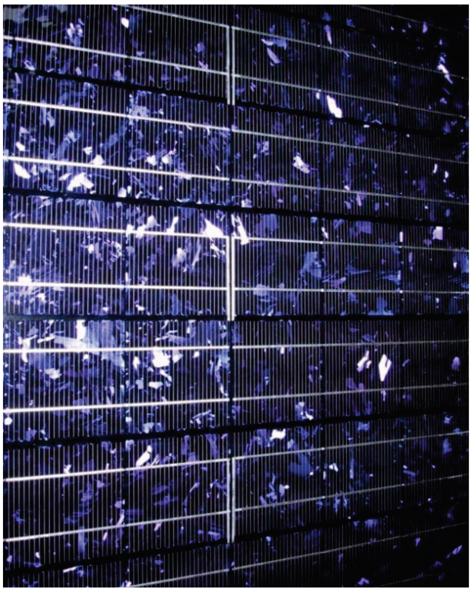

Figure 13. Micro-shading caused by the string connectors

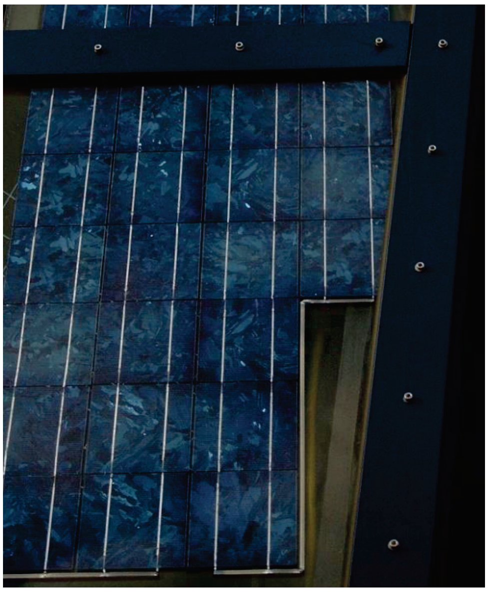

Figure 14. Mezzo-shading caused by over-sized cover caps of the mounting structure

Figure 14 shows a BIPV module that is permanently shaded by the oversized pressure plate of the façade mounted BIPV array.

Figure 15 shows a typical example of the installation of two products that originally were not designed to be combined. The BIPV element is actually standard size 36 cell typical PV laminate. Such PV modules are mounted as façade infill elements using a conventional façade system. The standard PV module originally has been designed to be mounted using a circumferential aluminum frame, which has a glass bite of typically 2 to 3 mm, which permits enough spacing so that solar cells would not be shaded. Conventional glazing in façade systems has in contrast a typical glass bite of 10 mm. Consequently, the distance between solar cells and the cover cap (pressure plate) of the façade system is too small, which creates the circumstance at which solar cells in the top row of the PV module face continuous shading by the building envelope framing structure. Similarly, left and right solar cell columns are shaded in the morning and evening hours.

Figure 15. Mezzo-shading caused by a too small distance between solar cell and glass edge

A similar mezzo-shading caused by inadequate solar cell - glass edge distances can also be observed for the top row solar cells shown in fig. 14. In this case the reason for this fault is not the unsuitable combination of products, but rather lack of communication between façade integrator and the BIPV module manufacturer. The façade framing and the BIPV modules have been originally designed for the use in a façade system of 60 mm width. The façade contractor that supplied the system accidently used a 120 mm wide façade system without prior notice not anticipating any potential problems this might cause.

In comparison this fig. 16 shows the example of a good communication between architects, façade specialist, BIPV consultant and manufacturer of BIPV modules. The architects' façade design required cantilevering exterior cover caps to provide a strong and dominant horizontal patterning of the specialized BIPV façade. At the same time, it was considered essential to maintain a homogenous repetition pattern of solar cells and façade construction from the inside by keeping the distance between solar cell array within each BIPV glass unit and the façade structure quite even, fig. 17. As the BIPV system is oriented due South the cantilevering cover caps obviously cause a continuous shading of solar cells in each top row of BIPV modules. During summer time and even in the spring and fall a significant shading cannot be omitted.

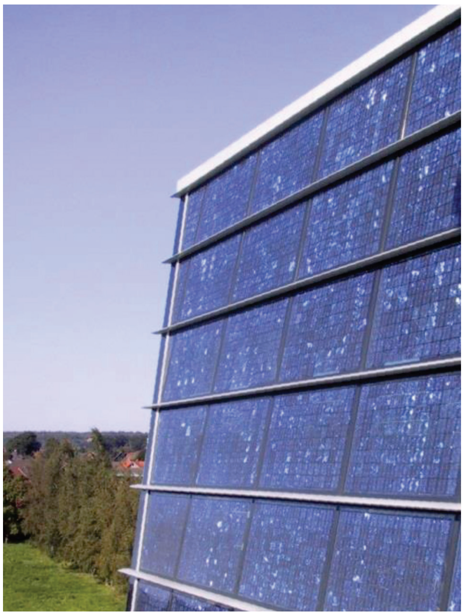

Figure 16. The BIPV façade with cantilevering cover caps to highlight horizontal patterning

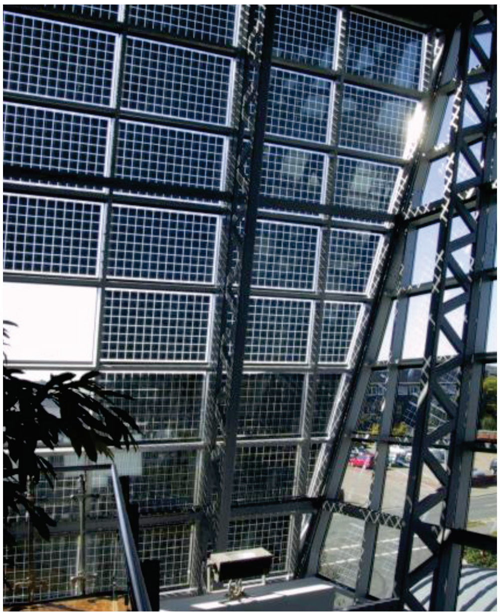

Figure 17. View from exterior of the same façade

The unconventional solution this design *vs*. power output setback is to incorporate inactive solar cells in the top row of each BIPV element. Thus, the shading by the cantilevering cover cap does not affect the rest of active solar cells. Considering that each BIPV module only had 8 rows of solar cells per module, the power output was reduced by 12,5%, but the remaining system operates without shading. Interestingly, the BIPV array simulationol calculating system performance without inactive solar cells forecasted an annual loss of approximately 70%.

The necessity of integrating inactive PV cells into the top row of BIPV modules complicated manufacturing of the modules to the extent that the reduced material price for inactive cells was more than compensated in power loses.

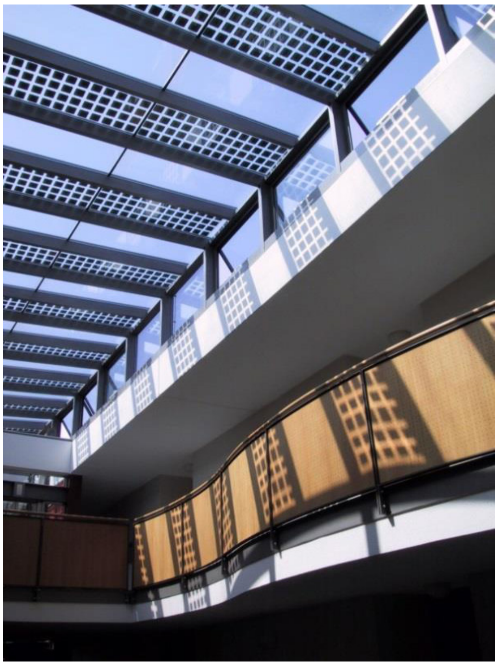

Figure 18. The BIPV skylight comprising an alternating pattern of glass and BIPV modules

In many countries metal mounting structures that are mounted either on the building envelope or serve as building skin – such as façade structures – are required to be electrically grounded in order to prevent electrical hazards to person on, within or next to a building. In addition, roofs are often equipped with an array of lightning protection ropes. Exposed locations such as eaves, ridges or building corners are equipped with lightning protection rods (LPR). The LPR protrude significantly the building envelopes surface in order to attract lightning strikes and thus to protect the building structure underneath. Roof openings, such as skylight windows or skylight structures, illustrated in fig. 18 provide the possibility for lightning strikes to enter into the building rather than to propagate on the buildings surface. For that reason, these openings are specifically equipped with LPR to prevent lightning entering the building. The number, diameter, location and the length of the LPR are subject to local building and electrical codes.

Figure 19 shows LPR used in the BIPV system showed in fig. 18, which causes a significant shadow on the adjacent BIPV module in the morning hours. The corresponding LPR on the other side of the skylight causes likewise a shadow in the evening hours. With few hours around noon time, the lightning protection system as installed causes an almost continuous shading.

This mezzo-shading could easily be omitted if involved consultant communicated properly. Problem could have been resolved by either installing the LPR on the Northern side of the BIPV array, thus their shadow would be affecting the clear glazing side, or by cranking the one row of LPR towards East, and the other row towards the West. The LPR shadow would then be much shorter and could not cause shading on the BIPV modules. The reduced height of the LPR over the building surface then would have to be compensated by using a correspondingly longer rod.

The lack of communication between different trades, and the lack of PV specific know-how is not only an issue during the erection of a building, but also during renovation operations. Figure 20 illustrates how modifications during renovation work, such as installation of exterior shading blinds, interfere with the façade integrated PV modules.

Macro-shading, fig. 21, could be instigated by external objects, such as trees or adjacent buildings [14]. Early in the design phase, it is advisable to ensure that BIPV elements receive maximum exposure to the Sun and will not be shaded by various site obstructions. The shading impact on a BIPV array has a much greater influence on the electrical harvest than the footprint of the shadow.

When analyzing potential complexity of shading on BIPV systems, it would also be interesting to consider temporary obstacles, fig. 22, as one of the most unpredictable shading influences.

Figure 19. The LPR causing a shadow on the adjacent PV module

Figure 20. Exterior shading blinds installed during building renovation not considering the shading of the adjacent BIPV modules

The BIPV modules and colors

The saying you can get PV modules in any color as long as they are black, blue or *brown* was a common joke at conferences, BIPV system design courses, and architects' discussions. And it was true as colored solar PV cells were available only at a prohibitively high price. Only very expensive highly customized specialized BIPV modules were accessible in the past, fig. 23.

Figure 21. Macro-shading of BIPV modules due to adjacent buildings

Figure 22. Shading due to temporary obstacles

Figure 23. The PV modules with colored PV cells and colored matching glass exhibited at the *glass technology-live* at the Glasstec fair in Dusseldorf, Germany, 2016

The reasons for the higher price of colored PV devices in the past are diverse, and result from some of the following arguments:

- Conventional PV cells are optimized for maximum power output (which is by the way not equivalent to maximum annual energy yield). Consequently, any colored PV cell would provide less power than the optimized black or dark blue one. The power loss due to color ranges from approximately 12 to 19%. It is important to recognize that the power reduction associated with the solar cell color is not identical to the power loss of a PV module that contains colored cells. The reason is that solar cells are characterized for their performance in the free air environment, and not embedded into an interlayer as they later are in PV modules. The consequence is a relative power increase due to cell-interlayer coupling. The interlayer coupling is one of various effects influencing the power output of PV cells as they are being processed into PV modules [15]. An online tool to simulate and investigate various effects of solar cells colors is available from Fraunhofer ISE Freiburg [16].
- Since PV cells are typically sold on the basis of price per Wp, both arguments – the higher manufacturing costs in the numerator, and the lower Wp in the denominator – result in an exponential price increase.
- Colored PV cells used to be manufactured on the same production-lines than conventional cells. Just the anti-reflection coating thicknesses are of different magnitude. Even if neglecting the prices related to additional material and machine hours, as well as engineering costs for developing the related manufacturing recipes, each color change trial (and later resume to the original color production) required a number of solar cells wasted that had neither the desired new color, nor the original color. The price for those non-usable off-spec solar cells had to be added on the price of the manufactured colored PV cells.
- Any production procedure change, including the alterations to manufacture different PV cell colors, in a manufacturing line embraces a specific risk. This could potentially negatively influence the performance of the standard products. This risk has to be quantified and imposed on the price of a colored solar cell [17],
- Colored solar cells are similarly as standard cells being sorted into, so called BIN classes according to their power output. As the power output commonly shows a Gauss distribution, considerably more solar cells have to be manufactured for a desired amount of colored PV cells of a specific BIN class. Usually the number of cells with very low power and very high power is too small to suffice a required amount for other PV projects, the cells were considered unsaleable. Their costs again had to be compensated by the price of the colored cells,

The high price of PV cells in combination with two main disadvantages – only very few cell colors were available, and the homogeneity of the solar cell colors could not be guaranteed especially for non-perpendicular examination angles as illustrated in fig. 24 – led to the development of various new technologies of colored PV modules [18].

These developments comprise of either printed or coated glass, or printed or coated interlayers mounted in front of the solar PV cells during PV module manufacturing, fig. 25. The most important advantages of such solutions are:
- homogeneous color,
- more colors are available,
- use of standard solar cells, thus lower material costs, and
- low impact on power reduction.

Figure 24. Color variation of PV cells under non-perpendicular examination

Figure 25. Project specific colored PV modules manufactured by SUNOVATION

The BIPV glazing and building physics

According to the European Parliament Directive 2010/31/EU, Article 9.1, all new buildings are proposed to be *nearly net zero energy* by 2022. Therefore, any energy required for the operation of the building will have to be compensated over the course of one year by the equivalent amount of energy supplied by the building itself. In order to be creditable, the energy supplied by the building has to be obtained from renewable energy resources, since otherwise again primary energy from conventional sources would be used [19]. This directive immediately has three implications for the future usage of energy within buildings:
- consumption of energy from primary sources has to be reduced significantly,
- energy usage within buildings has to be as efficient as possible, and
- utilization of renewable energy resources is imperative to compensate for any energy acquired from sources external to the building.

Due to the fact that the stipulation and the usage of energy from some renewable energy resources, such as hydroelectricity, wind energy or biomass, within any building is very limited. It is much more likely that the energy used for compensation will have to be converted from solar energy by PV systems especially onsite BIPV installations. Solar energy not only possesses the advantage of being comparatively evenly available to everybody, but it is also widely accessible and harvestable in systems with dimensions ranging from very small, such as those used in individual households, to very large, for office or industrial buildings. BIPV products that ensure reliable and sustainable kWh generation have been developed and are available worldwide at reasonable prices.

The energy consumption of buildings is typically in the form of heat or electricity. Thermal energy is required to either heat or cool the building to a desired operation temperature. Consequently, the required energy is related primarily to the type of building usage, and thermal losses or gains through the building envelope. This correlation is mainly described by the U-value and g-value of the product or the combination of products [20]. As both properties are available for the products used in the building skin, almost any wall composition and construction can be calculated, and the energy requirements can be predicted. The BIPV elements completely comply, fig. 26.

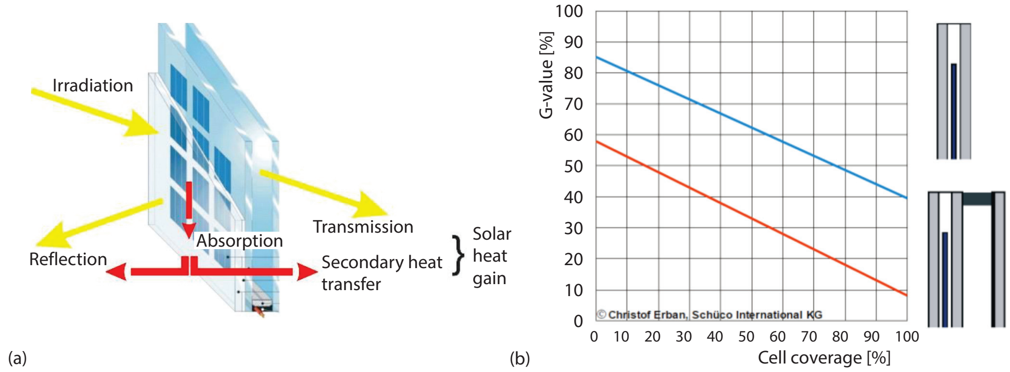

Figure 26. (a) Interaction of solar radiation and BIPV modules and (b) total solar energy transmittance (g-value) of semi-transparent BIPV elements *vs.* solar cell coverage for monolithic panels and insulating glazing

Unfortunately, constant boundary conditions are assumed when the U- or g-value is determined experimentally or calculated as described in the relevant standards. Especially the g-value, describing the total solar gain through a BIPV element, is strongly affected by the reflectance, absorbance and transmittance of the BIPV module. Shown in figs. 27 and 28, these characteristics for glass are not constant (under varying incident angles).

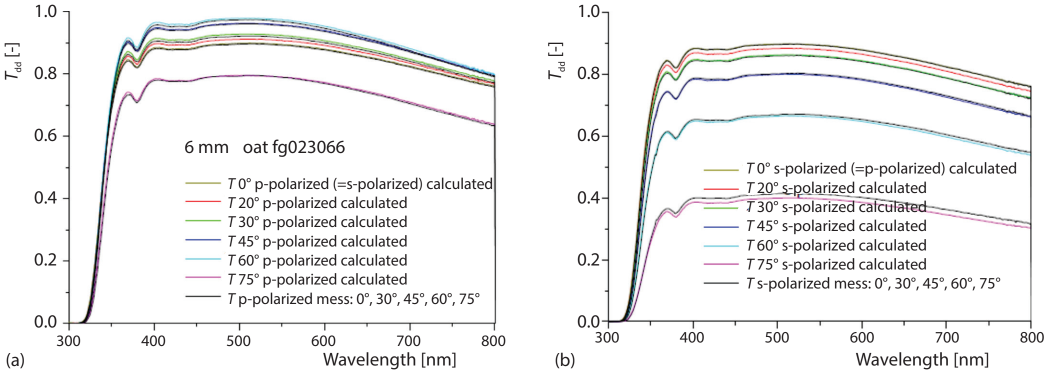

Figure 27. Transmittance spectra of 6 mm float glass for p- and s-polarized light and different angles of incidence [21] (*for color image see journal web site*)

As both the reflectance and transmittance values depend significantly on the glazing configuration, including the number of panes, glass chemical composition, coatings, and surface structures, different glazing varieties not only have different U-values and g-values for normal incidence, but also show different behavior when the incident angle is changed [22].

Inadequate consideration of the incident angle dependence would not be of interest for calculating the thermal impact on buildings if the total irradiation at non-zero angles did not contribute significantly, since the solar gain is the product of the g-value and the incident solar energy. However, the opposite is the case. The incidence angle of 0°, for which the solar heat gain coefficient is determined conventionally, contributes insignificantly to the annual total,

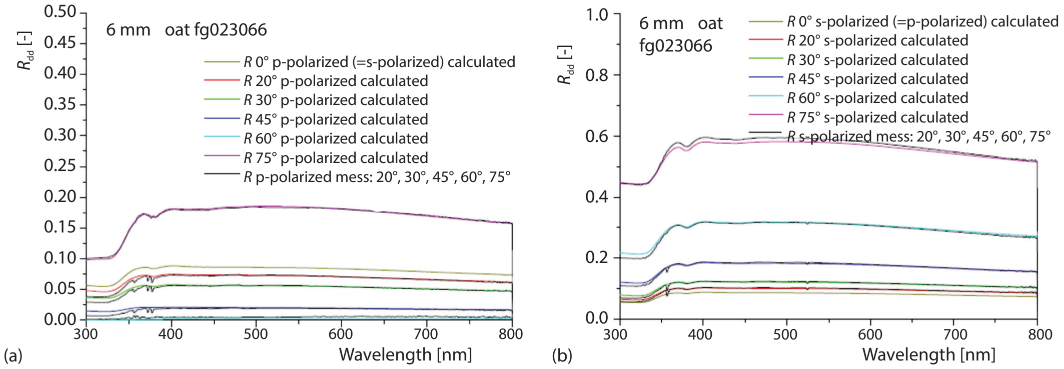

Figure 28. Reflectance spectra of 6mm float glass for p- and s-polarized light and different angles of incidence [21] (*for color image see journal web site*)

whereas significant thermal impact results for solar irradiation at incidence angles deviating from 0°. Variations in orientation have a less significant effect on the angular distribution than variations of the tilt angle for constant orientation.

The incidence angle of solar irradiation on a BIPV glass surface depends on the position of the Sun, the orientation and the tilt angle of the surface itself, and the location of the building. Consequently, surfaces that are oriented differently will have very different thermal impacts on a building. Likewise, surfaces that are oriented identically, but are situated at different locations will have very different thermal impacts on a building.

The constant solar heat gain coefficient (g-value), as defined in the relevant standards, provides a simple means to compare one product with another, but it is practically useless on its own when the energy consumption of a building is to be optimized. If the dependence on incidence angle is not considered, even simulations that account for the orientation of the surface, as well as the solar position, are not exact enough to really optimize the thermal behavior of a building [23]. For residential buildings there seems to be a lack of an adequate consideration of the angular dependence of the total solar transmittance. The same BIPV glass type is most likely being used on all sides of these buildings.

A low value for a solar heat gain coefficient is not desirable. It does not necessarily lead to the optimum, when the annual energy performance of buildings is investigated. In the winter, a rather high, but controlled solar heat coefficient is desired for passive heating, whereas in the summer, a rather low solar heat gain coefficient is desired to reduce the risk of overheating or eliminate the need for active cooling. This information is very important to consider when designing BIPV modules in the building performance context [24].

The low irradiance efficiency of BIPV modules is important to the optimization of PV systems. When PV modules are integrated into a building, architectural design considerations compete with maximizing PV energy production. As a result, BIPV arrays are often not facing South and are frequently mounted vertically. Under these conditions, a greater portion of the total sunlight striking the array is diffuse. In Northern latitudes a significant amount of the total yearly energy is produced at low light levels [25].

Pricing of BIPV modules

The pricing of BIPV modules follows entirely different principles than the pricing of conventional PV modules. These prices even contradict each other [26-28]. The price of conventional PV modules is given in currency unit per Wp, *e. g.* USD $/Wp or EUR €/Wp. Thus, the price mainly changes with the solar cell efficiency standard PV modules contain. The higher the efficiency → the higher the rated power → the higher the price of the PV module. Price reductions are mainly related to the volume that is manufactured, and it is small compared to the base price. The design of the standard PV module has a comparatively small impact on the pricing as all standard PV modules compete in the same market. Which is based on the fastest return on investment by producing and selling electricity.

For BIPV module pricing there are two approaches. The first one would be similar to standard PV modules quoted at the price per Wp. This price is used by the stakeholders that originate from the conventional PV business. The other price method is provided in currency unit per area covered, or in currency unit per article – *e. g.* USD \$/ft² or EUR €/m², respectively €/pcs. This type of pricing is commonly used in building industry. Therefore, it is familiar to architects, façade or roofing material suppliers, building investors or building developers. Price reductions not only depend on the size of the project, but also on the design of the BIPV product itself has a significant impact on its costs.

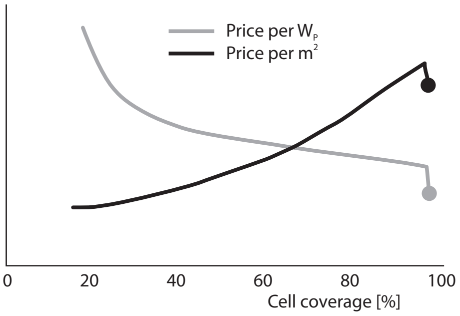

Figure 29. Pricing of crystalline BIPV modules [29]

Since many BIPV products are custom designed for a specific project, the number of PV cells per m² or ft² can be altered by the number of PV cells used within one BIPV module. Figure 29 shows the prices per Wp (in gray), as well as per area (in black), and the impact of solar cell coverage in a crystalline BIPV module. It is obvious that for crystalline BIPV modules the price per area is the highest in case the entire area is covered with solar cells, which is equivalent to highest material costs. The less solar cells a BIPV module contains the cheaper the product will be in terms of covered surface. This means that the lowest price/Wp is obtained for a crystalline BIPV module in case of the module that is fully covered with solar cells. The higher material price is overcompensated by the increase in power output. Reducing the number of solar cells will furthermore increase the Wp price as the relative reduction of power output is much higher than the relative reduction of material being used.

Even the construction effort, the required labor to reprogram machines, or to manufacture the specific customized semi-transparent BIPV modules might even furthermore increase the module price. Consequently, the perception of the procedure to generate a cost effective BIPV module is dissimilar for different stakeholders of the building industry. Some intend to get as much BIPV module m² for their budget, while for stakeholders in PV industry to get as much revenue from their investment.

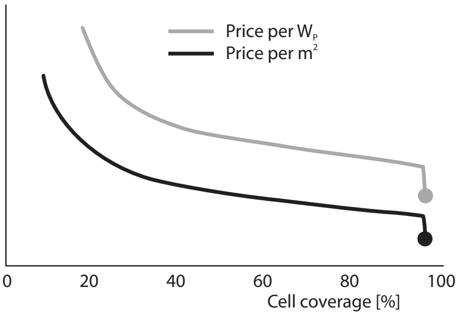

Figure 30. Pricing of thin film BIPV modules [29]

Figure 30 shows the prices per Wp, as well as per area, and the impact of solar cell reduction in a thin-film PV module. The dots indicate the price for densely covered PV modules, such as standard thin-film BIPV modules. Thin-film PV modules are, in contrast to crystalline PV modules for both Wp and area, the cheapest in case they are densely covered. The reason is that price for thin-film PV modules is not dominated by the material price of the solar active material, but rather by the complexity and the duration of the PV module processing. The higher the complexity, and the higher the required machine hours the more costly the product will be.

Reducing the cell coverage typically does not provide the price reduction as it does for crystalline BIPV modules. The reason is that in thin-film PV modules first the entire area is covered with solar active material, which then being reduced by laser ablation of the non-desired areas. As laser ablation is both time consuming and risky, the price of thin-film PV modules will increase when reducing the cell coverage.

The IEA PVPS task 15 [30]

The International Energy Agency (IEA), founded in 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD). IEA involves more than 6.000 experts across government, academia, and industry dedicated to advancing common research and the application of specific energy technologies. The IEA Photovoltaic Power Systems Programme (IEA PVPS) was established in 1993. The mission of the programme is to *enhance the international collaborative efforts which facilitate the role of photovoltaic solar energy as a cornerstone in the transition sustainable energy systems*.

The BIPV is seen as one of the five major tracks for large market penetration of PV, besides price decrease, efficiency improvement, lifespan, and electricity storage. The IEA PVPS task 15 is an international collaboration create an enabling framework and to accelerate the penetration of BIPV products in the global market of renewables and building envelope components, resulting in an equal playing field for BIPV products, and regular building envelope components, respecting mandatory, aesthetic, reliability and financial issues. To reach this objective, an approach based on five key developments has been developed, focused on growth from prototypes to large-scale producible and applicable products. The key developments are dissemination, business modelling, regulatory issues, environmental aspects, and research and development sites.

This Task contributes to the ambition of realizing zero energy buildings and built environments. The scope of this Task covers new and existing buildings, different PV technologies, different applications, as well as scale difference from single-family dwellings to large-scale BIPV application in offices and utility buildings.

Conclusions

The BIPV modules are well established products that provide a numerous design possibilities and additional functionalities in combination with the mere electricity generation known from standard PV systems. Still the know-how within building industry, as well as the architects' community has not yet reached a state that BIPV can be planned and installed without the assistance of specialized BIPV consultants that provide expertise and solutions concerning the questions and requirements of the various trades that are involved. The understanding on how BIPV modules should be developed more cost effectively are distinctive in building industry and PV community.

Once put in the building context, BIPV elements should not be viewed only from the energy production point of view. Because of the physical characteristics of the BIPV module itself, these components can be regarded as multifunctional building elements that provide both shelter and power. Being a mixture of technology, architecture and social behavior, PV in building eludes unambiguous evaluation of its cost-effectiveness and market potential. The problem of architecturally integrating photovoltaic technology requires an interdisciplinary design approach. This not only imposes collaboration and the presence of highly specialized professionals on the project team, but also introduces a sensitivity to problems that go beyond the building itself.

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