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State-of-the-art building integrated photovoltaics

Bjørn Petter Jelle[a,b,*] and Christer Breivik[b]

[a] SINTEF Building and Infrastructure, Department of Materials and Structures, NO-7465 Trondheim, Norway
[b] Norwegian University of Science and Technology, Department of Civil and Transport Engineering, NO-7491 Trondheim, Norway

Abstract

Building integrated photovoltaic (BIPV) systems may represent a powerful and versatile tool for achieving the ever increasing demand for zero energy and zero emission buildings of the near future. In this respect BIPVs offer an aesthetical, economical and technical solution to integrate solar cells harvesting solar radiation to produce electricity within the climate envelopes of buildings. This work summarizes the current state-of-the-art of BIPVs, including both BIPV foil, tile, module and solar cell glazing products.

Keywords: Building integrated photovoltaic; BIPV; Solar cell; State-of-the-art

1. Introduction

As the world's demand and focus on renewable and non-polluting energy, together with energy efficiency, are ever increasing, zero energy and zero emission buildings are rapidly drawing attention. In order to become a zero energy or zero emission building, such a building need to harvest energy from its surroundings, where energy from the sun is one of the obvious choices. Building integrated photovoltaic (BIPV) systems, where solar cells are integrated within the climate envelopes of buildings and utilizing solar radiation to produce electricity, may represent a powerful and versatile tool for reaching these goals with respect to both aesthetical, economical and technical solutions.

Building integrated photovoltaic (BIPV) systems replace parts of the conventional building materials and systems in the climate envelope of buildings, such as the roofs and facades. BIPV systems are

* Corresponding author. Tel.: +47 73 593377; fax: +47 73 593380.
E-mail address: bjorn.petter.jelle@sintef.no.

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considered as a functional part of the building structure, or they are architecturally integrated into the building's design (Peng et al. [1]). Hence, the BIPV system serves as a building envelope material and power generator simultaneously (Strong [2]).

This work summarizes the current state-of-the-art of BIPVs, including both BIPV foil, tile, module and solar cell glazing products, also mentioning building attached photovoltaic (BAPV) systems. For further overview and elaborations including investigations of several possible research opportunities and pathways for the future BIPVs it is referred to the study by Jelle et al. [3].

2. Building integration of photovoltaic cells

Building integration of photovoltaic (PV) cells are carried out on sloped roofs, flat roofs, facades and solar shading systems. PV cells may be mounted above or onto the existing or traditional roofing or wall systems. However, BIPV systems replace the outer building envelope skin, thus serving simultanously as both a climate screen and a power source generating electricity. Hence, BIPVs may provide savings in materials and labour, in addition to reducing the electricity costs. Nevertheless, as the BIPVs act as the climate protection screens it is of major importance to have satisfactory or strict requirements of rain tightness and durability.

Several aspects have to be considered and evaluated related to the integration of the PV cells into the outer building envelope skin. One aspect is to ensure an air gap underneath the solar cells in order to provide an air flow reducing the temperature of the solar cells, as an elevated temperature decreases the efficiency of the solar cells, especially for mono- and polycrystalline Si cells. Another aspect to be considered are the inclination of the BIPVs, both with respect to existing and new buildings, as the solar cells necessarily need to follow the roof inclination (or the wall for that matter) to be integrated solutions. Geographical position and orientation towards the sun and area coverage are yet another aspects to be considered during integration of the BIPV systems. In fact, some BIPV manufacturers also offer dummy modules to provide a more aesthetical and consistent appearance of the roofs and facades.

Hence, in short BIPVs have to fulfil all the requirements, with respect to several properties, of the building envelope skins they are substituting. Various building physical issues like e.g. heat and moisture transport in the building envelope also have to be considered and accounted for.

Examples of solar cells integrated as BIPV tiles and BIPV modules are shown in Fig. 1. Furthermore, BIPVs as solar cell glazing products in the facade and on the roof are depicted in Fig. 2. Solar cell glazing products offer a solution for utilizing the fenestration with regard to daylight, solar heat gain, solar shading, miscellaneous architectural expressions, and finally solar energy gain by converting solar radiation into electricity.

Figure 1. Examples of BIPV tiles (left) and BIPV modules (right) (Applied Solar 2010 [4], DuPont 2011 [5]).

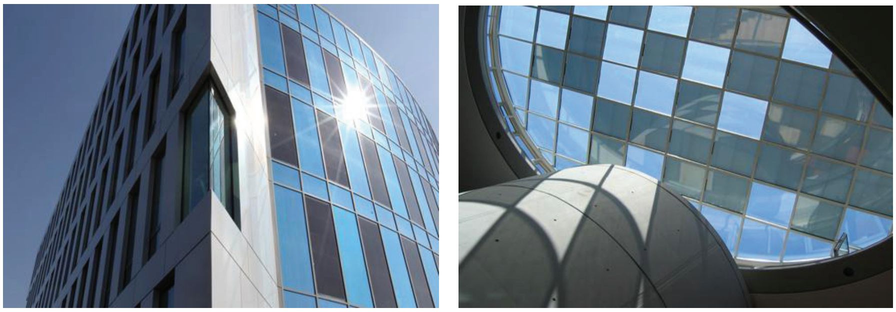

Figure 2. Examples of BIPVs as solar cell glazing products for facades (left) and roofs (right) (ASI® Glass photovoltaic modules, Schott Solar AG [6]).

3. BIPVs and architectural aspects

Various opportunities for innovative architectural design, which may also be aesthetically appealing, are provided by miscellaneous BIPV systems, see e.g. Fig. 1 and Fig. 2. BIPVs may be utilized as shading devices and also form semi-transparent elements of fenestration [7,8]. Silicon tiles may be applied to make a BIPV roof look very much like a standard tiled roof, while semi-transparent modules may be applied in facades or glass ceilings to create different visual effects.

To present a BIPV roof as a roof giving a clear visual impression is preferred by some architects, while others want the BIPV roof to look as much as a standard roof as possible. Additional information about building integration of solar energy systems in general, and architectural integration of PV and BIPV in particular, may be found in the studies by Hestnes [9], Farkas et al. [10] and Peng et al. [1], respectively.

4. Test methods and standards

Evaluation of BIPVs involve several properties, e.g. solar cell efficiency $\eta = P_{max}/(\Phi A)$ where Φ is the input solar radiation in W/m^2 and A is the solar cell surface area in m^2, maximum power point P_{max} in W or Watt-peak (Wp), open circuit potential or voltage U_{oc}, short circuit electrical current I_{sc}, fill factor $FF = P_{max}/(U_{oc}I_{sc}) = (UI)_{max}/(U_{oc}I_{sc})$, band gap E_g and quantum yield φ = number of photo-electrons divided by number of photons.

The values reported by solar cell manufacturers are mainly obtained according to standard test conditions (STC) or nominal operating cell temperature (NOCT).

Important standards for PV modules in this respect are the standards EN 61646 ”Thin-film terrestrial photovoltaic (PV) modules - design qualification and type approval” (equal to IEC 61646) [11], EN 61215 ”Crystalline silicon terrestrial photovoltaic (PV) modules - Design qualification and type approval” (equal to IEC 61215) [12], EN 61730-1 ”Photovoltaic (PV) module safety qualification – Part 1: Requirements for construction” [13], EN 61730-2 ”Photovoltaic (PV) module safety qualification – Part 2: Requirements for testing” [14] and UL 1703 ”UL standard for safety flat-plate photovoltaic modules and panels” [15]. For further and detailed information it is referred to the standards themselves.

5. State-of-the-art of BIPVs

5.1. BIPV categorization

The range of BIPV products is very wide, and they may be categorized in several different ways. Within this work the categorization is mainly performed based on the product descriptions from the manufacturers and what other material types the products are customized to be combined with. In this work the BIPV products or systems have been categorized into the following groups:

- BIPV foil products
- BIPV tile products
- BIPV module products
- Solar cell glazing products

In addition, related to the various BIPV products, the group building attached photovoltaic (BAPV) products should also be mentioned:

- BAPV products

Building attached photovoltaic (BAPV) products are regarded as add-ons to the buildings, hence not directly related to the building structures' functional aspects (Peng et al. [1]). That is, BAPVs are not BIPVs, i.e. the BAPVs are not integrated into the outer building envelope skin, thus not replacing the traditional building parts as the BIPVs are doing.

Some BIPV products exhibit a variety of properties, thereby making it more difficult to categorize them. Yet in other cases it might even be rather difficult to determine whether a PV product should be considered as a BIPV product or not, e.g. due to lack of information and uncertainty about how the product is mounted. In the following there is given more details and some examples from each of the different BIPV product groups. For a comprehensive state-of-the-art review of these BIPV systems, including references and contact information, it is referred to the work by Jelle et al. [3].

5.2. BIPV foil products

BIPV foil products are lightweight and flexible, which is beneficial with respect to easy installation and prevailing weight constraints for roofs. The PV cells are often made from thin-film cells to maintain the flexibility in the foil and the efficiency regarding high temperatures for use on non-ventilated roof solutions. Unfortunately, currently there are few manufacturers on the market that provide weather tight solutions. Table 1 and Fig. 3 present an example of one BIPV foil product. PV foil products have a low fill factor due to both the low efficiency and the large solar cell resistances of thin-film cells. However, it is possible to vary the degree of inclination of the product to a great extent providing flexible solutions.

Table 1. Literature data for one of the BIPV foil products [3].

Manufacturer	Product*	η (%)	U_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Area (mm x mm)	P_{max}/area (W/m^2)
Alwitra GmbH & Co.	Evalon V Solar 408		138.6	5.1	408 /module	0.58	1550 x 6000	42.9
	Evalon V Solar 136		46.2	5.1	136 /module	0.58	1050 x 3360	38.5

*Several models are available from the producer in the Evalon V Solar series.

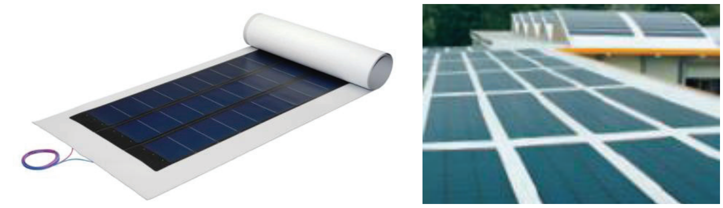

Figure 3. Example of a BIPV foil product from Alwitra GmbH & Co. using amorphous silicon cells from Uni-Solar [16].

5.3. BIPV tile products

BIPV tile products may cover the entire roof or selected parts of the roof. They are normally arranged in modules with the appearance and properties of standard roof tiles and substitute a certain number of traditional roof tiles, thus also enabling easy retrofitting of roofs. The cell type and tile shape varies. Some tile products may resemble curved ceramic tiles (see Fig. 3 in section 2.5) and will not be as area effective due to the curved surface area, but may be more aesthetically pleasing. Some examples of BIPV tile products on the market today are given in Table 2, with two of them depicted in Fig. 4.

Table 2. Literature data for some of the BIPV tile products [3].

Manufacturer	Product*	η (%)	U_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Area (mm x mm)	P_{max}/area (W/m^2)
Solardachstein	STEPdesign		23.15	2.40	1.36 /cell	0.76	8 units 100 x 100	136
SRS Energy	Solé Powertile		6.3	4.6	15.75 /module	0.54	868 x 457.2	39.7
Lumeta	Solar Flat Tile		7.4	5.2	28 /module	0.73	432 x 905	71.6
Solar Century	C21e Tile	20/cell	12.0	5.55	52 /module	0.78	1220 x 420	101.5

*Lumeta has also a Solar S Tile available.

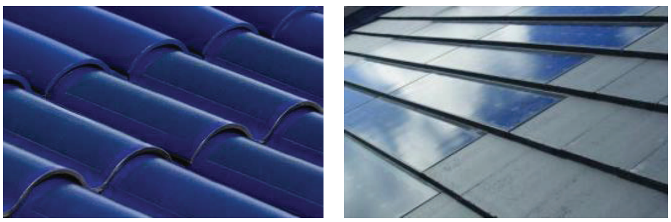

Figure 4. Example of BIPV tile products from SRS Energy (left) [17] and Solar Century (right) [18].

The BIPV products from Solardachstein, Lumeta and Solar Century (Table 2) provide the highest FFs indicating that the efficiencies are high. In fact, Solar Century reports an efficiency of 20 % per cell for their C21e Tile. The design concept of the STEPdesign and the Solé Powertile is one module appearing as standard roof tiles that displaces several standard roof tiles. The module has an integrated panel of poly- or monocrystalline cells. i.e. parts of the module are not covered with PV cells, thus the total area efficiency will not be as high as indicated. The STEPdesign solution from Solardachstein can be mounted on several different tile products. The C21e Tile from Solar Century has a larger active area than the previous products since monocrystalline silicon cells cover the entire module area, and is compatible with a series of named tiles and slates. Solé Powertile from SRS Energy has a design much like standard roof tiles and the amorphous silicon cell cover from Uni-Solar acts as the skin of the tiles.

5.4. BIPV module products

The BIPV module products presented are somewhat similar to conventional PV modules. The difference, however, is that the BIPV modules are made with weather skin solutions. Some of the products may replace various types of roofing, or they fit with a specific roof solution produced by its manufacturer. These mounting systems increase the ease of installation.

There is a large amount of products on the market and some of them are promoted as BIPV products without in fact functioning as weather skins, whereas other products are not very specific on how they are actually mounted which leads to uncertainty whether they are BIPVs or BAPVs. Some of the BIPV module products are premade modules with thermal insulation or other elements included in the body. Some examples of BIPV module products are given in Table 3, with two of them depicted in Fig. 5.

The given FF values for the BIPV module products in Table 3 are approximately the same. The efficiencies for Abakus Solar AG products in Table 3 are between 13.2 % and 14.6 %, DuPont provides an efficiency of 17.7 %, while the Schott Solar modules are stated with efficiencies 12.5 % and 13.1 %. Solar Century gives an efficiency of 20 % per cell for their C21e Slate.

Table 3. Literature data for some of the BIPV module products [3].

Manufacturer	Product*	η (%)	U_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Area (mm x mm)	P_{max}/area (W/m^2)
Creaton AG	Creaton Solesia		13.86	8.46	90/module	0.77	1778 x 355	142.6
Rheinzink	PV Quickstep		17.10	5.12	68/module	0.78	2000 x 365	93.2
Abakus Solar AG	Peak On P235-60	14.6	37.21	8.48	235	0.74	1630 x 1000	144.2
DuPont	Gevity	17.7	24.20	8.77	160	0.75	1332.5 x 929	129.36
		17.7	24.43	8.87	165	0.76	1332.5 x 929	133.4
Suntech	MSZ-190J-D		45.2	5.62	190/module	0.75	1641 x 834.5	139
Schott Solar	InDax 214	12.5	36.3	8.04			1769 x 999	
	InDax 225	13.1	33.5	6.60			1769 x 999	
Solar Century	C21e Slate	20/cell	12.0	5.55	52	0.78	1174 x 318	139.3

*Several models are available from various producers.


Figure 5. Example of BIPV module products from Creaton AG (left) [19] and Rheinzink (right) [20].

5.5. Solar cell glazing products

BIPVs as solar cell glazing products provide a great variety of options for windows, glassed or tiled facades and roofs, Different colours and transparencies can make many different aesthetically pleasing results possible. Some solar cell glazing product examples are given in Table 4 and Fig. 6.

The solar cell glazing modules transmit daylight and serve as water and sun protection. The distance between the solar cells (normally 3 - 50 mm) depends on wanted transparency level and the criteria for electricity production. The space between the cells transmits diffuse daylight. Hence, both shading and natural lighting are provided while producing electricity.

The solar cell glazing manufacturers usually offer customized products regarding shape, cell material, colour and transparency level, i.e. the distance between the cells, whereas Table 4 presents some predefined modules. For example, the transparency level varies from 16 % to 41 % for various Vidursolar models, while it is 25 % for the Abakus Solar AG Peak In P210-60 product. The different models from Sapa Building System depicted in Fig. 6 are using either amorphous, polycrystalline or monocrystalline cells with different cell separations.

Table 4. Literature data for some solar cell glazing products [3].

Manufacturer	Product*	η (%)	U_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Area (mm x mm)	P_{max}/area (W/m^2)
Abakus Solar AG	Peak In P210-60		36.50	7.70			2000 x 1066	
Vidursolar	FV VS16 C36 P120		21.6	7.63			1600 x 720	
Glaswerke Arnold GmbH & Co KG	Voltarlux-ASI-T-Mono 4-fach		93	1.97	100/module	0.55	2358 x 1027	41.3
Schott Solar	ASI THRU-4-IO	6	111	2.22	190	0.77	1122 x 2619	64.7
Sapa Building System	Amorphous silicon thin film	5/cell			32/cell		576 x 976 /cell	50
	Poly-crystalline	16/cell			1.46-3.85 /cell		156 x 156 /cell	120
	Mono-crystalline high efficient	22/cell			2.90-3.11 /cell		125 x 125 /cell	155

*Several models are available from various producers.

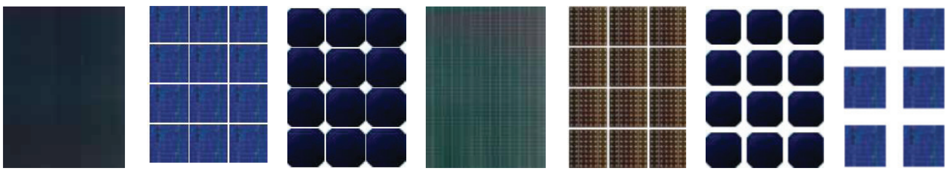

Figure 6. Example of various solar cell glazing products from Sapa Building System [21] using either amorphous, polycrystalline or monocrystalline cells with different distances between the cells.

5.6. BAPV products

As mentioned earlier, the BAPV products are added on rather than integrated in the roof or facade. The BAPV products are not the focus of this study, but it is still interesting to look at some of them. Besides, the flexible product from Uni-Solar is used by several other manufacturers. Some examples of BAPV products are given in Table 5, with two of them depicted in Fig. 7.

The efficiency for the Hauptsitz product is stated to be 17.7 %, while Isofoton gives an efficiency of 14.5 % for their product (Table 5). The Uni-Solar laminate is flexible, thus making it easy to incorporate with other building materials.

Table 5. Literature data for some of the BAPV products [3].

Manufacturer	Product*	η (%)	U_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Area (mm x mm)	P_{max}/area (W/m^2)
Uni-Solar	PVL-68		23.1	5.1	68/module	0.58	2849 x 394	60.6
	PVL-144		46.2	5.3	144/module	0.59	5486 x 394	66.6
Hauptsitz	SunPower 220 Solar Panel	17.7	48.6	5.75			1559 x 798	
Isofoton	ISF-240	14.5	37.1	8.45	240	0.77	1667 x 994	144.8

*Several models are available from various producers.

Figure 7. Example of BAPV products from Uni-Solar (left) [22] and Hauptsitz (right) [23].

6. Economical aspects of BIPVs

The global market for BIPVs is expected to grow from $\$1.8\cdot10^9$ in 2009, to $\$8.7\cdot10^9$ in 2016, according to consulting firm NanoMarkets, New York [24]. In addition, NanoMarkets say that copper indium gallium selenide (CIGS) solar cells will account for 17 % of the BIPV market by volume in 2016 and polysilicon-based BIPVs volume will drop from 75 % of the market to 33 % by 2016 [24]. As PV panels occupy a large area for installation, the associated financial challenge could be best answered by space-saving technologies like BIPVs [25]. Incorporation of PV materials into products such as roofing materials, windows, awnings and glassed facades provides the opportunity for cost reduction by replacing common building materials with PV materials at marginal costs [8]. When compared to glass, steel or other more conventional cladding materials, installing BIPVs adds only a marginal extra cost (2 - 5 %) to the overall construction costs of a commercial building [26]. For a building owner, the installation and operation cost of the BIPV system might be offset by selling the surplus electricity to a utility company [27]. Over time, the cost of a PV system will decline with the improvement of technical advances, resulting into a lower price per kW installed [28], which is an important part of the development to make installation and building integration of PV products profitable without subsidies. The energy payback time is essential when considering different renewable energy systems, which describes the amount of time it takes the solar cell system to create as much energy as was used to create itself. In order to determine the energy payback time the embodied energy of the system must be estimated [29]. For further studies of the energy payback time it is referred to the literature [29-33].

Development within the PV materials and solutions and their technologies may have an even stronger impact on the development of BIPVs in the years to come if one is able from the PV based research to tailor-make solar cell materials and solutions for building integration.

As for the advances in PV technology, it is referred to the timeline for reported best research-cell efficiencies, depicting all verified records for various PV conversion technologies, given by the National Renewable Energy Laboratory (NREL) [34]. The advances in these PV technologies and their increasing efficiencies will naturally be exploited in the coming BIPV products to be made.

7. Conclusions

The state-of-the-art building integrated photovoltaic (BIPV) products existing on the market today offer a wide range of integration of photovoltaic (PV) systems into buildings. Continued research and development within both PV and BIPV materials and technologies will yield better and better BIPV solutions in the years to come, e.g. with respect to increased solar cell efficiency, reduced production costs and improved building integration. New and innovative solutions may reduce costs and increase the market share, amongst other in the retrofitting market.

Acknowledgements

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