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Science and Technology

Building Integrated Photovoltaics - A State-of-the-Art Review, Future Research Opportunities and Large-Scale Experimental Wind-Driven Rain Exposure Investigations

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Submission date: June 2012
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Master of Science Thesis Title: **Building Integrated Photovoltaics - A State-of-the-Art Review, Future Research Opportunities and Large-Scale Experimental Wind-Driven Rain Exposure Investigations**	Date: 2012-06-11 Number of pages: 99 (total)			
	Master Thesis	X	Project Work	
M. Sc. student: **Christer Breivik**				
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Abstract:
This work consists of three scientific journal articles on the subject building integrated photovoltaics (BIPVs), and was initiated by a student project work which consisted of a major revision and extension of an article on BIPVs (appendix A).

BIPVs are photovoltaic materials that replace conventional building materials in parts of the building envelopes, such as the roof covering or facades. 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.

Firstly, this work summarises the current state-of-the-art of BIPVs, including BIPV foil, tile, module and solar cell glazing products (article 1).

Secondly, this work addresses possible future research opportunities and pathways for the BIPVs of tomorrow (article 2).

Thirdly, this work illustrates challenges linked to the building envelope properties of a BIPV system, and attempts to develop and evaluate relevant methods for testing the building envelope properties of BIPV systems (article 3). Based on this, a sample roof area with two BIPV modules was built and inserted in a turnable box for rain and wind tightness testing of sloping building surfaces with the purpose of investigating the rain tightness of the BIPV system, and observing how it withstood wind-driven rain at large-scale conditions. The BIPV sample roof went through testing with run-off water and wind-driven rain with incremental pulsating positive differential pressure (overpressure) over the sample at different inclinations. The BIPV sample roof was during testing constantly visually monitored, and various leakage points were detected. In order to prevent such water penetration, the steel fittings surrounding the BIPV modules should ideally be better adapted to the BIPV modules and constricted to some extent. It is however important to maintain a sufficient ventilation rate simultaneously.

Keywords:

1. Building integrated photovoltaic
2. BIPV
3. State-of-the-art
4. Experiment
5. Rain tightness

(sign.)

Preface

The Master of Science thesis is the last compulsory activity required of graduate students at the Norwegian University of Science and Technology (NTNU). The work is delivered under the Department of Civil and Transport Engineering in cooperation with SINTEF Building and Infrastructure. This work has been part of research activities carried out within the NTNU and SINTEF research project "The Research Centre on Zero Emission Buildings" (ZEB).

The work has been written as three scientific journal articles, and is based on my student project work on building integrated photovoltaics (BIPVs) from the autumn 2011, which was a major revision and extension of an article submitted to Solar Energy Materials and Solar Cells (SOLMAT) by Hilde Drolsum Røkenes and Bjørn Petter Jelle. Comments from four reviewers at SOLMAT were addressed and the article underwent a major revision and extension, and was accepted and published in SOLMAT a few months later (appendix A).

Results from laboratory investigations in my Master of Science thesis work have been the basis for an experimental scientific article (article 3) which has been submitted to the board of "The Research Centre on Zero Emission Buildings" (ZEB) before submission for publication in *Solar Energy*. In addition, two scientific articles were written for presentation at the *Renewable Energy Research Conference (RERC) 2012 - Technoport 2012 - Sharing Possibilities* in Trondheim 16-18 April. These two articles were published in *Energy Procedia* (article 1 and 2), and presented as a lecture at RERC the 17th of April (appendix B). The same lecture, i.e. only with a different front page, was given at the seminar *Supervarmeisolasjon og nye teknologier i bygningskroppen - Nytt i nær framtid* (High Performance Thermal Insulation and New Technologies for the Building Envelope - Emerging in the Near Future) in Sandnes the 22nd of May (appendix C).

Working on the subject building integrated photovoltaics has been inspiring and challenging, and it has given me the possibility to utilize the knowledge I have acquired during my studies. It has also provided me with new insights into the field of solar energy, building and material technology.

I would like to extend my gratitude to the staff at the Department of Building Materials and Structures at SINTEF Building and Infrastructure that has supported this work in different ways. Special thanks are given to my supervisor Bjørn Petter Jelle at SINTEF and NTNU for his invaluable contribution.

Trondheim, June 2012

Christer Breivik

Norsk sammendrag (Norwegian abstract)

Dette arbeidet består av tre vitenskapelige artikler innenfor feltet bygningsintegrerte solceller (BIPVs), og ble innledet av en hovedprosjektoppgave som bestod av en større revidering og utvidelse av en vitenskapelig artikkel vedrørende BIPVs (vedlegg A).

BIPVs er solcellematerialer som erstatter tradisjonelle bygningsmaterialer i deler av bygningskroppen, som for eksempel taktekkingen eller diverse fasadematerialer. BIPV-systemer kan vise seg å være et kraftig og allsidig verktøy i prosessen med å oppnå den økende etterspørselen etter nullenergi- og nullutslippsbygninger i nær framtid. BIPV representerer en estetisk, økonomisk og teknisk løsning på å integrere energiproduserende solceller i bygningskroppen.

For det første sammenfatter dette arbeidet de nåværende BIPV-løsningene og -produktene som finnes på markedet. Dette inkluderer BIPV folie-, flis-/helle-, modul og solcelleglassprodukter (artikkel 1).

For det andre omhandler dette arbeidet mulige fremtidige forskningsmuligheter, samt veien videre for utviklingen av fremtidens BIPV-produkter (artikkel 2).

For det tredje belyser dette arbeidet utfordringer knyttet til BIPV som klimaskjerm, i tillegg til at det forsøker å utvikle og evaluere relevante metoder for å teste klimaskjerm-knyttede egenskaper til BIPV-systemer (artikkel 3). På bakgrunn av dette ble et takfelt med to BIPV-moduler bygget og plassert i en dreibar boks for regn- og vindtetthetstesting av skrå bygningsoverflater. Hensikten med dette var å undersøke regntettheten til BIPV-systemet, og å observere hvordan det tålte slagregn i stor skala. Takfeltet gikk gjennom testing med nedsilende vann og slagregn med økende pulserende trykkforskjell over takfeltet ved to forskjellige helningsvinkler. Takfeltet ble kontinuerlig visuelt overvåket under testing, og diverse lekkasjepunkt ble oppdaget. For å hindre slike lekkasjer bør stålbeslagene som omgir BIPV-modulene ideelt sett tilpasses bedre og innsnevres til en viss grad. Det er imidlertid samtidig viktig å opprettholde en tilstrekkelig god ventilasjon under BIPV-modulene.

Master thesis contents

Article 1

B. P. Jelle and C. Breivik, “State-of-the-Art Building Integrated Photovoltaics”, *Energy Procedia*, In press, 2012.

Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2012) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

Technoport RERC Research

State-of-the-art building integrated photovoltaics

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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

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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]).

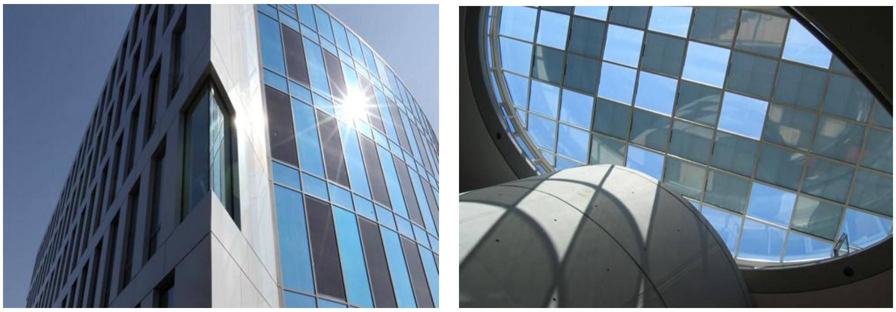

Figure 2. Examples of BIPVs as solar cell glazing products for facades (left) and roofs (right) (ASI® Glass photovoltaic modules, Schott Solar AG [6]).

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 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.

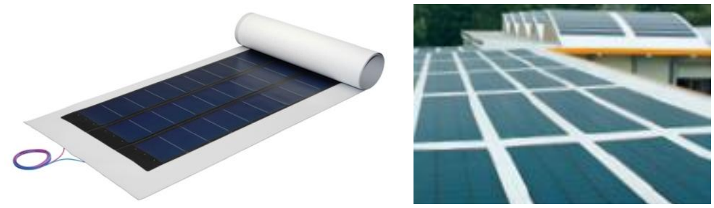

Figure 3. Example of a BIPV foil product from Alwitra GmbH & Co. using amorphous silicon cells from Uni-Solar [16].

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.

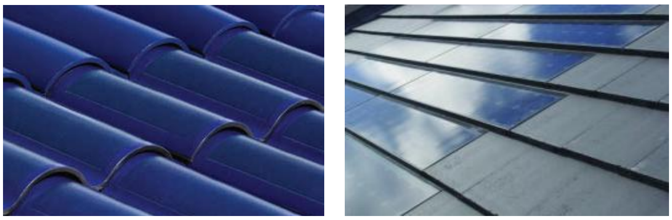

Figure 4. Example of BIPV tile products from SRS Energy (left) [17] and Solar Century (right) [18].

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 17.7	24.20 24.43	8.77 8.87	160 165	0.75 0.76	1332.5 x 929 1332.5 x 929	129.36 133.4
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

This work has been supported by the Research Council of Norway and several partners through the NTNU and SINTEF research project ”The Research Centre on Zero Emission Buildings” (ZEB).

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Article 2

B. P. Jelle and C. Breivik, “The Path to the Building Integrated Photovoltaics of Tomorrow”, *Energy Procedia*, In press, 2012.

Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 00 (2012) 000–000
Energy Procedia
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The path to the building integrated photovoltaics of tomorrow

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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, offering an aesthetical, economical and technical solution to integrate solar cells producing electricity within the climate envelopes of buildings. This work addresses possible research opportunities and pathways for the BIPVs of tomorrow.

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

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 considered as a functional part of the building structure, or they are architecturally integrated into the

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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 investigates several possible research opportunities and pathways for the BIPVs in the future. For further overview and elaborations within various aspects of BIPVs it is referred to the study by Jelle et al. [3].

2. Categorization of state-of-the-art BIPVs

The range of state-of-the-art BIPV products is very wide, and they may be categorized in several different ways, where one possible categorization is into BIPV foil products, BIPV tile products, BIPV module products and BIPV solar cell glazing products [3]. In addition, the group building attached photovoltaic (BAPV) products should also be mentioned. 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.

Examples of solar cells integrated as BIPV tiles and BIPVs as solar cell glazing products for roofs are shown in Fig. 1. 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 BIPVs as solar cell glazing products for roofs (right) (Applied Solar 2010 [4], ASI® Glass photovoltaic modules Schott Solar AG [5]).

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 lack of of information and uncertainty about how the product is mounted. 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].

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).

3. The path to the BIPVs of tomorrow

3.1. PV development and impact on BIPVs

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, in Fig. 2 there is given a timeline for reported best research-cell efficiencies, depicting all verified records for various PV conversion technologies, including crystalline

Si, thin-film, single-junction GaAs, multijunction and emerging technologies, collected from solar companies, universities and national laboratories [6]. The advances in these PV technologies and their increasing efficiencies will naturally be exploited in the coming BIPV products to be made.

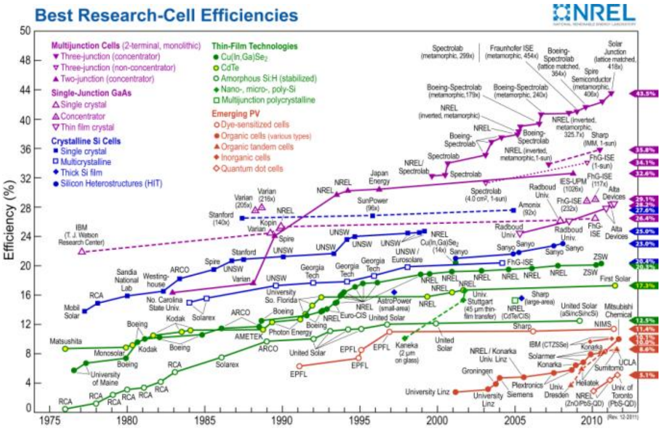

Figure 2. A timeline for reported best research-cell efficiencies, depicting all verified records for various PV conversion technologies like crystalline Si, thin-film, single-junction GaAs, multijunction and emerging technologies [6].

3.2. New materials and solutions for BIPVs

The research paths for possible new PV technologies that may initiate and advance into new innovations, and which may be developed into BIPVs, may be found in miscellaneous fields, e.g. ultra-low cost and low-medium efficiency organic based modules, ultra-high efficiency modules, solar concentrator and/or solar trapping systems embedded in the solar cell surface and material beneath, and flexible lightweight inorganic thin film solar cells, and several others some of them yet to be discovered. Carrying out the research and development of the PV and BIPV materials and solutions for the future one may bear in mind the following words: "*think thoughts not yet thought of*" and "*the more we know the more we know we don't know*" [7].

One strategy utilized to achieve high solar cell efficiencies is to make so-called sandwich or stack solar cells, which use several different material layers and cells with different spectral absorbances to harvest as much as possible of the solar radiation in a wide wavelength range. An example of a triple solar cell with its configuration and spectral responses is shown in Fig. 3 [8]. The top cell layer absorbs the blue light and allows the other wavelength parts of the solar radiation to pass through. The green and yellow light is then absorbed by the middle cell layer, and the red light is absorbed by the bottom cell layer. Hence, a much larger portion of the solar radiation is utilized.

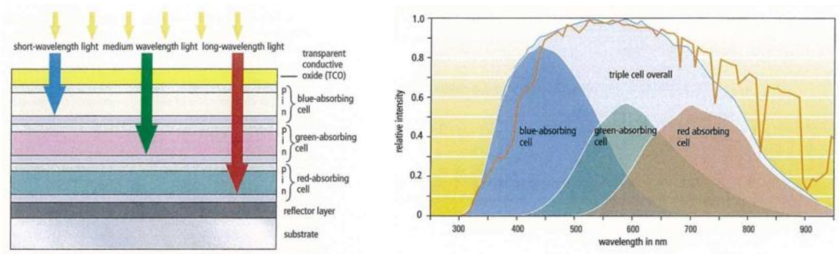

Figure 3. An amorphous triple solar cell with its configuration (left) and spectral responses (right) [8].

Ultra-low cost and low-medium efficiency organic based modules are based on dye sensitized solar cells (DSSC), extremely thin absorbers, organic polymer cells and others. Organic semiconductors are less expensive than inorganic semiconductors like Si. The superior material properties of polymers combined with cheap processing techniques has made polymer-based materials present in almost every part of the modern society [9]. The highest reported efficiency for an organic solar cell (with the exception of DSSC) is 6.5%, and this makes them competitive with CO_2-producing technologies [10]. However, the polymer solar cells are more sensitive to degradation, where ultraviolet solar radiaion and oxygen from the atmosphere may oxidize the organic layer. More stable devices have already been made and progress in this field is important for polymer solar cells to have a future as commercial devices and to be used in various BIPVs [11].

Ultra-high efficiency modules are based on quantum cells and nano-structured devices, where e.g. the record efficiencies for polymer-based solar cells have been observed in disordered nano-structured heterojunctions, and further gains are expected upon optimizing ordered nano-structure architectures [10]. Solar concentrator systems are described with arrays of PV modules that are mounted onto large movable structures which are continuously aimed at the sun.

Dye sensitized solar cells (DSSC) usually have a titanium dioxide (TiO_2) substrate material like in the Grätzel solar cell. The technology is often compared with and stated to imitate the photosynthesis, and is by Grätzel called ”the artificial leaf” [12]. The cells absorb across the visible spectrum and therefore lead to an increased efficiency ranging from 7% under direct solar irradiation (AM1.5) and up to 11% in diffuse daylight [13,14,15,16]. The TiO_2 material is a renewable and non-toxic white mineral, thus giving smaller environmental impacts, where an easy manufacturing process contributes to lower costs. Coloured dyes for use in DSSC based on the TiO_2 cell are developed by Massey University’s Nanomaterials Research Centre and they predict costs of one 10th of the Si based cells [17]. The reduced production costs and the decreased environmental impacts result in shorter energy and economical payback time, and therefore makes the technology very promising. The market share for this technology is still very small, but it is expected to rise and may achieve a great influence in the future.

Yet another innovative option for more effective harvesting of solar energy is so-called ”antennas” depicted in Fig. 4, which can harvest several wavelengths, i.e. a much broader spectrum of the solar radiation. This may be compared to the more ”traditional” sandwich solar cells. ”The use of antenna-sensitizer molecular devices may constitute a viable strategy to overcome problems of light harvesting efficiency in the spectral sensitization of wide-bandgap semiconductors.” [18].

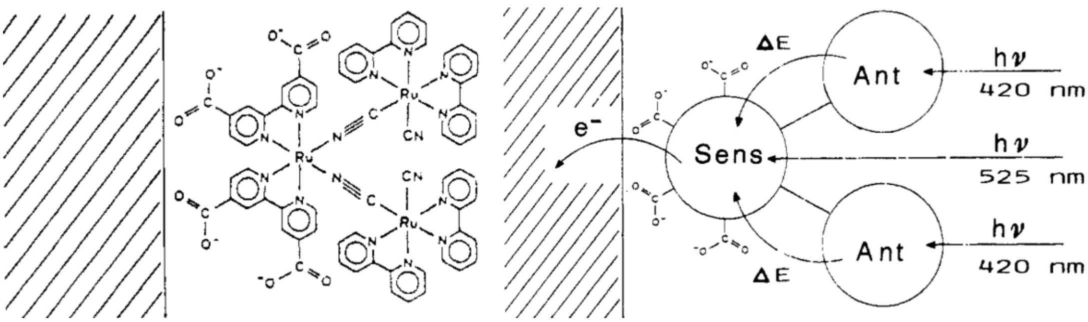

Figure 4. Illustrative representation of the adsorption mode of the trinuclear complex on the TiO_2 surface (left) and block diagram showing the function of the trinuclear complex as an antenna-sensitizer molecular device (right) [18].

As noted in the above (Fig. 2), research laboratories have for many years produced high-performance solar cells with efficiencies up to 25% - 40% [8,19]. One approach is to use materials with higher purity and to eliminate the impurities along in the process. Also the back surface can be passivated with silicon oxide and amorphous silicon to minimize recombination losses at the surfaces and contacts. Textured surfaces and buried contacts with minimal shading reduce optical losses. The total production is very expensive and is to date for use in laboratories only. Another way of increasing the efficiency may be concentrated photovoltaic (CPV) cells. Efficiencies reaching 43.5% has been achieved for commercial-ready CPV cells [19]. These cells are typically applied in the concentrator modules based on a concept of the small-aperture refractive concentrators [20].

Flexible CIGS (copper indium gallium selenide) and CdTe solar modules are shown in Fig. 5 (configurations) and Fig. 6 (photos). In an experiment performed by Buecheler et al. [21], the flexible and lightweight CIGS and CdTe solar devices have yielded an active area efficiency of 14.7% (CIGS) and 9.4% (CdTe). These lightweight devices allow building integration in structures which can not take the additional load of heavy and rigid glass laminated solar modules. ”The flexible solar modules can be laminated to building elements such as flat roof membranes, tiles or metallic covers without adding weight and thus, the installation costs can be reduced significantly.” [21].

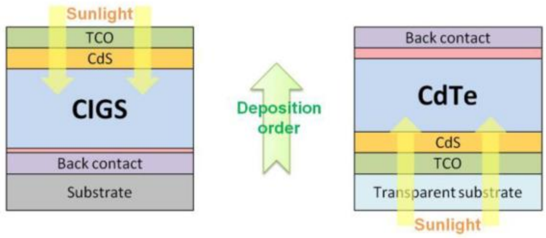

Figure 5. Schematic built-up of CIGS (left) and CdTe (right) thin film solar cells [21].

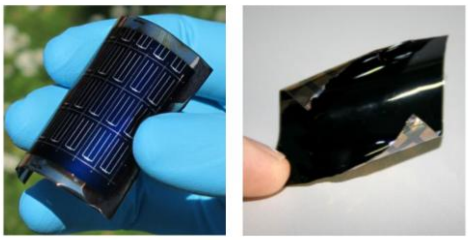

Figure 6. Flexible CIGS (left) and CdTe (right) solar cells on polyimide substrates [21].

The German company PVflex Solar GmbH has said that ”thanks to flexible lamination, CIGS solar cells now have the ability to both realize their potential as the most efficient thin film technology and to dominate the building-integrated photovoltaics (BIPV) market in the future” [22].

New solar cell material technology includes crystalline Si on glass (CSG), copper indium gallium diselenide (CIGS), microamorphous Si cells, concentrating systems and hybrid solar cells (HIT). Dow Chemical has introduced a line of CIGS-based solar shingles that will be commercially available in late 2011. The BIPV solar shingle installs and performs like a standard asphalt shingle, has an expected lifespan of 15-20 years (on par with conventional asphalt shingles), and has received a GLOBE Foundation award for ”Environmental Excellence in Emerging Technology” [23,24]. This is expected to be a huge contribution in bringing affordable renewable energy to consumers. Hence, the development of new PV materials and technologies will in the future contribute to new and improved BIPV products, e.g. with higher solar efficiencies.

In the recent experimental investigations carried out by Semonin et al. [25], they have reported photocurrent quantum efficiencies exceeding 100% in a quantum dot solar cell, being enabled by multiple exciton generation (MEG). The MEG process may occur in semiconductor nanocrystals or quantum dots where absorption of a photon with at least twice the bandgap energy creates two or more electron-hole pairs. Thus, miscellaneous new and exciting discoveries within solar cell research will with time find its way into the PV and BIPV systems for the buildings of tomorrow.

Furthermore, the solar cell glazing products available today have potential for optimization, e.g. the solar radiation utilized in a solar cell cannot be exploited as daylight in the buildings. Hence, ”one might also envision incorporating solar cells or photovoltaics with electrochromic materials in completely new fenestration products, where the photovoltaic and electrochromic material or materials cover the whole glazing area.” [26].

The PV industry offers many and various solutions. Normally, there is room for improvement in each specific system, e.g. regarding ventilation rate, positioning, removing of snow, etc. To ensure a good integration, the BIPV systems should be included early in the planning process. Therefore, a well-established communication between the planners and manufacturers of BIPV products is important for the development of new BIPV solutions. For mono- or polycrystalline PV cells it is very important to achieve a sufficient ventilation rate, as the solar cell efficiency normally decreases with increasing temperature, and should thus be planned ahead of the construction phase. The BIPV systems are expected to improve in the near future both regarding efficiency of the product and the production phase, hence leading to decreased energy payback time. However, this will be dependent on the market situation and/or subsidies.

Miscellaneous PV surface solutions for increasing solar cell efficiency and/or profitability may be envisioned. Various solar radiation trapping mechanisms might be embedded in the surface. Furthermore, one may be able to make an exterior surface capable of harvesting as much solar energy as if the whole exterior surface was covered with a PV material, while in fact the actual PV material surface is considerably smaller and located somewhat beneath the exterior surface, hence reducing the PV material costs. In principle, the latter solution might be viewed as a special built-in concentrator system integrated within the PV surface, thus requiring less (expensive) solar cell material. Thus, the idea may then be to fabricate a ”solar concentrator” at a microscopic material level embedded in the solar cell surface and beneath [3].

Inverted pyramid texturing of a solar cell as illustrated in Fig. 7 is another option for more effective solar energy harvesting [27]. The great light trapping properties of the inverted pyramid geometry is due to the following three effects: (a) reduced front surface reflectance by providing the opportunity for a portion of the incoming solar rays to undergo a triple bounce, (b) increase in path length of the solar ray through the cell, thus absorbing a larger fraction of the solar rays which has entered the cell before exiting the cell, and (c) increase in amount of solar rays reflected from the back surface, by total internal reflection at the front surface/air interface by making the incident angle greater than the critical angle. The inverted pyramid texture on solar cells is estimated to give cell efficiencies of approximately 24% with realistic cell design and material parameters [27].

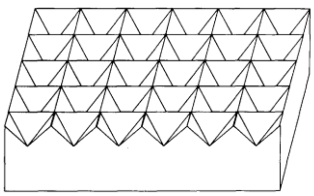

Figure 7. The inverted pyramids geometry utilized for light trapping on Si solar cells [27].

An option for the future that e.g. Enecolo and SolarPower Restoration Systems Inc. have looked into is to integrate the PV cells in materials at an early stadium, e.g. in prefabricated concrete plates [16,28]. As concrete is one of the most widely used construction materials in the world, and the integration of PV with concrete surfaces has remained largely undeveloped, this research field has a huge potential.

Thin laminate or paint layer solar cell materials represent another future option. Javier and Foos [29] fabricated a complete photovoltaic cell using a handheld airbrush, dilute solutions of CdSe and CdTe nanorods, commercially available silver paint, and transparent-conducting-electrode-coated glass, as depicted in Fig. 8. They explored the suitability of a handheld airbrush to create high-quality films and were able to form ultra smooth surfaces from 20 to 500 nm thickness. The current estimated efficiency is very low, but the research demonstrates the variety in the potential of PV cells [29].

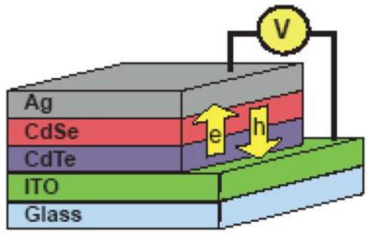

Figure 8. Schematic view of a PV cell composed of ITO-coated glass, CdTe and CdSe nanorods, and silver paint. Electrons (holes) are preferentially pushed towards the Ag (ITO) electrode as depicted by the arrows [29].

Integrating PV with smart windows in a way so that the PV elements will provide shading when there is need for it is yet another research path [30]. Hence, electricity will be produced while the window blocks the solar radiation. In the building industry electrochromic windows with no external wiring are at the moment most desirable. The National Renewable Energy Laboratory of Golden (USA) has built self-powered photovoltaic electrochromic devices up to 25 cm^2 [31]. For these self-powered PV electrochromic devices, "…the main concerns for future large-area applications are the possible loss of the energy generated by the PV device for larger dimensions, a small range of optical modulation and rather low transmittances in the clear state." [31].

3.3. Long-term durability of new materials and solutions

Incorporation of new building materials, integrated technology and solutions need to be planned simultaneously with the building envelope. Various requirements for rain, wind and air tightness, building physical considerations and long-term durability towards climate exposure have to be evaluated. Building physical considerations include investigation of the heat and moisture transport and with this any condensation risks. New materials might change the heat and moisture transport and distribution within the building elements and envelopes, and knowledge about these aspects are hence crucial in order to avoid any building damages and performance degradations.

Long-term durability versus the various climate exposure factors need to be considered. Examples of this are: Solar radiation (UV-VIS-NIR), ambient infrared (IR) heat radiation, high and low temperatures, temperature changes/cycles giving freezing/thawing processes, water (e.g. moisture and wind-driven rain), physical strains (e.g. snow loads), wind, erosion (also from above factors), pollutions (e.g. gases and particles in air), microorganisms, oxygen and time for all the factors above to work [32].

All new products should achieve approval in accordance with the current standards. For thin-film PV cells the test procedures are given in standard EN 61646 [33], and for crystalline Si PV cells EN 61215

[34] applies. Several of the given tests are to determine the durability of the product at different conditions, and all climate exposure factors above except for pollution and microorganisms are included. Test procedures for these factors may be found in the standard UL 1703 [35]. Naturally, some new materials and technologies will not be covered by these standards. Thus, the further development of new materials and solutions will arise a need for new standards specifying procedures for these materials and solutions.

Note that the standards describe test procedures for the robustness of terminations test. However, since the standards are based on the PV module only, further testing procedures of the module integrated in the building should be developed with the increasing interest and production of BIPVs.

3.4. Future visions for BIPVs

The main target of BIPVs replacing conventional roof and facade materials is already in progress as the global market for BIPVs was $\$1.8 \cdot 10^9$ in 2009, and is expected to grow to $\$8.7 \cdot 10^9$ in 2016 [23]. Nevertheless, in the world of today, there is still a great need of increasing the volume of PV and BIPV produced electricity for the world of tomorrow.

Several new possible pathways and opportunities exist beyond the current BIPVs. Some of them have already been mentioned in the previous chapters. New developed technologies may give a huge variety of solutions. Low production costs, low environmental impacts and high efficiencies are key factors for the future BIPVs.

The research and development of solutions regarding BIPVs for the retrofitting market are of great importance as the volume of existing buildings is many times greater than the volume of buildings to be constructed in a foreseeable future. The market for retrofitting of roofs is already under development and is growing, e.g. in Hong Kong, where similar BIPV concepts can be applied to facade systems [36]. Easy application of PV cells in existing materials is essential, and it may in the future be performed by e.g. various paint techniques.

Internal energy storage may also be envisioned in future solar cell materials, e.g. analogous to a photoelectrochemical solar cell (PEC) with internal storage. Various battery-technologies, e.g. metal hydrides, and nano technologies, could represent some of many possible ways of increasing the energy storage density.

There is a great need for governmental subsidies in various countries to get the industry started, e.g. as it has been carried out with success in southern Europe. Furthermore, a system for feeding the grid with PV electricity is necessary.

An almost unlimited range of opportunities is offered by BIPVs as solar cell glazing products, providing both solar shading, daylight transmission and producing electricity.

Forthcoming theoretical and experimental explorations may provide the PV and BIPV industry with several new and innovative materials and solutions. ”Future solar cell materials may also be envisioned as thin laminate or paint layers, hence also enabling application by paint brush or spray.” [26]. A development towards higher efficiency and better thermal insulation properties increases the energy efficiency and shortens the payback time, e.g. highly relevant in the northern part of Europe and elsewhere with colder climate seasons.

4. Conclusions

The several 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. The chosen solutions should be easily applicable, where one example of a future vision is paint applications of PV cells. It is crucial that all new technologies and solutions are thoroughly tested and approved in accordance with existing standards, and furthermore, there is also a need for development of new standards and methods, e.g. regarding long-term durability versus climate exposure.

Acknowledgements

This work has been supported by the Research Council of Norway and several partners through the NTNU and SINTEF research project ”The Research Centre on Zero Emission Buildings” (ZEB).

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Article 3

C. Breivik, B. P. Jelle, B. Time, Ø. Holmberget, J. Nygård, E. Bergheim, A. Dalehaug and A. Gustavsen, “Large-Scale Experimental Wind-Driven Rain Exposure Investigations of Building Integrated Photovoltaics”, Submitted for publication in *Solar Energy*, 2012.

Submitted for publication in *Solar Energy,* 2012.

Large-Scale Experimental Wind-Driven Rain Exposure Investigations of Building Integrated Photovoltaics

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Abstract

Building integrated photovoltaics (BIPVs) are photovoltaic materials that replace conventional building materials in parts of the building envelopes, such as the roofs or facades, i.e. the BIPV system serves dual purposes, as both a building envelope material and a power generator. Hence, it is important to focus on the building envelope properties of a BIPV system in addition to energy generation performance when conducting experimental investigations of BIPVs. The aim of this work was to illustrate challenges linked to the building envelope properties of a BIPV system, and to develop and evaluate relevant methods for testing the building envelope properties of BIPV systems.

A sample roof area with two BIPV modules was built and tested in a turnable box for rain and wind tightness testing of sloping building surfaces with the aim of investigating the rain tightness of the BIPV system, and observing how it withstood wind-driven rain at large-scale conditions. The BIPV sample roof went through testing with run-off water and wind-driven rain with incremental pulsating positive differential pressure over the sample at two different inclinations. The BIPV sample roof was during testing constantly visually monitored, and various leakage points were detected. In order to prevent such water penetration, the steel fittings surrounding the BIPV modules should ideally be better adapted to the BIPV modules and constricted to some extent. It is however important to maintain a sufficient ventilation rate simultaneously.

Keywords: *Building integrated photovoltaic, BIPV, Solar cell, Building, Roof, Experiment, Rain tightness.*

Contents

1. Introduction

Global demand and focus on renewable and non-polluting energy are ever increasing. Meanwhile, the world is using fossil fuel at an alarming rate. With emissions of 10.9 gigatonnes of carbon dioxide equivalents ($GtCO_2e$) per year in 2005, the power industry is responsible for 24 % of global Greenhouse Gas (GHG) emissions, and this is expected to increase to 18.7 $GtCO_2e$ per year in 2030 (McKinsey 2009). "Carbon dioxide equivalent is the unit for emissions that, for a given mixture and amount of greenhouse gas, represents the amount of CO_2 that would have the same global warming potential (GWP) when measured over a specified timescale (generally, 100 years)" (McKinsey 2009).

Zero energy and zero emission buildings are rapidly drawing attention, and in order to become a zero energy or zero emission building, the building will need to harvest energy from its surroundings. Energy from the sun is one of the obvious choices, and of all the renewable energy sources currently available, it is the most abundant, inexhaustible and clean one (Peng et al. 2011). In one day, the irradiation from the sun on the earth gives about 10 000 times more energy than the daily use of mankind (Swiss BiPV Competence Centre 2010). Annual solar radiation is illustrated and compared to both traditional energy sources and renewable energy sources in fig. 1.

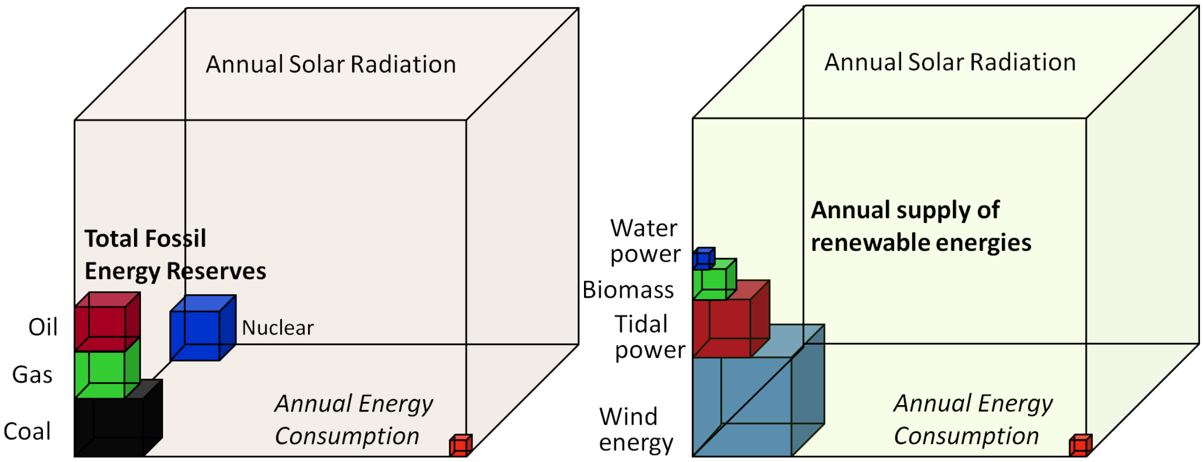

Fig. 1: Annual solar radiation compared to; traditional energy sources (left) and renewable energy sources (right) (SolMic 2012).

With photovoltaics (PV) one can produce electricity on site, directly from the sun, without concern for energy supply or environmental harm (Strong 2011). Building integrated photovoltaic (BIPV) systems replace parts of the conventional building materials in the building's climate envelope, such as the roof covering and facades. To be classified as a BIPV system, the system must be considered as a functional part of the building structure, or it must be architecturally integrated into the building's design (Peng et al. 2011). Hence, the BIPV system serves as a building envelope material and power generator simultaneously (Strong 2011). I.e., the BIPV system must fulfill the requirements of both the building envelope material and construction, and the PV solar cells. For a state-of-the-art review and future research opportunities within various aspects of BIPVs it is referred to the studies by Jelle et al. (2012), Jelle and Breivik (2012a) and Jelle and Breivik (2012b).

Wind-driven rain is one of the most important moisture sources affecting the hygrothermal performance and the durability of building facades and roofs (Blocken and Carmeliet 2004, Blocken and Carmeliet 2012, Eldridge 1976). A BIPV module replacing the roof covering has to be rain proof above all. Infiltration of water in discontinuous roof coverings may principally depend on factors such as the roof slope, the external wind pressure creating a pressure gradient between the inside and the outside of the building, the quantity of streaming water, the joint dimensions, the surface tension between the water and the fixings, the quantity and nature of dirt present, etc. (Fasana and Nelva 2011).

Different methodologies for evaluation of rain tightness of discontinuous roofing systems have been tested in the world. E.g. at the French Technical Center for Tiles and Bricks (CTTB) where an open sloping wind tunnel that exposed a test specimen to grazing wind, streaming water, and an applied differential air pressure between the outside and the inside of the roof was experimented (Fasana and Nelva 2011). In England a large closed wind tunnel has been built where the roof specimen is placed in the centre of the section of the horizontal wind tunnel (Fasana and Nelva 2011, Hazelwood 1979).

Regarding BIPV systems, some climate testing, both outdoor and indoor, has been undertaken, by e.g. Bloem (2008) and Mei et al. (2009), whereas mechanical testing has been carried out by e.g. Jol et al. (2009). Basic studies on irradiance and energy output, including temperature and generation performance, of PV-/BIPV systems and -modules have been performed (Carr and Pryor 2004, Celik 2003, Chenni et al. 2007, Mattei et al. 2006, Smiley 2001). Many BIPV manufacturers state that their products contain innovative rain tightness systems for extreme conditions. However, in total, little experimental testing of rain tightness of BIPV systems has been conducted.

Based on this background, the objective of this work was firstly to investigate the rain tightness of a specific BIPV module product integrated in a roof construction, and evaluate how it withstood precipitation in form of wind-driven rain at large-scale conditions, using a turnable box for rain and wind tightness testing of sloping building surfaces. The second objective was to develop and evaluate relevant methods for testing BIPV systems regarding its' building envelope properties. This experimental set-up enabled a controlled test environment. Rain tightness of various BIPV modules must however be specified according to the water tightness of the underroof, and its drainage and drying out capability.

2. Experimental

2.1. Sample materials and components

A sample roof area with dimensions 2.75 m x 2.75 m was built on a wooden frame using a transparent polycarbonate (Lexan) board as wind barrier, and with double furring strips (23 mm x 36 mm vertically and 36 mm x 48 mm horizontally on top) as shown in fig. 2 (left). Two DuPont Gevity - 165M BIPV modules, with dimensions as presented in table 1, were mounted together (side by side) onto the furring strips using the adaptable flashing system which allows flashing between the modules as depicted in fig. 3.

Table 1: Basic physical data (DuPont 2010). See also the studies by Jelle and Breivik (2012a) and Jelle et al. (2012) for information about DuPont Gevity.

Product	Area	Free space in frame	Glass thickness	Frame weight	Cells	Flashing material
DuPont Gevity 165M	1332.5 mm x 929 mm	820 mm x 1304 mm x 6 mm	4 mm	< 5.4 kg	5x8 mono-crystalline silicon cells	Pre-coloured galvanised steel

The limited size of the apparatus, although a large-scale apparatus, made it impossible to mount more than two BIPV modules together onto the sample roof. The BIPV modules were then surrounded by tailor-made steel fittings from DuPont as shown in fig. 2 (right). A 0.5 mm thick cold-rolled steel plate roofing (Isola Powertekk tile) was installed around the BIPV panels using 4.5 mm x 70 mm wood screws (Isola 2012). A heavy-duty siliconised paper (DuPont FlexWrap NF) was used as a seal between the steel roofing and the tailor-made DuPont steel fittings (DuPont 2008). The completed BIPV roof area is shown in fig. 4.

Fig. 2: Roof area with transparent Lexan board wind barrier with double furring strips (left), and the two DuPont Gevity - 165M BIPV modules surrounded by the tailor-made steel fittings from DuPont (right).

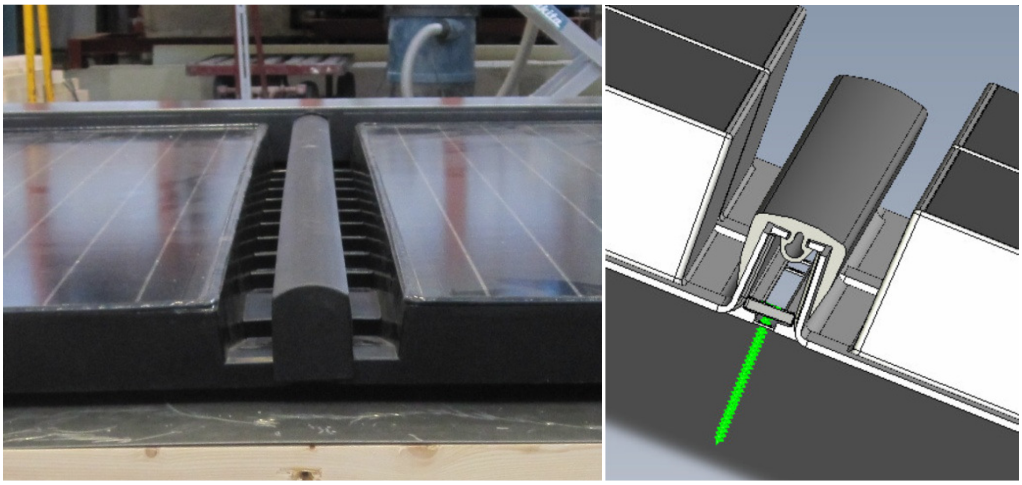

Fig. 3: Sleeve system which allows flashing between the modules (left) with detailed drawing of the sleeve flashing system splice (right) (DuPont 2010).

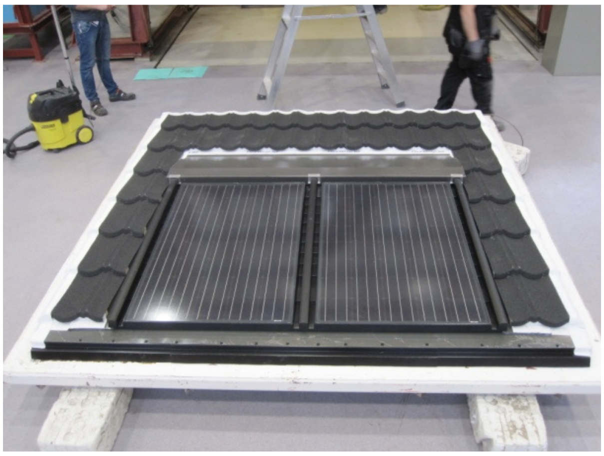

Fig. 4: Completed BIPV roof area with steel plate roofing.

2.2. Test method

The experimental testing was conducted in a large-scale turnable box for rain and wind tightness testing of sloping building surfaces (RAWI box) as depicted to the left in fig. 5. The RAWI box allows stepless variable inclination, controlled differential air pressure across the test specimen, running run-off water at the top of the test area, and spraying of wind-driven rain across the test area from a horizontal boom (row) (fig. 6, right) which moves back and forth (up and down) along the sample 0.6 m above the exterior roof surface. The sample roof was installed in the RAWI box as shown in fig. 5 (left and right), and the testing was carried out according to the principles given in EN 12865 and NT Build 421 with some minor modifications (European Committee for Standardization 2001, Nordtest Method NT Build 421, 1993). The rain tightness test was divided into three phases, as shown in table 2.

Table 2: Test phases for the large-scale turnable box for rain and wind tightness testing of sloping building surfaces (RAWI box).

Test phase 1	Test phase 2	Test phase 3
Run-off water without wind pressure.	Run-off water and wind-driven rain with pulsating positive differential pressure (overpressure) over the wind barrier.	Run-off water and wind-driven rain with pulsating positive differential pressure (overpressure) over the BIPV modules integrated with a steel plate roofing.

Fig. 5: Visual inspection of BIPV sample roof from below the inclined RAWI box (left) and sample roof inside the RAWI box during testing, viewed from outside the box through a window (right). The coloured ellipses denote leakage points.

2.2.1. Test phase 1 - Run-off water without wind pressure

During test phase 1 the BIPV sample roof was only exposed to run-off water without wind pressure or wind-driven rain. This was conducted at two different inclinations (30 and 15 degrees) for 10 minutes each (table 3). The run-off water was applied through a row of tubes situated just above the top of the sample, at a rate of 1.7 $dm^3/(m\ min)$ (Pedersen et al. 2008). During test phase 1 the BIPV sample roof was constantly and carefully visually monitored from below through the transparent wind barrier (fig. 5, left) with the purpose of observing any possible water leaks. After test phase 1 was completed, the sample roof was taken out of the RAWI box and thoroughly dried with a fan heater, as shown to the left in fig. 6.

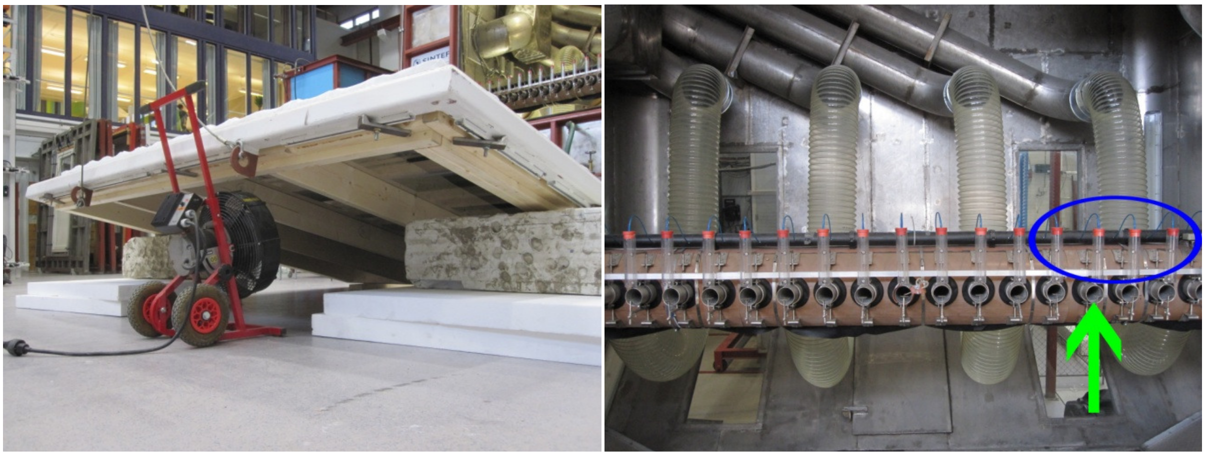

Fig. 6: Drying of BIPV sample roof with fan heater between test phases (left), and the boom inside the RAWI box which delivers wind-driven rain across the sample area (right). Water runs from the blue tubes on top (blue ellipse), drips down the transparent vertical cylinders (blue ellipse), and is blown onto the sample area as it hits the air stream that blows out of the air tubes (green arrow).

2.2.2. Test phase 2 - Run-off water and wind-driven rain with pulsating positive differential pressure over the wind barrier

During test phase 2 the BIPV sample roof was exposed to run-off water from the row of tubes situated just above the top of the sample, as in test phase 1. In addition, water was blown onto the sample, i.e. wind-driven rain, by means of air tubes with pulsating air velocities depicted in fig. 6 (right). The air tubes were mounted to a horizontal boom (fig 6, right) 0.6 m above the sample. The boom moved back and forth (up and down) along the surface of the sample at a velocity of 0.2 m/sec. Thus allowing the entire sample to be exposed to wind-driven rain at a rate of 0.3 $dm^3/(m^2min)$ (Pedersen et al. 2008, Pedersen et al. 2009). During test phase 2 both the velocity of pulsating air from the tubes and the pulsating positive pressure (overpressure) inside the RAWI box was increased with increments each 10 minutes (table 4). The transparent Lexan wind barrier board was continuous during test phase 2, thus almost absolutely airtight. Hence, the pulsating positive differential pressure occurred over the wind barrier. The BIPV sample roof was taken out of the RAWI box and thoroughly dried again after test stage 2.7 (table 4) was finished, before altering the inclination from 30 to 15 degrees at test stage 2.8. During each test stage of test phase 2 the BIPV sample roof was constantly and carefully visually monitored from below through the transparent wind barrier with the purpose of observing and recording possible water leaks, and when they occurred. The sample roof was taken out of the RAWI box and thoroughly dried again after test phase 2 was completed.

2.2.3. Test phase 3 - Run-off water and wind-driven rain with pulsating positive differential pressure over the BIPV modules integrated with a steel plate roofing

In order to carry out test phase 3 the wind barrier had to be punctured. Hence, before test phase 3 was started, a hole (37 cm x 43 cm) was cut in the Lexan wind barrier board with the purpose of creating an extra strain with the pulsating positive differential pressure occurring over the BIPV modules integrated with a steel plate roofing. However, the desired differential pressures (as obtained in test phase 2) could not be obtained inside the RAWI box due to the relatively air open steel plate roofing. The hole was sealed, and a smaller hole (7 cm x 43 cm) was made, but as the differential pressure inside the RAWI box was still unable to reach the desired levels, phase 3 was terminated.

3. Results and discussion

In test phase 1 no leakages were recorded throughout the BIPV sample roof at any of the different inclination levels, as table 3 shows.

Table 3: Test phase 1 with observations. Run-off water without wind pressure.

Test stage	Duration (min)	Inclination (degrees)	Run-off water	Wind-driven rain	Wind velocity (m/s)	Differential pressure (Pa)	Observations
1.1	10	30	Yes	No	0	0	No leakages
1.2	10	15	Yes	No	0	0	

In test phase 2, scattered droplets of water occurred on the wind barrier underneath the transition between the BIPV module and the tailor-made steel fitting at test stage 2.2 with 30 degrees roof inclination (see table 4), i.e. at 0-200 Pa pulsating differential pressure. No water leakages were detected at test stage 2.1 with 30 degrees roof inclination (0-100 Pa). The mentioned transition area is denoted with a large yellow ellipse in both fig. 5 and fig. 7, and the mentioned droplets of water are depicted to the left in fig. 8. This development continued throughout test stages 2.2-2.7 (see table 4). Wind-driven droplets of water kept occurring on the wind barrier in the mentioned area, but the wind barrier did not get any wetter throughout the final test stages of differential pressure at this inclination (30 degrees) than depicted in fig. 8 (left). However, at test stage 2.7, small droplets of water (fig. 8, right) occurred on the inside face of the steel plate roofing between the tailor-made steel fitting and the steel plate roofing, which is marked with a small red ellipse in both fig. 5 and fig. 7.

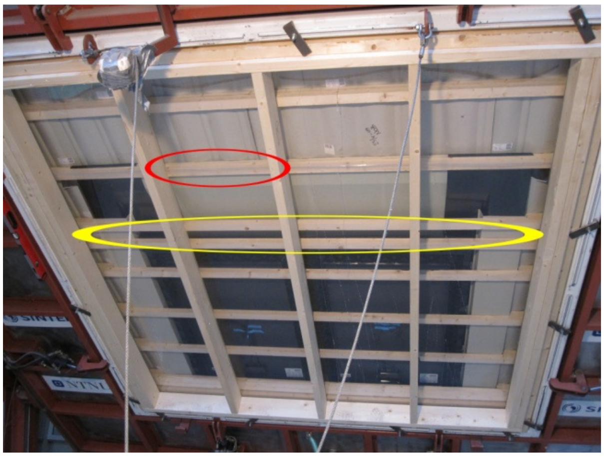

Fig. 7: The underside of the BIPV sample roof where the coloured ellipses denote leakage points.

Fig. 8: The droplets of water occurring on the wind barrier, marked with a large yellow ellipse (left), and the water droplets occurring between steel fitting and steel plate roofing, marked with small red ellipse (right).

After the BIPV sample roof was dried, test phase 2 continued with test stage 2.8, and the inclination was altered to 15 degrees. At test stage 2.8, scattered droplets of water occurred at the same location (on the wind barrier underneath the transition between the BIPV module and the tailor-made steel fitting, as marked with a large yellow ellipse in both fig. 5 and fig. 7), and in the same pattern as in the earlier test stages of this test phase (fig. 8, left). This development continued throughout test stages 2.8-2.14, but the wind barrier did not get any wetter altogether than it did in test stages 2.2-2.7 (fig. 8, left). At test stage 2.11 similar small droplets as the ones depicted to the right in fig. 8 occurred at the same location (between the tailor-made steel fitting and the steel plate roofing, as marked with a small red ellipse in fig. 5 and fig. 7). This occurrence of water did not grow throughout test stages 2.11-2.14. No other leakages than those mentioned earlier, were observed during the test phases.

Table 4: Test phase 2 with observations. Run-off water and wind-driven rain with pulsating positive differential pressure over of the wind barrier.

Test stage	Duration (min)	Inclination (degrees)	Run-off water	Wind-driven rain	Wind velocity[a] (m/s)	Differential pressure[b] (Pa)	Observations
2.1	10	30	Yes	Yes	0-12.9	0-100	No leakages
2.2	10	30	Yes	Yes	0-18.2	0-200	Scattered droplets of water on wind barrier underneath transition between BIPV and steel fitting (large yellow ellipse in fig. 5, fig. 7 and fig. 8)
2.3	10	30	Yes	Yes	0-22.3	0-300	
2.4	10	30	Yes	Yes	0-25.8	0-400	
2.5	10	30	Yes	Yes	0-28.8	0-500	
2.6	10	30	Yes	Yes	0-31.6	0-600	
2.7	10	30	Yes	Yes	0-35.3	0-750	Additional small droplets on inside face between steel fitting and steel plate roofing (small red ellipse in fig. 5, fig. 7 and fig. 8)
2.8	10	15	Yes	Yes	0-12.9	0-100	Scattered droplets of water on wind barrier underneath transition between BIPV and steel fitting (large yellow ellipse in fig. 5, fig. 7 and fig. 8)
2.9	10	15	Yes	Yes	0-18.2	0-200	
2.10	10	15	Yes	Yes	0-22.3	0-300	
2.11	10	15	Yes	Yes	0-25.8	0-400	Additional small droplets on inside face between steel fitting and steel plate roofing (small red ellipse in fig. 5, fig. 7 and fig. 8)
2.12	10	15	Yes	Yes	0-28.8	0-500	
2.13	10	15	Yes	Yes	0-31.6	0-600	
2.14	10	15	Yes	Yes	0-35.3	0-750	

[a)] Wind velocities are calculated from $v=(2p/\rho_a)^{1/2}$, where p is the differential pressure in Pa and ρ_a is the air density in kg/m^3 (here equal to 1,204 kg/m^3).
[b)] Pulsating positive differential pressure over the wind barrier, i.e. pulsating overpressure inside RAWI box relative to the surrounding laboratory.

During test phase 2 water droplets occurred on the wind barrier at a lower level of pulsating differential pressure (0-100 Pa) when the sample roof had an inclination of 15 degrees, compared to the level of pulsating differential pressure (0-200 Pa) the droplets occurred at when the sample roof had an inclination of 30 degrees. This is a result of slower run-off and larger accumulation of water on the sample roof surface due to smaller inclination. Hence, roofs with low inclination are more vulnerable to water penetration than roofs with high inclination.

Before test phase 3 started a hole was cut in the Lexan wind barrier board with the purpose of creating an extra strain with the pressure occurring over the BIPV modules integrated with the steel plate roofing. This corresponds to an extreme situation with BIPV modules mounted onto a non-insulated roof, e.g. a garage roof without any wind barrier or underroof beneath. But, as earlier mentioned, the differential pressure levels which the test required could not be obtained inside the RAWI box due to the relatively air open steel plate roofing. Thus test phase 3 was terminated without results.

The differential pressures occurring over the BIPV sample roof in these laboratory investigations translates to the wind forces shown in table 5.

Table 5: The differential pressures occurring in the laboratory investigations and their corresponding wind velocities compared to the Beaufort wind force scale.

Differential pressure (Pa)	100	200	300	400	500	600	750
Wind velocity[a] (m/s)	12.9	18.2	22.3	25.8	28.8	31.6	35.3
Beaufort wind force scale	Strong breeze (6)	Fresh gale (8)	Strong gale (9)	Storm (10)	Violent storm (11)	Violent storm (11)	Hurricane force (12)

[a)] Wind velocities are calculated from $v=(2p/\rho_a)^{1/2}$, where p is the differential pressure in Pa and ρ_a is the air density in kg/m^3 (here equal to 1,204 kg/m^3).

In these laboratory investigations the PV cells used in the BIPV modules were monocrystalline, thus it is very important to achieve a sufficient ventilation rate, as the solar cell efficiency is normally reduced with increasing temperature (Jelle and Breivik 2012a, Jelle and Breivik 2012b, Jelle et al. 2012, Wei et al. 2011). As depicted in fig. 9 the DuPont Gevity BIPV modules and the surrounding tailor-made steel fittings are constructed to obtain sufficient ventilation rates. The scattered water droplets which occurred on the wind barrier during testing (fig. 8, left) was transported with the airflow through the openings made in the tailor-made steel fittings for ventilation, as illustrated with blue arrows in fig. 9.

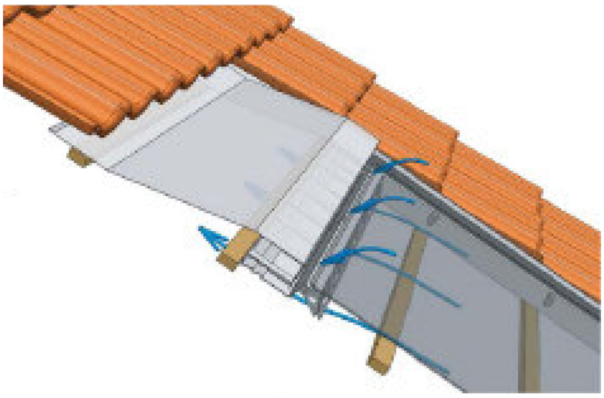

Fig. 9: Ventilation of the DuPont Gevity BIPV modules (DuPont 2010).

In order to prevent water penetration, the steel fittings surrounding the BIPV modules should ideally be better adapted to the BIPV modules, and the ventilation gaps should be constricted to some extent. This will, however, cause the ventilation rate to suffer, thus the degree of constriction must be evaluated in order to keep an acceptable ventilation rate. Moreover, the need for ventilation through these fittings depends on the roof construction beneath the BIPV modules, i.e. if the roof construction is well ventilated with an air gap between the underroof and the roofing, additional ventilation through these fittings (as illustrated with blue arrows in fig. 9) may not be necessary. Hence, if BIPV modules like the ones in question are mounted onto a roof construction with a well ventilated underroof, one can constrict the surrounding steel fittings to a greater extent, and obtain better rain tightness, without consideration for blocking the ventilation through these fittings.

The testing has demonstrated that the sample roof with the BIPV module system withstood the heavy wind-driven precipitation sufficiently. No leakages were detected in connection with the splices.

Nevertheless, different other leakage points were detected. A small quantity of penetrating water, such as detected during this investigation, will unlikely cause moisture problems for an adequately constructed and ventilated underroof (with an air gap between the underroof and the roofing). Thus, these leakages were not critical in terms of causing moisture problems for the roof construction, nevertheless they are still unwanted. However, if more severe leakages should occur, the water-resistance of the materials and the water tightness, drainage and drying out capability of the underroof in question determines whether it will lead to moisture problems in the roof construction or not.

In further studies, ideally four BIPV modules should be mounted together with the objective of testing both the vertical and the horizontal joint splices. This however, would require a rather large large-scale apparatus.

4. Conclusions

In this study a sample roof with two BIPV modules went through large-scale testing with run-off water and wind-driven rain with incremental pulsating differential overpressure over the sample at two different inclinations (15 and 30 degrees). The BIPV sample roof was constructed as a real roof would have been constructed, with steel plate roofing, double furring strips and an airtight wind barrier beneath. The aim of this work was to illustrate challenges linked to the building envelope properties of a BIPV system, and to develop and evaluate relevant methods for testing the building envelope properties of BIPV systems. Hence, the purpose of these experimental investigations was to imitate real climate conditions, where a roof experiences pressure differences primarily over the wind barrier.

The laboratory investigations proved that the sample roof with the BIPV module system withstood the heavy wind-driven precipitation sufficiently. No leakages were detected in connection with the splices. Nevertheless, different other leakage points were detected, and although not influential, leakages are still unwanted. Depending on the water tightness of the underroof, small leakages like the ones detected in these laboratory investigations would unlikely lead to any moisture problems as long as the roof construction is adequately constructed and ventilated, i.e. with an underroof of sufficient water tightness and water-resistant materials, and with drainage and drying out capability. In order to prevent such water penetration, the tailor-made steel fittings surrounding the BIPV modules, which are made to allow a sufficient ventilation rate, should ideally be better adapted to the BIPV modules, and the ventilation gap constricted to some extent. However, the degree of constriction must be evaluated to keep an acceptable ventilation rate in order not to reduce the solar cell efficiency. The need for ventilation through these fittings depends on how well the roof construction beneath the BIPV modules is ventilated, i.e. additional ventilation through these fittings may not be necessary to obtain a sufficient ventilation rate if the roof construction is ventilated with an air gap between the underroof and the roofing. Hence, if BIPV modules are mounted onto a roof construction with a well ventilated underroof, one can, without consideration for blocking the ventilation through these fittings, constrict the surrounding steel fittings, and thus obtain enhanced rain tightness. In addition, this work demonstrates a suitable rain tightness test method for BIPV systems.

Acknowledgements

This work has been supported by the Research Council of Norway and several partners through the NTNU and SINTEF research project ”The Research Centre on Zero Emission Buildings” (ZEB).

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Appendix A

B. P. Jelle, C. Breivik and H. D. Røkenes, "Building Integrated Photovoltaic Products: A State-of-the-Art Review and Future Research Opportunities", *Solar Energy Materials and Solar Cells*, **100**, 69-96, 2012.

Solar Energy Materials & Solar Cells 100 (2012) 69–96

Contents lists available at SciVerse ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Review

Building integrated photovoltaic products: A state-of-the-art review and future research opportunities

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ARTICLE INFO

Article history:
Received 21 December 2010
Received in revised form
14 December 2011
Accepted 19 December 2011
Available online 3 February 2012

Keywords:
Building integrated photovoltaic
BIPV
State-of-the-art
Review
Future

ABSTRACT

Building integrated photovoltaics (BIPVs) are photovoltaic (PV) modules integrated into the building envelope and hence also replacing traditional parts of the building envelope, e.g. the roofing. In this context, the BIPVs integration with the building envelope limits the costs by serving dual purposes. BIPVs have a great advantage compared to non-integrated systems because there is neither need for allocation of land nor stand-alone PV systems. This study seeks to outline various commercially available approaches to BIPVs and thus provides a state-of-the-art review. In addition, possible future research opportunities are explored.

The various categories of BIPVs may be divided into photovoltaic foils, photovoltaic tiles, photovoltaic modules and solar cell glazings. Silicon materials are the most commonly used, and a distinction is made between wafer-based technologies and thin-film technologies. In addition, various non-silicon materials are available. The main options for building integration of PV cells are on sloped roofs, flat roofs and facades. The evaluation of the different BIPV products involves, among others, properties such as solar cell efficiency, open circuit voltage, short circuit current, maximum effect and fill factor.

It is expected that the BIPV systems will improve in the years to come, regarding both device and manufacturing efficiency. The future seems very promising in the BIPV industry, both concerning new technologies, different solutions and the variety of BIPV options.

Contents

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doi:10.1016/j.solmat.2011.12.016

1. Introduction

Currently, the world is using fossil fuel at an alarming rate that not only will strain the sources in the near future, but will result in a great amount of pollution as well. The power industry emissions were 10.9 gigatonnes of carbon dioxide equivalents ($GtCO_2e$) per year in 2005, i.e. 24% of global Greenhouse Gas (GHG) emissions, and this is expected to increase to 18.7 $GtCO_2e$ per year in 2030 [41]. "Carbon dioxide equivalent is the unit for emissions that, for a given mixture and amount of greenhouse gas, represents the amount of CO_2 that would have the same global warming potential (GWP) when measured over a specified timescale (generally 100 years)" [41].

Of all the renewable energy resources currently available, solar energy is the most abundant, inexhaustible and clean one [48]. In one day, the irradiation from the sun on the earth gives about 10,000 times more energy than the daily use from mankind [61]. The challenge is collecting this available energy at a reasonable cost.

One of the most promising renewable energy technologies is photovoltaics. "Photovoltaics (PV) is a truly elegant means of producing electricity on site, directly from the sun, without concern for energy supply or environmental harm" [60].

Building integrated photovoltaics (BIPVs) are photovoltaic materials that replace conventional building materials in parts of the building envelopes, such as the roofs or facades. Furthermore, "BIPV are considered as a functional part of the building structure, or they are architecturally integrated into the building's design" [48]. The BIPV system serves as building envelope material and power generator simultaneously [60]. BIPVs have a great advantage compared to non-integrated systems because there is neither need for allocation of land nor facilitation of the PV system. Illustrating its importance, BIPVs are considered as one of four key factors essential for future success of PV [50]. The on-site electricity producing PV modules can reduce the total building material costs and achieve significant savings in terms of the mounting costs, especially since BIPVs do not require additional assembly components such as brackets and rails [43]. The BIPV system simply makes electricity out of sunlight, with no pollution. All these advantages have caused a worldwide growing interest in BIPV products [60].

The purpose of this study is to get an overview of the different BIPV producers and products, and to evaluate which products are the most suitable for different purposes. Furthermore, it is important to know to what extent BIPV products have been tested with respect to long time durability. These investigations may then form the background and backbone for a testing scheme of BIPV products and indicate future research opportunities. This work gives many tables with a lot of information, e.g. manufacturers, product names and various properties, both in the main text and in the appendices. Some of these properties are very important and even crucial to the performance of the various products. Hence, the tables provide the readers with valuable information concerning these products. However, unfortunately it is often hard to obtain all the desired information (e.g. product properties) from all the manufacturers. In general, many property values are often not available at the manufacturers' websites or other open information channels, which is then seen as open spaces in the tables within this work. Hopefully, our addressing of this fact could act as an incentive for the manufacturers to state all the important properties of their products at their websites and other information channels, and also as an incentive and reminder for the consumers and users to demand these values from the manufacturers.

2. Solar cell concepts

The development of building integrated photovoltaic (BIPV) systems follows the development within photovoltaic (PV) cells in general. Hence, some aspects of the PV industry will first be addressed, before moving on to the BIPV technology. The most commonly used solar cells are made from high-grade silicon, which is processed with negatively and positively charged semiconductors phosphorous and boron. When the light energy from the sun hits the photovoltaic cell, electrons are free to flow from the negative phosphorus to the positive boron. The current produced from the electric potential can be harnessed through a metal grid covering the cell and external circuit.

2.1. Silicon based photovoltaic cells

Silicon is the most commonly used material for PV modules. Types of silicon materials for solar cells are monocrystalline, polycrystalline and amorphous silicon. In addition there are ribbon cast polycrystalline cells that are produced by drawing, through ribbons, flat thin films from molten silicon, thus saving production costs due to reduction in silicon waste as no sawing from ingots is required, though at expense of lower solar cell efficiencies. Non-silicon based PV materials are gallium arsenide (GaAs), cadmium telluride (CdTe), copper indium diselenide (CIS) and copper indium gallium selenide (CIGS). Fig. 1 gives an overview of the different main PV technologies [50]. Monocrystalline silicon cells are made from pure monocrystalline silicon and have the highest efficiencies, but also slightly higher prices. The color is usually black or gray. The polycrystalline silicon cells are produced using ingots of multi-crystalline silicon. Due to an easier manufacturing process, the polycrystalline silicon cells are less expensive, but also less effective. They are recognized by the

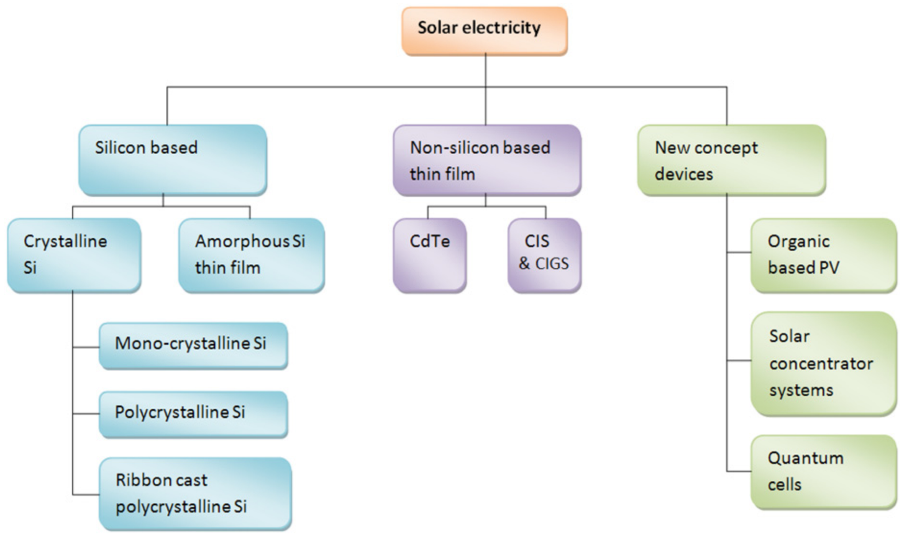


Fig. 1. PV technologies. Redrawn from Raugei and Frankl [50].

shiny blue color that comes from the many small crystals. Polycrystallines and monocrystallines form the wafer-based technologies. Amorphous silicon cells consist of a very thin layer of un-crystallized silicon deposited onto a substrate. This makes the cells thinner and amorphous cells are also referred to as thin-film cells. The color is brownish or reddish brown. Typical efficiencies for monocrystalline cells are 16–24%, and the most efficient monocrystalline modules to date have efficiencies of approximately 20% [13,24,56,70]. For polycrystalline cells the efficiency is typically 14–18% [24,66]. Amorphous silicon cell efficiencies vary from 4% to 10% [4,24,42,64]. The power per unit area is typically 75–155 Wp/m^2 for monocrystalline and polycrystalline modules, and 40–65 Wp/m^2 for thin-film modules [62]. See the later following Fig. 14 for a timeline for reported best research-cell efficiencies [71].

2.2. Non-silicon based photovoltaic cells

Other thin-film cells in addition to amorphous silicon are CdTe, CIS and CIGS. Buecheler et al. [8] names CdTe and CIGS as the most promising technologies for cost-effective decentralized solar electricity production. CdTe solar cells are manufactured on a substrate glass with a transparent conducting oxide (TCO) layer usually made from flourinated tin oxide (FTO) as the front contact. This is initially coated with an n-type cadmium sulpfide (CdS) window layer and secondary with the p-type CdTe absorber layer. CdTe technology has the lowest production costs among the current thin-film modules, and is one of the most promising for wide scale application [34]. The color is reflective dark green to black and typical cell efficiencies are 9.4–13.8% [8,34,64]. CIS and CIGS cells are currently the most effective of the thin-film cells with typical cell efficiencies of 11–18.7% and the color is dark gray to black [8,24,28,51,64]. The most efficient CIS/CIGS modules to date have efficiencies of approximately 13% [56]. Values for the highest reported efficiencies of CdTe and CIGS solar cells are shown in Fig. 2 [8]. See the later following Fig. 14 for a timeline for reported best research-cell efficiencies [71].

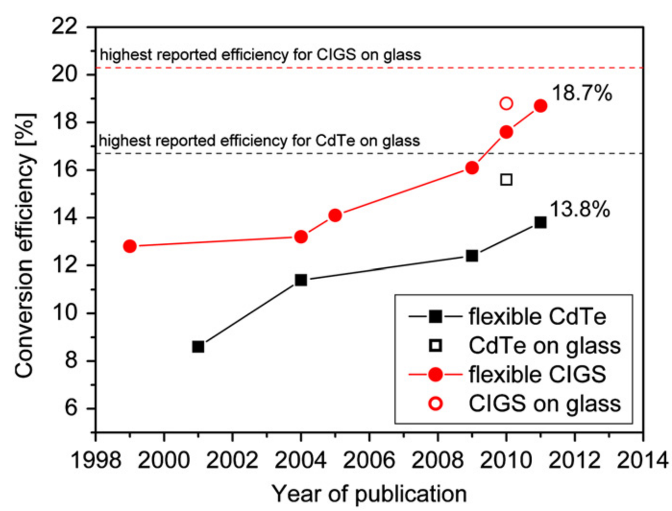


Fig. 2. Conversion efficiencies of flexible CdTe and CIGS solar cells fabricated by low temperature processes. Also shown is the in-house reference on glass and the highest reported efficiency for each technology [8].

2.3. Solar cell production

The solar cells are strung together in series to one or more strings of several solar cells. Thin-film materials can be made directly into modules. This is done by sputtering the cell material onto a substrate of glass, polyamide or stainless steel and then it is interconnected by laser to a module. The cells in the PV module are encapsulated between a transparent cover and weatherproof backing. In order to be protected from the external environment, the solar cells are usually laminated with a tempered, low iron-content glass on the front. The glass is inexpensive, strong and stable with high transparency, and it prevents penetration of water, water vapor and gases.

On the rear side there is usually a thin polymer sheet or, if the module is bi-facial or semi-transparency is wanted, glass is used. On each side of the cell there is a layer of ethylvinylacetate (EVA) to provide adhesion. The stability of this encapsulant is one of the major contributors to the durability of the module. To increase strength an aluminum frame is sometimes introduced. Modules can be connected in series to strings and then in parallel to form larger units, arrays. The modules or arrays give power to components transporting and converting the DC electricity into AC electricity.

2.4. Building integration of photovoltaic cells

The four main options for building integration of PV cells are on sloped roofs, flat roofs, facades and shading systems. South-facing sloped roofs are usually best suited for PV installation because of the favorable angle with the sun. One option is to mount PV modules above the roofing system. Another option is PV modules that replace conventional building materials in parts of the building envelopes, such as the roofs or facades, i.e. BIPVs. ''BIPV are considered a functional part of the building structure, or they are architecturally integrated into the building's design'' [48]. The BIPV system serves as building envelope material and power generator simultaneously [60]. This can provide savings in materials and labor, and also reduce the electricity costs, but obviously increases the importance of water tightness and durability of the BIPV product.

An elevated temperature in the module decreases the performance of the solar cells, especially for mono- and polycrystalline modules. Therefore, an air gap underneath the module is important to decrease the temperature. The thin-film products, on the other hand, perform more independently of the temperature.

For flat roofs there are three options: (1) modules mechanically fixed to the roof structure, (2) based on weight foundation and (3) an integrated solution. Depending on the geographical position of the structure, the PV modules might have to be inclinated. This is more difficult with integrated solutions. The integrated systems can include the properties of one roofing element or several. Lack of air flow underneath the module can be a challenge (in order to decrease the temperature). The use of PV in the facade can replace a glass or tile skin. Geographic position plays an important role when planning the use of photovoltaic cells in facades, and the output is higher at northern and southern latitudes. The two main categories are ventilated and non-ventilated facades. The category sets the criteria for the choice of solar cell material.

The area to be covered by PV modules varies from case to case. In general, areas that are shaded for the majority of the day should be avoided. If the project is subsidized, the subsidies might be given for a certain level of power produced, and therefore the size of the PV-covered area may depend upon this. This can lead to solutions with only a few spread PV modules, and therefore some producers offer dummy modules to provide a more aesthetical and consistent look for the roof or facade.

2.5. Architectural aspects of BIPVs

BIPV systems provide many opportunities for innovative architectural design and can be esthetically appealing. BIPVs can act as shading devices and also form semi-transparent elements of fenestration [30,44]. Amorphous silicon tiles can be used to make a BIPV roof look very much like a standard tiled roof (as shown in Fig. 3), while on the other hand semi-transparent modules can be used in facades or glass ceilings to create different visual effects (as shown in Fig. 4). Some architects enjoy presenting a BIPV roof as a roof giving a clear visual impression, while others want the BIPV roof to look as much as a standard roof as possible. Further 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 [72], Farkas et al. [73] and Peng et al. [48], respectively.

3. State-of-the-art building integrated photovoltaic products

3.1. General

The evaluation of the different BIPV products may involve the following property parameters:

- Solar cell efficiency $\eta = P_{max}/(EA)$, where P_{max} is the maximum power point in W or Watt-peak (Wp), E is the input light irradiance in W/m^2 and A is the surface area of the solar cell in m^2
- Open circuit potential or voltage, U_{OC}
- Short circuit electrical current, I_{SC}
- Maximum power point, $P_{max} = (UI)_{max}$
- Fill factor FF is given by $FF = P_{max}/(U_{OC}I_{SC}) = (UI)_{max}/(U_{OC}I_{SC})$
- Band gap, E_g
- Quantum yield, ϕ = no. of photo-electrons/no. of photons

Fig. 3. Curved clay looking solar tiles [55].

Fig. 4. Glass ceiling with transparent BIPV modules [21].

The values are achieved by the manufacturers using mainly Standard Test Conditions (STC) and also Nominal Operating Cell Temperature (NOCT).

The air mass (AM) determines the radiation impact and the spectral combination of the light arriving on the surface of the earth [16]. The air mass coefficient is given by $AM = L/L_0 \approx 1/(\cos z)$, where L is the path length through the atmosphere for solar radiation at angle z relative to the normal to the earth's surface, L_0 is the zenith path length (i.e. normal to the earth's surface) at sea level and z is the zenith angle in degrees [69].

The Standard Test Conditions (STC) and the Nominal Operating Cell Temperature (NOCT) test conditions are given in Table 1.

3.2. Building integrated photovoltaic related standards

The European Standard EN 61646 "Thin-film terrestrial photovoltaic (PV) modules—design qualification and type approval" gives detailed test procedures for PV modules. It is equal to International Standard IEC 61646. The procedures consist of (1) visual inspection, (2) maximum power determination, (3) insulation test, (4) measurements of temperature coefficients, (5) measurement of NOCT, (6) performance at STC and NOCT, (7) performance at low irradiance, (8) outdoor exposure test, (9) hot-spot endurance test, (10) UV preconditioning test, (11) thermal cycling test, (12) humidity-freeze test, (13) damp heat test, (14) robustness of terminations test, (15) wet leakage current test, (16) mechanical load test, (17) hail test, (18) bypass diode thermal test, and (19) light-soaking [20]. EN 61215, equal to IEC 61215, "Crystalline silicon terrestrial photovoltaic (PV) modules—design qualification and type approval" includes the same tests as EN 61646 with one exception: light-soaking [17].

The EN 61730 gives the photovoltaic (PV) module safety qualification. Part 1 gives the requirements for construction while the content of part 2 is the requirements for testing. The procedures are as follows (1) visual inspection MST 01, (2) accessibility test MST 11, (3) cut susceptibility test MST 12, (4) ground continuity test MST 13, (5) impulse voltage test MST 14, (6) dielectric withstand test MST 16, (7) temperature test MST 21, (8) fire test MST 23, (9) reverse current overload test MST 26, (10) module breakage test MST 32 [18,19].

The procedures of the standards can be similar, but as described above they apply for the various cases of thin-film, crystalline silicon and module safety.

The manufacturers from USA relate to the standard UL 1703 "UL Standard for Safety Flat-Plate Photovoltaic Modules and Panels". It includes both the construction and the performance of the PV module. The tests procedures given are as follows: (1) temperature test, (2) voltage, current and power measurements tests, (3) leakage current test, (4) strain relief test, (5) push test, (6) cut test, (7) bonding path resistance test, (8) dielectric voltage-withstand test, (9) wet insulation–resistance test, (10) reverse current overload test, (11) terminal torque test, (12) impact test, (13) fire test, (14) water spray test, (15) accelerated ageing test, (16) temperature cycling test, (17) humidity test, (18) corrosive atmosphere test, (18) metal coating thickness test, (19) hot-spot endurance test, (20) arcing test, (21) mechanical loading test and (22) wiring compartment securement test [65]. This standard describes more test procedures than the European standards and might therefore seem more thorough.

Table 1
STC and NOCT test conditions.

	Irradiance (W/m^2)	Temperature of PV cell (°C)	Ambient air temperature (°C)	Solar radiation distribution	Wind speed (m/s)
STC	1000	25	–	AM1.5	–
NOCT	800	–	20	–	1

3.3. Building integrated photovoltaic products

There is a wide range of different BIPV products, which can be categorized in different ways. In this work the categorization is mainly based on how the manufacturer describes the product, and what other type of material the product is customized to be combined with. The product categories considered are foils, tiles, modules and solar cell glazing products. The modules can normally be used with various kinds of roofing material. The solar cell glazing products can be integrated in the facade, roof or in fenestration products, e.g. windows, and provide various esthetic solutions. Some products hold a variety of properties, thus making it more difficult to categorize them. This study has been carried out on a variety of products and the tables in Appendices A–D denote a representative selection of state-of-the-art BIPV products. This study is limited to BIPVs. Nevertheless, in Appendix E there are given building attached photovoltaic (BAPV) products that are not BIPVs, or it is uncertainty regarding how the product is mounted. Peng et al. [48] refers to BAPV as an add-on to the building, thus not directly related to the structure's functional aspects.

3.3.1. BIPV foil products

The BIPV foil products are lightweight and flexible, which is ideal for easy installation and the weight constraints most roofs have. The photovoltaic 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, there are few producers in the market that provide weather tight solutions. Table 2 presents an example of one foil product, showing the open circuit potential/voltage U_{OC}, short circuit current I_{SC}, maximum power point P_{max} and the fill factor FF. A full table containing more information can be found in Appendix A.

The fill factor is low for photovoltaic foil products due to both the low efficiency and the large solar cell resistances of thin-film cells, in this case amorphous silicon cells. However, it is possible to vary the degree of inclination of the product to a great extent providing flexible solutions. The foil product uses the PV laminates from Uni-Solar and is tested and approved according to, amongst others, EN 61646 and EN 61730 [18–20].

3.3.2. BIPV tile products

The BIPV tile products can cover the entire roof or just 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 tiles. This is a good option for retrofitting of roofs. The cell type and tile shape varies. Some tile products resemble curved ceramic tiles (see Fig. 3) and will not be area effective due to the curved surface area, but may be more esthetically pleasing. Table 3 gives examples of four photovoltaic tile products that are on the market today.

STEPdesign, Solar Flat Tile and C21e Tile (Table 3) 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

Table 2
Literature data for one of the BIPV foil products (references and further details given in Appendix A).

Manufacturer	Product[a]	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Material
Alwitra GmbH & Co.	Evalon V Solar 408		138.6	5.1	408/module	0.58	1550 × 6000	42.9	Amorphous silicon cells
	Evalon V Solar 136		46.2	5.1	136/module	0.58	1050 × 3360	38.5	Amorphous silicon cells

[a] Several models are available from the producer in the Evalon V Solar series.

Table 3
Literature data for some of the BIPV tile products (references and further details given in Appendix B).

Manufacturer	Product[a]	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Material
Solar-dachstein	STEP-design		23.15	2.40	1.36/cell	0.76	8 units 100 × 100	136	Poly-crystalline silicon cells
SRS Energy	Solé Powertile		6.3	4.6	15.75/module	0.54	868 × 457.2	39.7	Amorphous silicon cells from Uni-Solar
Lumeta	Solar Flat Tile		7.4	5.2	28/module	0.73	432 × 905	71.6	Mono-crystalline silicon cells
Solar Century	C21e Tile	20/cell	12.0	5.55	52/module	0.78	1220 × 420	101.5	Mono-crystalline cells

[a] Lumeta has also a Solar S Tile available.

Table 4
Literature data for some of the BIPV module products (references and further details given in Appendix C).

Manufacturer	Product[a]	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Material
Creaton AG	Creaton Solesia		13.86	8.46	90/module	0.77	1778 × 355	142.6	Mono-crystalline silicon cells
Rheinzink	PV Quickstep		17.10	5.12	68/module	0.78	2000 × 365	93.2	Crystalline silicon cells
Abakus Solar AG	Peak On P220-60	13.2	36.77	8.22	220	0.73	1667 × 1000	132.0	Poly-crystalline silicon cells
	Peak On P235-60	14.6	37.21	8.48	235	0.74	1630 × 1000	144.2	Poly-crystalline silicon cells
	ANT P6-60-230	14.07	36.77	8.42	230	0.74	1658 × 986	140.7	Poly-crystalline silicon cells
DuPont	Gevity	17.7	24.20–24.43	8.77–8.87	160–165	0.75–0.76	1332.5 × 929	129.36–133.4	Mono-crystalline silicon cells
Suntech	MSZ-190J-D		45.2	5.62	190/module	0.75	1641 × 834.5	139	Mono-crystalline silicon cells
	MSZ-90J-CH		22.4	5.29	90/module	0.76	879 × 843.5	125	Mono-crystalline silicon cells
Schott Solar	InDax 214	12.5	36.3	8.04			1769 × 999		Poly-crystalline silicon cells
	InDax 225	13.1	33.5	6.60			1769 × 999		Poly-crystalline silicon cells
Solar Century	C21e Slate	20/cell	12.0	5.55	52	0.78	1174 × 318	139.3	Mono-crystalline silicon cells

[a] Several models are available from various producers.

standard roof tiles. The module has an integrated panel of poly- or monocrystalline cells. This means that parts of the module are not covered with photovoltaic cells, and therefore the total area efficiency will not be as high as indicated. The solution from Solardachstein can be mounted on several different tile products. C21e Tile has a larger active area than the previous products since monocrystalline silicon cells cover the entire module area. It is compatible with a series of named tiles and slates. Solé Powertile has a design much like standard roof tiles and the amorphous silicon cell cover from Uni-Solar acts as the skin of the tiles. Solardachstein's STEPdesign is approved according to EN 61215, while Lumeta's and Solar Century's products are certified with EN 61215 and EN 61730 [17–19]. For further details see Appendix B.

3.3.3. BIPV module products

The BIPV module products presented are somewhat similar to conventional PV modules. The difference, however, is that they are made with weather skin solutions. Some of the products can replace different types of roofing, or they fit with a specific roof solution produced by its manufacturer, e.g. Rheinzink's "Solar PV Click Roll Cap System" [52]. 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 functioning as weather skin. Other products are not very specific on how they are mounted, which leads to uncertainty whether they are BIPVs or BAPVs. Some of the products in this category are premade modules with insulation or other elements included in the body. Table 4 gives examples of BIPV module products.

Creaton AG, Rheinzink and Suntech obtain approximately the same fill factor for their products. Abakus Solar, DuPont and Schott Solar do not provide a value for the maximum power, but are three of the few producers that provide a value for the module efficiency. The efficiency for Abakus Solar is between 12.7% and 14.6%, DuPont provides an efficiency of 17.7%, while Schott Solar's models are given with 12.5–13.1%. Solar Century reports an efficiency of 20% per cell for their C21e Slate. The distinction comes from the different materials, polycrystalline versus monocrystalline. Rheinzink have approved their product according to EN 61215, while both EN 61215 and EN 61730 have been applied for Abakus Solar's products, Dupont's Gevity, Suntech's products and Schott Solar's InDax [17–19]. For further details see Appendix C.

3.3.4. Solar cell glazing products

Solar cell glazing products provide a great variety of options for windows, glassed or tiled facades and roofs. Different colors and transparencies can make many different esthetically pleasing results possible. The modules transmit daylight and serve as water and sun protection. "The technology involves spraying a coating of silicon nanoparticles on to the window, which work as solar cells" [30]. The distance between the cells depends on wanted transparency level and the criteria for electricity production, but normally the distance is between 3 and 50 mm. The space in between cells transmits diffuse daylight. This way, both shading and natural lighting are provided while producing electricity. The producers of solar cell glazing products usually offer customized products for the specific project, whereas Table 5 presents some predefined modules.

The producers also offer customized modules regarding shape, cell material, color and transparency level, i.e. distance between cells. Values for the efficiencies are not given for these products, but for Voltarlux a FF value of 0.55 is given with a transparency level of 10%. The transparency level varies from 16% to 41%, respectively, for smallest to largest size, for the Vidursolar models, and is 25% for Abakus' Peak In P210-60. Other products and further details, including description of customized solutions, can be found in Appendix D.

3.3.5. Building attached photovoltaic products

The BAPV products are, as mentioned earlier, added on rather than integrated in the roof or facade. These products are not focused on in this study, but it is still interesting to have a look at

Table 5
Literature data for some solar cell glazing products (references and further details given in Appendix D).

Manufacturer	Product[a]	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Material
Abakus Solar AG	Peak In P210-60		36.50	7.70			2000 × 1066		Poly-crystalline silicon cells
Vidursolar	FV VS16 C36 P120		21.6	7.63			1600 × 720		Poly-crystalline silicon cells
Glaswerke Arnold GmbH & Co KG	Voltarlux-ASI-T-Mono 4-fach		93	1.97	100/ module	0.55	2358 × 1027	41.3	Amorphous silicon cells from Schott Solar
Schott Solar	ASI THRU-1-L	6	111	0.55	48	0.79	1122 × 690	62.0	Amorphous silicon cells
	ASI THRU-4-IO	6	111	2.22	190	0.77	1122 × 2619	64.7	Amorphous silicon cells
Sapa Building System	Amorphous silicon thin film	5/cell			32/cell		576 × 976/cell	50	Amorphous silicon thin film
	Poly-crystalline	16/cell			1.46–3.85/cell		156 × 156/cell	120	Poly-crystalline
	Mono-crystalline high efficient	22/cell			2.90–3.11/cell		125 × 125/cell	155	Mono-crystalline high efficient

[a] Several models are available from various producers.

Table 6
Literature data for some of the building attached photovoltaic (BAPV) products (references and further details given in Appendix E).

Manufacturer	Product[a]	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Material
Uni-Solar	PVL-68		23.1	5.1	68/module	0.58	2849 × 394	60.6	Amorphous silicon cells
	PVL-144		46.2	5.3	144/module	0.59	5486 × 394	66.6	Amorphous silicon cells
Hauptsitz	SunPower 220 Solar Panel	17.7	48.6	5.75			1559 × 798		Mono-crystalline silicon cells
Isofoton	ISF-240	14.5	37.1	8.45	240	0.77	1667 × 994	144.8	Mono-crystalline silicon cells

[a] Several models are available from various producers.

some of them. In addition, Uni-Solar is used by several other manufacturers as given in Sections 3.3.1 and 3.3.2. Table 6 gives the properties for some of the BAPV products.

The laminate from Uni-Solar is flexible, thus making it easy to incorporate it with other building materials. It is tested according to UL 1703, EN 61646 and EN 61730 [18–20,65]. The efficiency for Hauptsitz' product is 17.7% and Isofoton states an efficiency of 14.5% for their product. Further details and a small selection of various BAPV products are given in Appendix E.

3.3.6. *Comparison*

The tile products are more likely to be used on tiled roofs, i.e. residential houses. Due to the easy retrofitting with these products, this market is large, e.g. for roofs on residential buildings there is a 6800 km^2 BIPV area potential, fulfilling good solar yield criteria (80% of the maximum local annual solar input), in the United States alone [45,49]. The other products can be used on most structures either together with traditional roofing material or covering the entire roof. The PV foil has a very wide range of usage due to the flexibility, but the efficiency is low, thus the applied area must be relatively large in order to achieve an output comparable with the other products. The modules and the solar cell glazing products can be used on both roofs and facades achieving esthetically pleasing results. This also facilitates using the areas with the highest levels of solar irradiance on geographically challenging locations. However it is not justified to make a comparison between these products, due to different areas of application as well as different demand for effect, costs and available area. In order to simplify the information exchange, the BIPV manufacturers may improve their specifications and availability regarding the mounting of their products.

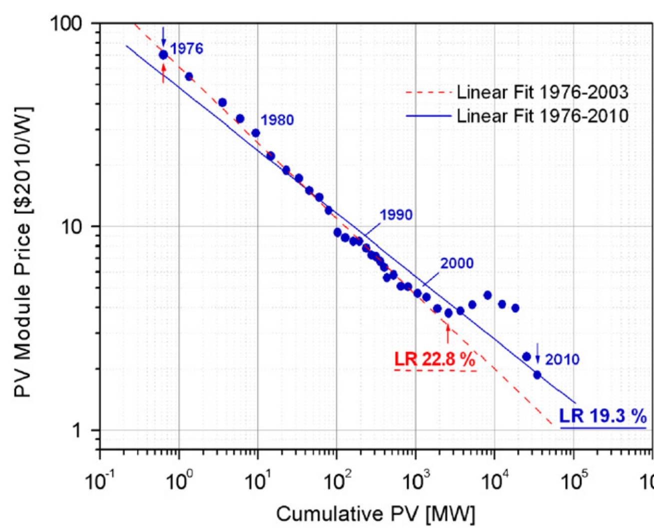


Fig. 5. Learning curve for PV modules for the mid 1970s–2010. Long-term cost trend of reducing PV module cost by 20% per doubling of historic cumulative average production and installations has been stable for the entire period [7,66].

3.4. *Economics*

The global market for BIPVs is expected to grow from \$1.8 × 10^9 in 2009 to \$8.7 × 10^9 in 2016, according to consulting firm NanoMarkets, New York [9]. In addition, NanoMarkets say that CIGS 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 [9]. A long term cost trend for PV module costs is shown in Fig. 5, and the historical growth of the worldwide PV market is shown in Fig. 6 [7,66].

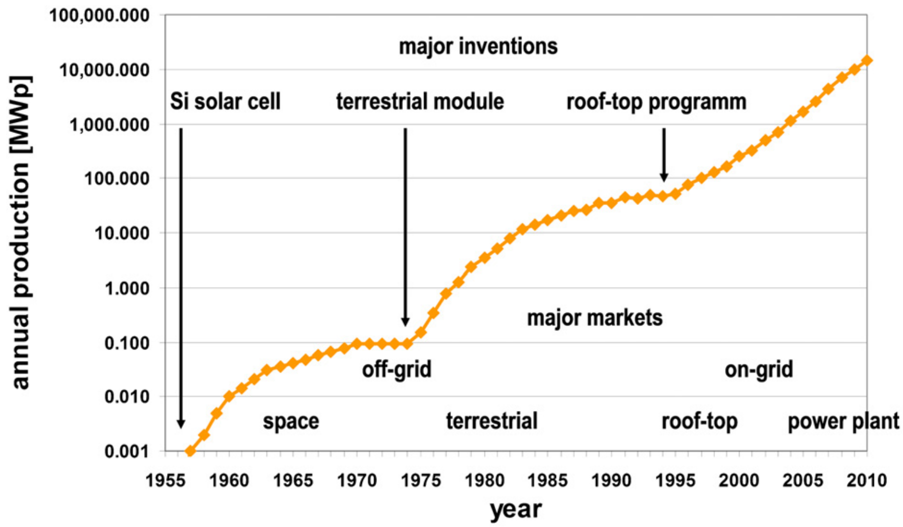


Fig. 6. Historical growth of worldwide PV market [7,66].

The growth of the photovoltaic industry has been investigated by a patent growth analysis carried out by Liu et al. [38]. "Life cycle cost (LCC) is the time-adjusted sum of all time-adjusted costs of a given system over the specified period, and must be compared with the LCC alternative system in order to make an informed choice between them. Basically BIPV system requires a big capital construction cost but no operating fuel cost" [14].

As PV panels occupy a large area for installation, the associated financial challenge could be best answered by space-saving technologies like BIPVs [46]. 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 [44]. 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 [15]. BIPV technology is still rather expensive. One of the reasons for this is that the PV technology is still a growing technology, so BIPV manufacturers are at the beginning of their technological development [27]. In Europe today a maximum payback time for PV modules of ten years is generally expected, which is not possible to achieve without subsidies. The countries developed for grid connected PV systems give a higher price into the grid than exerting from the grid. In many countries there are no systems for buying the electricity produced by PV systems even though the technical solutions for redistribution of the electricity exist. If a system like the one mentioned above is established, the PV industry may have a brighter future. However, a better solution would be to distribute the electricity locally and then buy from/sell to the grid whenever needed, even though this might result in a more difficult technical solution for the electricity companies. 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 [26]. Over time, the cost of a PV system will decline with the improvement of technical advances, thus a lower price per kW installed will be obtained [58]. This is an important part of the development to make installation and building integration of PV products profitable without subsidies.

3.5. Energy payback time for photovoltaic systems

When considering different renewable energy systems, the energy payback time is essential. It describes the amount of time it takes for the solar module 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 [25]. The embodied energy in the materials required to manufacture a 2.1 kWp BIPV system is displayed in Fig. 7 [25].

A study carried out in Switzerland on life cycle analysis (LCA) of twelve small PV power plants, each with the capacity of 3 kWp, gave an energy payback time of 4 to 6 years for monocrystalline cells and 3.5 to 4.5 years for polycrystalline cells [11]. The values are influenced by the choice of reference system and indicators. These numbers are more or less supported by energy payback times in Germany, 5.6–6.1 years for monocrystalline PV systems and approximately 4.5 years for polycrystalline PV systems as shown in Fig. 8 [64].

The study conducted on PV modules installed in Switzerland estimates 2.5–3.5 years energy payback time for future monocrystalline based modules and 2–3 years for future polycrystalline modules, while the study for Europe in general predicts below one year of energy payback time for both mono- and polycrystalline based modules [2,11]. Both studies assume higher efficiencies of the PV cells, hence shorter payback time.

Another LCA study presented at the 21st European Photovoltaic Solar Energy Conference in Germany in 2006 resulted in an energy payback time of 2 years in Southern Europe and 3–3.5 years in Middle-Europe with little variation between mono- and polycrystalline cells. The irradiation considered is 1700 kWh/(m^{2}year) for Southern Europe and 1000 kWh/(m^{2}year) for Middle-Europe. The energy payback time results for amorphous silicon are 1–1.5 years in Southern Europe [2].

When it comes to service life, avoiding too high temperatures is essential. "Heat is the key of the BIPV design. If the temperature of photovoltaic modules is too high, it will affect the efficiency of solar cells, the structure performance of the components and service life" [67]. Sunpower offers a 10 year complete system warranty, and a 25-year limited warranty on solar electricity output for their SunTile BIPV product (see Appendix B). Solon on the other hand gives an output guarantee of 90% for 10 years, and an 80% output guarantee for 25 years for their BIPV product Solon Black (see Appendix C). This applies for many of the manufacturers listed in the appendices. The energy analysis of a case study conducted in the United Kingdom revealed that a 2.1 kWp installed BIPV system, despite requiring large amounts of embodied energy to manufacture, had a short energy payback period of just 4.5 years, in contrast to an expected 25 years system lifetime [25].

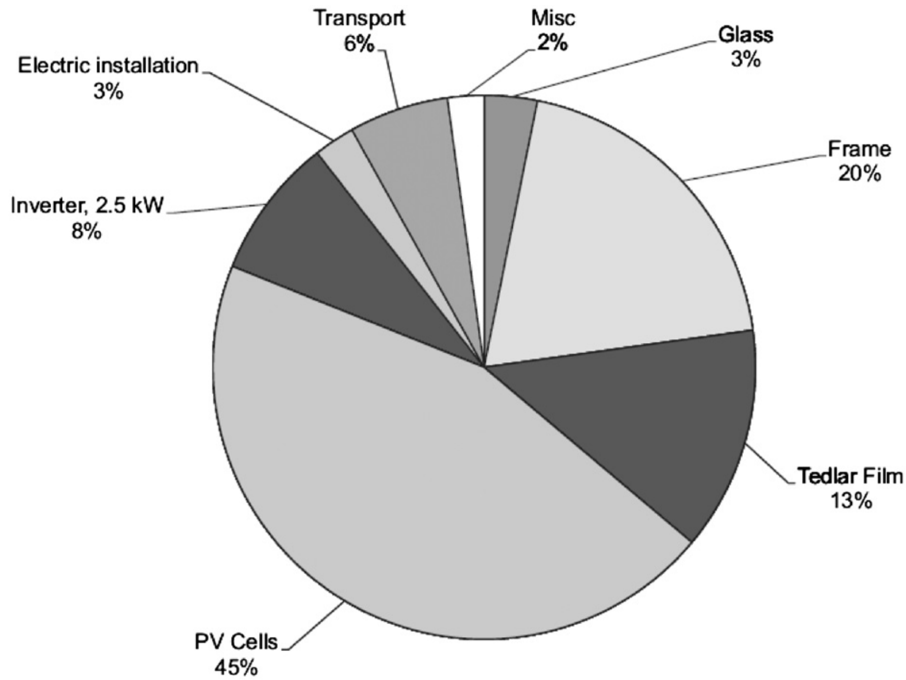


Fig. 7. Embodied energy of a 2.1 kWp BIPV grid-tied system [25].

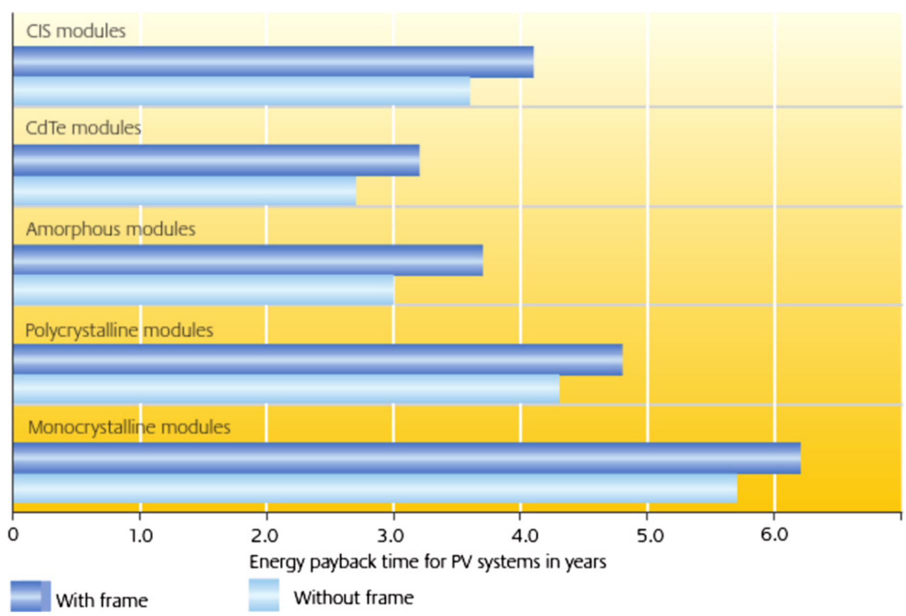


Fig. 8. Energy payback time for PV systems in Germany based on the average values from various studies [1,32,36,47]. From The German Energy Society (DGS) [64].

4. Future research opportunities

4.1. New materials and solutions for BIPVs

The future research opportunities are based on the existing products. Many of the products can achieve a higher efficiency with better materials and better solutions. Naturally, advances in the development of PV materials will lead to advances for the BIPV systems. The challenge is achieving this at a viable cost.

4.1.1. New materials and technologies

New PV technologies that may initiate and advance new innovations, which may be developed into building integrated photovoltaics, might be found in various fields, e.g. (a) ultra-low cost, low-medium efficiency organic based modules, (b) ultra-high efficiency modules, (c) solar concentrator and/or solar trapping systems embedded in solar cell surface and material beneath and (d) flexible lightweight inorganic thin film solar cells, or others.

The ultra-low cost, low-medium efficiency organic based modules are based on dye sensitized solar cells (DSSC), extremely thin absorbers, organic polymer cells, etc. Organic semiconductors are less expensive than inorganic semiconductors like Si. The superior material properties of polymers combined with cheap processing techniques have made polymer based materials to be present in almost every part of the modern society [59]. The highest reported efficiency for an organic solar cell (with the exception of DSSC) is 6.5%, and this makes them competitive with CO_2-producing technologies [40]. The polymer solar cells are however more sensitive when it comes to degradation. Oxygen from the atmosphere will oxidize the organic layer. More stable devices have already been made and progress in this field is important for polymer solar cells to have a future as commercial devices and to be used in various BIPVs [33].

The ultra-high efficiency modules are based on quantum cells and nano-structured devices, e.g. the record efficiencies for polymer-based solar cells have been observed in disordered nano-structured heterojunctions, and further gains are expected upon optimizing ordered nano-structure architectures [40]. Solar concentrator systems are described with arrays of PV modules that are mounted onto large movable structures, which are continuously aimed at the sun.

A great deal of this new technology is already well known. However, it takes time for the products to establish themselves in the market. The dye sensitized solar cell (DSSC) is an example of this. DSSCs usually have a titanium dioxide (TiO_2) substrate material like in the Grätzel solar cell. The technology imitates the photosynthesis and is by Grätzel called "the artificial leaf" (see Fig. 9 [22]). The cells absorb across the visible spectrum and therefore lead to increased efficiency ranging from 7% under direct solar irradiation (AM1.5) and up to 11% in diffuse daylight [23,35,37,49]. The TiO_2 material is a renewable and non-toxic white mineral, and will therefore give smaller environmental impacts. An easy manufacturing process contributes to lower costs.

Colored dyes for use in DSSC based on the TiO_2 cell are developed by Massey University's Nanomaterials Research Centre and they predict costs of 1/10th of the silicon based cells [53]. The reduced production costs and the decreased environmental impacts result in shorter energy and economical payback time, and therefore makes the technology very promising. The market share for this technology is still very small, but it is expected to rise and may achieve a great influence in the future.

An option for more effective harvesting of solar energy is the so-called "antennas" (Fig. 10), which can harvest several wavelengths, i.e. a much broader spectrum of the solar radiation. This may be compared to more "traditional" sandwich solar cells. "The use of antenna-sensitizer molecular devices may constitute a viable strategy to overcome problems of light harvesting efficiency in the spectral sensitization of wide-bandgap semiconductors" [3].

Research laboratories have for many years produced high-performance cells with efficiencies up to 25–40% [64,68]. One approach is to use materials with higher purity and to eliminate the impurities along with the process. Also the back surface can be passivated with silicon oxide and amorphous silicon to minimize recombination losses at the surfaces and contacts. Textured surfaces and buried contacts with minimal shading reduce optical losses. The total production is very expensive and is to date for use in laboratories only. Another way of increasing the efficiency can

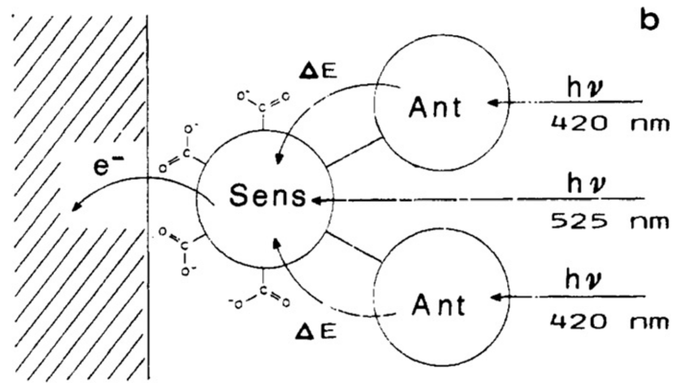


Fig. 10. Block diagram showing the function of the trinuclear complex as an antenna-sensitizer molecular device [3].

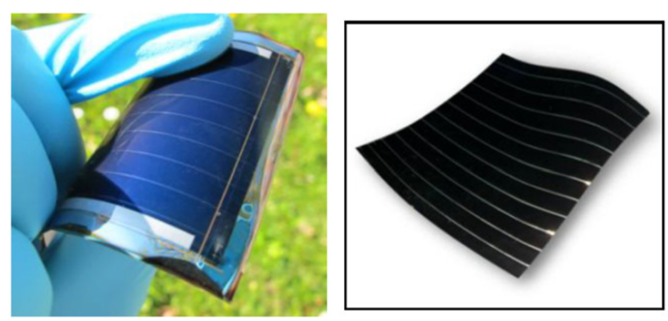


Fig. 11. Flexible and lightweight CIGS (left) and CdTe (right) solar modules [8].

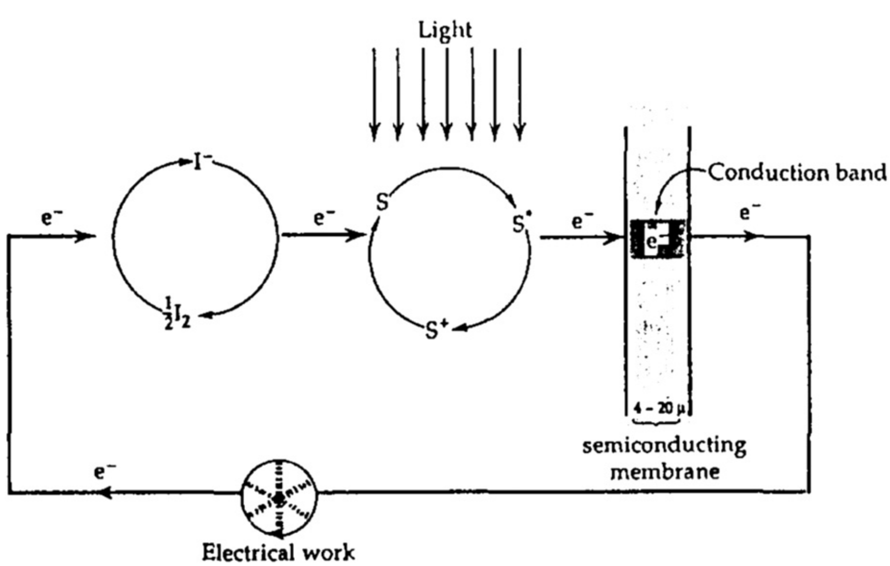


Fig. 9. The principles of the artificial leaf: the chlorophyll in plants is replaced by a transition metal sensitizer while the phospholipid membrane is exchanged for a ceramic semiconducting membrane made of TiO_2. As in photosynthesis, the new solar converter constitutes a molecular electron pump driven by sunlight [22].

be concentrated photovoltaic (CPV) cells. Efficiencies reaching 43.5% have been achieved for commercial-ready CPV cells [68]. These cells are typically applied in the concentrator modules based on a concept of the small-aperture refractive concentrators [5].

Fig. 11 shows photographs of flexible CIGS and CdTe solar modules. The flexible and lightweight CIGS and CdTe solar devices have in an experiment by Buecheler et al. [8] yielded an active area efficiency of 14.7% (CIGS) and 9.4% (CdTe). These devices allow building integration in structures, which cannot take the additional load of heavy and rigid glass laminated solar modules. “The flexible solar modules can be laminated to building elements such as flat roof membranes, tiles or metallic covers without adding weight and thus, the installation costs can be reduced significantly” [8].

The solar cell glazing products available today have potential for optimization, e.g. the solar radiation utilized in a solar cell cannot be exploited as daylight in the buildings. “One might also envision incorporating solar cells or photovoltaics with electrochromic materials in completely new fenestration products, where the photovoltaic and electrochromic material or materials cover the whole glazing area” [30].

More of the new material technology includes crystalline silicon on glass (CSG), copper indium gallium diselenide (CIGS), microamorphous silicon cells, concentrating systems and hybrid solar cells (HIT). Dow Chemical has introduced a line of CIGS-based solar shingles that will be commercially available in late 2011. This BIPV solar shingle installs and performs like a standard asphalt shingle, has an expected lifespan of 15–20 years (on par with conventional asphalt shingles) and has received a GLOBE Foundation award for “Environmental Excellence in Emerging Technology” [9,12]. This is expected to be a huge contribution in bringing affordable renewable energy to consumers. The development of new PV materials and technologies will in the future contribute to new and improved BIPV products, e.g. with higher solar efficiencies.

Note also the recent experimental investigations by Semonin and co-workers [74] where they reported photocurrent quantum efficiencies exceeding 100% in a quantum dot solar cell, being enabled by multiple exciton generation (MEG). The MEG process may occur in semiconductor nanocrystals or quantum dots where absorption of a photon with at least twice the bandgap energy creates two or more electron-hole pairs. Certainly, miscellaneous new and exciting discoveries within solar cell research will with time find its way into the PV and BIPV systems for the buildings of tomorrow.

4.1.2. New solutions

The new solutions in the PV industry are many and various. There is usually room for improvement in each specific system, e.g. regarding ventilation rate, positioning, removing of snow, etc. For good integration results, the BIPV system has to be included early in the planning process. Communication between the planners and manufacturers of BIPV products is important for the development of new BIPV solutions. If the PV cells used are mono- or polycrystalline, it is very important to achieve a sufficient ventilation rate, as the solar cell efficiency normally decreases with increasing temperature, and should therefore be planned ahead of the construction phase. If the temperatures reach high levels one might have to install compensating solutions, such as fans, etc., although usually not optimal regarding maintenance and energy efficiency.

It is expected that the systems will improve in the near future both regarding efficiency of the product and the production phase leading to decreased energy payback time. This is, however, dependent on the market situation and/or subsidies.

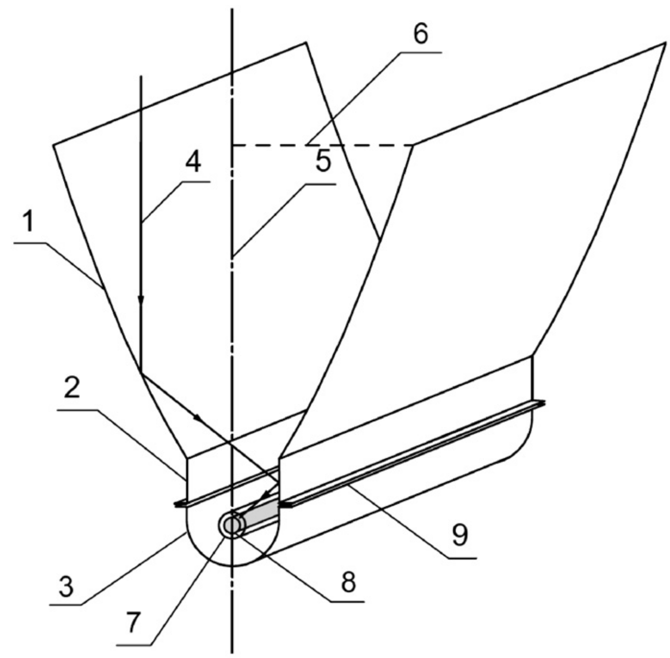


Fig. 12. Schematic diagram of the new trough solar concentrator. (1) the new compound parabolic concentrator; (2) secondary reflection plane mirror; (3) lower trough parabolic concentrator; (4) parallel light; (5) symmetry axis; (6) half aperture of import light; (7) transparent vacuum glass tube; (8) high-temperature solar receiver [63]. One may envision to manufacture a “solar concentrator” at a microscopic material level embedded in the PV surface and beneath.

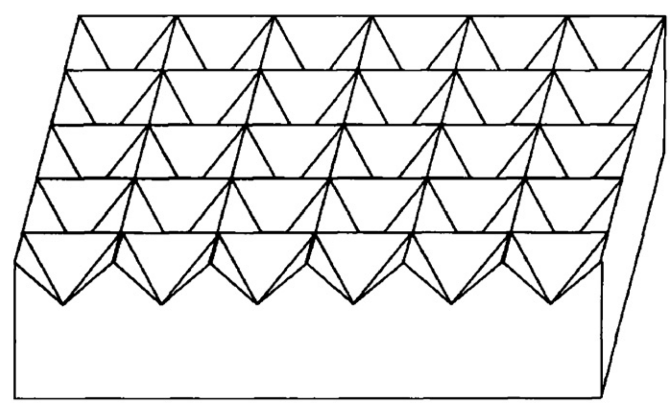


Fig. 13. The inverted pyramids geometry used for light trapping on silicon solar cells [54].

One might envision miscellaneous PV surface solutions for increasing solar cell efficiency and/or profitability. For example, various solar radiation trapping mechanisms might be embedded in the surface. Furthermore, one may be able to make an exterior surface capable of harvesting as much solar energy as if the whole exterior surface was covered with a PV material, while in fact the actual PV material surface is considerably smaller and located somewhat beneath the exterior surface, hence reducing the PV material costs. In principle, the latter one might be viewed as a special built-in concentrator system integrated within the PV surface, thus requiring less (expensive) solar cell material.

A macroscopic or full scale solar cell concentrator is shown in Fig. 12 [63]. Tao et al. [63] found that a new type of trough solar concentrator “...can actualize reflection focusing for the sunlight using the multiple curved surface compound method. It also has the advantages of improving the work performance and environment of high-temperature solar absorber and enhancing the configuration intensity of the reflection surface''. With referral to the discussion in the preceding paragraph, the idea might then be to fabricate a ''solar concentrator'' at a microscopic material level embedded in the PV surface and beneath.

Inspiration for new solutions for BIPV systems can be gathered from this type of application. The BIPV might be formed as a trough at a material level, and hence lead to improved efficiency and reduced costs of the building integrated PV cells.

Another option for more effective solar energy harvesting is the inverted pyramid texturing of the solar cell (Fig. 13) [54]. The great light trapping properties of the inverted pyramid geometry is due to the following three effects: (1) reduced front surface reflectance by providing the opportunity for a portion of the incoming solar rays to undergo a triple bounce, (2) increase in path length of the solar ray through the cell, thus absorbing a larger fraction of the solar rays, which has entered the cell before exiting the cell and (3) increase in amount of solar rays reflected from the back surface, by total internal reflection at the front surface/air interface by making the incident angle greater than the critical angle. The inverted pyramid texture on solar cells is estimated to give cell efficiencies of approximately 24% with realistic cell design and material parameters [54].

4.1.3. Further integration of photovoltaic cells

A future option that e.g. Enecolo and SolarPower Restoration Systems Inc. has looked into is integrating the PV cells in materials at an early stadium e.g. in prefabricated concrete plates [49,57]. Concrete is the most widely used construction material in the world, and the integration of PV with concrete surfaces has remained largely undeveloped, thus presenting a research field with very high potential.

Another future option can be thin laminate or paint layer solar cell materials. Javier and Foos [29] fabricated a complete photovoltaic cell using a handheld airbrush, dilute solutions of CdSe and CdTe nanorods, commercially available silver paint and transparent-conducting-electrode-coated glass. They explored the suitability of a handheld airbrush to create high-quality films and were able to form ultra smooth surfaces from 20 to 500 nm thickness. Current estimated efficiency is very low, but the research demonstrates the variety in the potential of PV cells [29].

Another option, which is already being explored, is integrating PV with smart windows in a way that the PV elements will provide shading when there is need for it [10]. This way, electricity will be produced while the window blocks the solar radiation. In the building industry electrochromic windows with no external wiring are the most desirable. The National Renewable Energy Laboratory of Golden (USA) has built self-powered photovoltaic electrochromic devices up to 25 cm^2 [6]. For these self-powered PV electrochromic devices, ''…the main concerns for future large-area applications are the possible loss of the energy generated by the PV device for larger dimensions, a small range of optical modulation and rather low transmittances in the clear state'' [6].

4.2. Long-term durability of new materials and solutions

It is important that the new building materials, integrated technology and solutions are planned simultaneously with the building envelope. This includes requirements for rain, wind and air tightness, building physical considerations and long-term

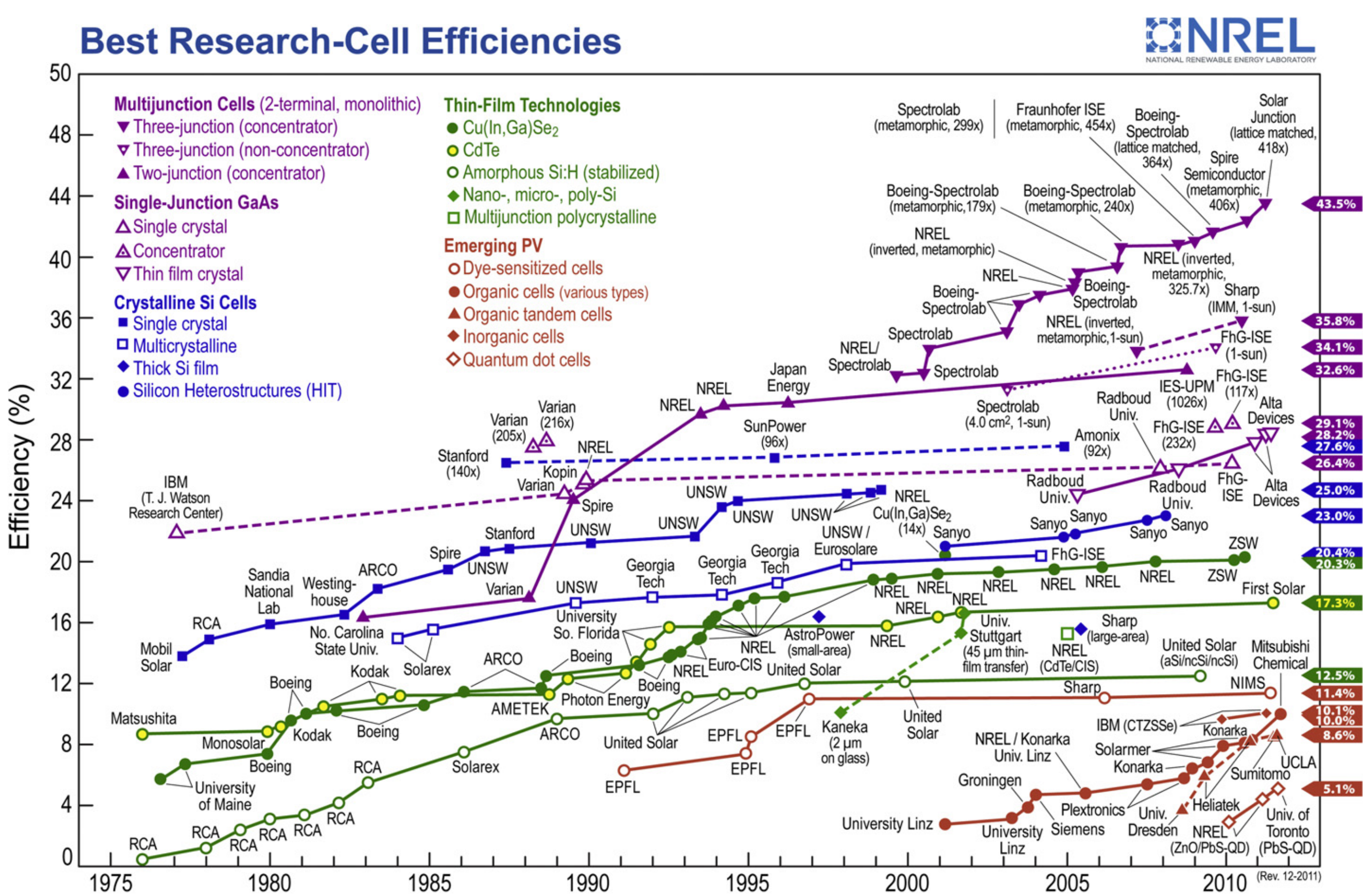


Fig. 14. A timeline for reported best research-cell efficiencies, depicting all verified records for various PV conversion technologies [71].

durability regarding climate exposure. Building physical considerations include investigation of the moisture transport and with this the condensation risk. With new materials the moisture transport and distribution within the building element might change, and knowledge about these aspects are important.

The long-term durability versus the various climate exposure factors need to be considered. Examples of this are as follows [31]:

- Solar radiation (UV–VIS–NIR)
- Ambient infrared (IR) heat radiation
- High and low temperatures
- Temperature changes/cycles giving freezing/thawing processes
- Water, e.g. moisture and wind-driven rain
- Physical strains, e.g. snow loads
- Wind
- Erosion, also from above factors
- Pollutions, e.g. gases and particles in air
- Microorganisms
- Oxygen
- Time for all the factors above to work

All new products should achieve approval in accordance with the current standards. For thin-film PV cells the test procedures are given in standard EN 61646 [20], and for crystalline silicon PV cells EN 61215 [17] applies. Many of the tests given are to determine the durability of the product in the different conditions, and all climate exposure factors above except for pollution and microorganisms are included. Test procedures for these factors may be found in the standard UL 1703 [65]. Some of the new technology will not be considered by these standards. As far as it is possible the existing standards can be used. With further development of new materials, there is a need for new standards specifying procedures for these materials.

The standards describe test procedures for the robustness of terminations test. However, since the standards are based on the PV module only, further testing procedures of the module integrated in the building should be developed with the increasing interest and production of BIPVs.

4.3. Visions for the future

The main target is BIPVs replacing conventional roof and facade materials. This is already in progress as the global market for BIPVs in 2009 was $1.8 $\times 10^9$, and is expected to grow to $8.7 $\times 10^9$ in 2016 [9]. Nevertheless, there is still a great need of increasing the volume of PV and BIPV produced electricity.

Many new pathways exist beyond the current BIPVs. Some of the possible paths have already been mentioned in the previous chapters. New developed technologies may give a huge variety of solutions. Low production costs, low environmental impacts and high efficiencies are key factors for the future development. A timeline for reported best research-cell efficiencies is shown in Fig. 14, depicting all verified records for various PV conversion technologies, including crystalline Si, thin-film, single-junction GaAs, multijunction and emerging technologies, collected from solar companies, universities and national laboratories [71].

The research and development of solutions regarding BIPVs for the retrofitting market are of great importance as the volume of existing buildings is many times greater than the volume of buildings to be constructed in a foreseeable future. The market for retrofitting of roofs is already under development and is growing, e.g. in Hong Kong, where similar BIPV concepts can be applied to facade systems [39]. Easy application of PV cells in existing materials is essential, and it may in the future be performed by e.g. various paint techniques.

Future solar cell materials may be envisioned with the possibility of internal energy storage, e.g. analogous to a photoelectrochemical solar cell (PEC) with internal storage. There are various battery-technologies out there, e.g. metal hydrides. Nano technologies could be one of many possible ways of increasing the energy storage density.

In various countries there is a great need for governmental subsidies to get the industry started as it has been carried out with success in southern Europe. Along with this, a system for feeding the grid with PV electricity is necessary.

Solar cell glazing products enable an almost unlimited range of opportunities. BIPVs as solar cell glazing products, providing both solar shading, daylight transmission and producing electricity, are very valuable and may be even more utilized in the future. Furthermore, forthcoming theoretical and experimental explorations may provide the PV and BIPV industry with several new and innovative materials and solutions. "Future solar cell materials may also be envisioned as thin laminate or paint layers, hence also enabling application by paint brush or spray" [30]. A development towards higher efficiency and better thermal insulation properties increases the energy efficiency and shortens payback time, e.g. highly relevant in the northern part of Europe.

5. Conclusions

The present study has shown that there are great variations in the available building integrated photovoltaic (BIPV) products. This study has encountered only one photovoltaic foil BIPV product commercially available. In general, foil products may have a great range of application due to the flexibility of the material. The categories tiles and modules include numerous products and some of them are not very distinctive when it comes to how they are mounted, thus making it somewhat difficult to categorize them. However, there are many interesting products that both seem to give good weather tightness, satisfactory appearance and fairly high efficiencies. In most of the products, many opportunities exist regarding what type of roof material to be combined with the PV material. The solar cell glazing products included in this study are mainly predefined modules. These may give a great esthetical appearance in addition to provide weather tightness, solar shading and natural lighting. However, the total area efficiencies are quite low. This is, among other factors, due to the glass spacing between the PV cells.

New technologies under development will in the future provide BIPVs with higher efficiencies and lower production costs. This will lead to shorter energy and economical payback times. Some of the new concepts are organic based PVs, such as dye sensitized TiO_2 cells, and high efficiency modules. New solutions can also both reduce costs and increase the market share, amongst other in the retrofitting market. The solutions should be easily applicable, and an example of future visions is paint applications of PV cells. All new technologies and solutions should be thoroughly tested and approved in accordance with existing standards. Furthermore, with new products there is a need for development of new standards and methods, e.g. regarding long-term durability versus climate exposure.

Acknowledgments

This work has been supported by the Research Council of Norway and several partners through the NTNU and SINTEF research project "The Research Centre on Zero Emission Buildings" (ZEB).

Appendix A. BIPV foil products

See Table A1 below.

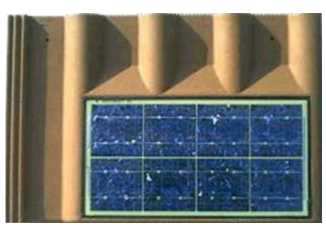
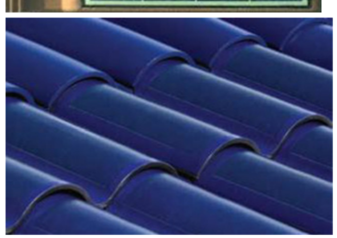
Table A1
Literature data for building integrated photovoltaic foil products.

Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m²)	Further information
Alwitra GmbH & Co. P.O. Box 3950, D-54229 Trier, Germany; T.: +49 651 9102 0; F: +49 651/91 02 248; alwitra@alwitra.de, www.alwitra.de	 	EVALON V Solar 408	STC		138.6	5.1	408	0.58	1550 × 6000 × 5.1	43.9	Amorphous silicon cells from Uni-Solar, EN 61646, CEC 701, EN 50178, EN 12311-2, EN 12691, EN 1548, EN 13501-1, ENV 1187/BS 476 Part 3, Inclination > 3°, http://www.cythelia.fr/images/file/membranes/Brochure_evalon-solar_en.pdf [06.12.2011]
		EVALON V-Solar 272	STC		92.4	5.1	272	0.58	1050 × 6000 × 5.1	43.2	
		EVALON V-Solar 204	STC		69.3	5.1	204	0.58	1550 × 3360 × 5.1	39.1	
		EVALON V-Solar 136	STC		46.2	5.1	136	0.58	1050 × 3360 × 5.1	38.5	

Appendix B. BIPV tile products

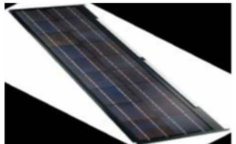
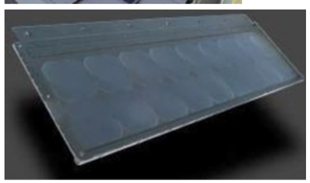
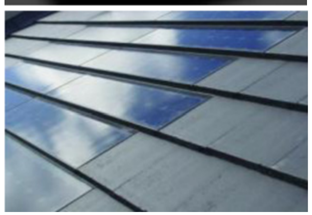
See Table B1 below.

Table B1
Literature data for building integrated photovoltaic tile products.

Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m²)	Further information
Solardachstein www.solardachstein.com; Several partners in various countries distribute their products: http://www.solardachstein.com/en/faq/partner.html		STEPdesign	STC		0.595	3	1.36/ per cell	0.76[a]	1 cell 100 × 100 photo shows 8 cells	136	Polycrystalline silicon cells, EN 61215, http://www.solardachstein.com/en/power/index.html [12.12.2011]
SRS Energy Corporate Headquarters, 2400 Market Street, Suite Five, Philadelphia, Pennsylvania 19103, USA; T.: 1267 515 5895; www.srsenergy.com		Solé Powertile			6.3	4.6	15.75	0.54	868 × 457.2 × 76.2	39.7	Amorphous silicon cells from Uni-Solar, http://www.srsenergy.com/maint/files/SPT16%20Technical%20Specifications%20090310.pdf [05.10.2010]

Eagle Corporate Office, 3546 N. Riverside Avenue, Rialto CA 92377, USA; T.: 909 822 6000; www.eagleroofing.com		SolarBlend Roofing Tiles	STC	8.6	7.95	50	0.73	1194 × 432 × 32	96.9	Cells from Suntech, UL 1703, http://www.eagleroofing.com/pdf/ProductLiturature/EagleGreen/Eagle_Green_Brochure_11-2009_FINAL.pdf [09.12.2010]
Lumeta Inc. 17182 Armstrong Ave. Irvine, CA 92614, USA; T.: 949 266 1990; F: 949 266 1960; www.lumetasolar.com/		Solar S Tile	STC	7.4	5.2	28	0.73	432 × 968 × 76	67.0	Monocrystalline silicon cells, UL 1703 < 600 V, IEC 61215 < 1000 V, IEC 61730 < 1000 V, Inclination > 14°, http://www.lumetasolar.com/Resources/Documents/Lumeta_Solar_Tile_Eng.pdf [06.12.2011]
		Solar Flat Tile	STC	7.4	5.2	28	0.73	432 × 905 × 35	71.6	
Applied Solar Applied Solar, LLC, 3560 Dunhill Street, San Diego CA 92121, USA; T.: 858 909 4080; F: 858 909 4099; inquiries@appliedsolar.com, www.appliedsolar.com		3 ft Roofing tile 4 ft Roofing tile		6.07 8.61	7.76 7.95	34 48	0.72 0.70	914 × 432 × 25 1194 × 445 × 25	86.1 90.3	Cells from Suntech, UL 1703, Inclination > 14°, http://www.appliedsolar.com/roofingsystems/roofingtiles.php [09.12.2010]

Table B1 (*continued*)

Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m²)	Further information
Sharp 5901 Bolsa Avenue, Huntington Beach, CA 92647, USA; T.: 1-800-SOLAR-06; sharpsolar@sharpusa.com, www.sharpusa.com/solar	 	ND-62RU1 ND-62RU2	STC STC		10.8 10.9	8.0 7.9	62 62	0.72[a] 0.72[a]	1498 × 396 × 34 1498 × 396 × 34	104.5 104.5	Polycrystalline silicon cells, UL 1703, http://www.sharpusa.com/SolarElectricity/SolarProducts/LiteratureDownloads_Archive.aspx [09.12.2010]
Solar Century 91-94 Lower Marsh, Waterloo, London SE1 7AB; T.: +44 (0)20 7803 0100, F: +44 (0)20 7803 0101; Your-Home@solarcentury.com, www.solarcentury.com	 	C21e Tile	STC	20/cell	12.0	5.55	52	0.78	1220 × 420 × 30	101.5	Monocrystalline cells, IEC 61215, IEC 61730, BPS 7001, prEN 15601, BS 476-3:2004, BS EN 490:2004, http://www.solarcentury.co.uk/installers-and-roofers/products/solar-tiles/c21e-solar-roof-tiles/ [14.12.2011]
SunPower SunPower Corporation, Corporate Headquarters, 77 Rio Robles, San Jose, California, 95134; T.: 1-800-SUNPOWER (1 800 786 7693); us.sunpowercorp.com	 	SunTile	STC		14.6	5.65	63	0.76	1499 × 432	97.3	Monocrystalline cells, UL 790: Class A, UL 997: 110 mph, TAS-100: 110 mph, Hail impact resistance: 1 in. at 50 mph, Inclination: 3:12–12:12, http://us.sunpowercorp.com/home-builders/products-services/products/ [01.12.2011]

[a] The values are calculated from $FF=P_{max}/(U_{OC}I_{SC})$.

Appendix C. BIPV module products

See Table C1 below.

Table C1
Literature data for building integrated photovoltaic module products.

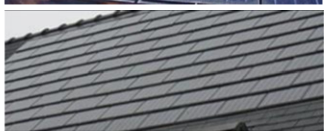
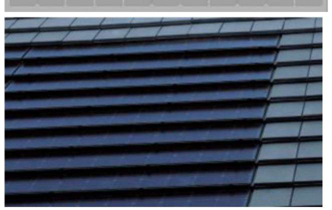
Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Further information
Atlantis Energy Systems International Sales, 4517 Harlin Drive, Sacramento, CA 95826, USA; T.: 916 438 2930; info@atlantisenergy.com, www.atlantisenergy.com		Sunslates5™	STC		3.70	4.80			400 × 327		Monocrystalline silicon cells, Sunslates5™: UL 1703, UL 790, http://www.atlantisenergy.com/sunslates.html [05.10.2010]
		Sunslates6™	STC		3.70	8.0			500 × 368		
		TallSlate™	STC		11.11	5.35			1200 × 400		
		TallSlate™ Grandee	STC		25.05	8.00			1386 × 974		
		MegaSlate®			24	7.70			1320 × 998		http://adesignconsulting.com/products.html#nogo [05.10.2010]
CREATON AG Stephan Führling Dillinger Str. 60, D-86637 Wertingen, Germany; T.: +49 (0) 82 72/86 0; . F: +49 (0) 82 72/86–500; vertrieb@creaton.de, www.creaton.de	 	Creaton Solesia			13.86	8.46	90	0.77	1778 × 355	142.6	Monocrystalline silicon cells, http://www.creaton.de/en/productrange/roof-accessories/photovoltaics/ [06.12.2012]

Table C1 (*continued*)

Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Further information
PV Solar Energy Pty Ltd 28 Florence Street ST PETERS NSW 2044, Australia; T.: +61 (02) 9557 6657; F:+61 (02) 9557 6692; PV Solar Tiles, Peter Erling (Australia) info@pvsolar.com.au www.pvsolar.com.au www.pvsolartiles.com		Sharp BP BP BP					185 160 75 new 75 old		1634 × 868 × 15 1648 × 841 × 15 1264 × 588 × 15 1250 × 583 × 15	130.4 115.4 100.9 102.9	http://www.pvsolar.com.au/ http://www.pvsolartiles.com/ [2010]
RHEINZINK Bahnhofstr. 90, 5711 Datteln, Germany; T.: +49 2363 605-0; F.: +49 2363 605-209; info@rheinzink.de, www.rheinzink.de		PV Quickstep			17.10	5.12	68 ± 10%	0.78	2000 × 365	93.2	Crystalline silicon cells, Inclination: 10–75°, IEC 61215, http://www.rheinzink.com/en/products/roof-systems/roof-covering-systems/quick-stepr-the-rheinzink-stepped-roof/ [06.12.2011]
		Solar PV Standing Seam		6	23.10	5.10	68 ± 5%	0.58	2848 × 394	60.6	Amorphous silicon cells from Uni-Solar, IEC 61646, http://www.pvdatabase.org/pdf_prod/SolarPVStandingSeamandClickRollCapSystem_en.pdf [01.12.2011]
Würth Solar Alfred-Leikam-Straße 25 74523 Schwäbisch-Hall Germany; T.: +49 (0) 7 91/9 46 00 0; F: +49 (0) 7 91/9 46 00 1 19; wuerth-solar@we-online.de, www.wuerth-solar.de		WSG0036E070 WSG0037E070 WSG0036E075 WSG0037E075 WSG0036E080	STC STC STC STC STC		42.3 42.5 43.1 43.4 44	2.4 2.4 2.4 2.4 2.5			1205 × 605 × 35 1200 × 600 × 22.75 1205 × 605 × 35 1200 × 600 × 22.75 1205 × 605 × 35		CIS cells, These modules can be used building integrated in the system DESIGNline, IEC 61646, IEC 61730, http://www.wuerth-solar.de/solar/en/wuerth_solar/produkte_8/unser_modul__genecis/genecis_datenblaetter/GeneCIS_Datenblaetter_1.php [05.12.2010]

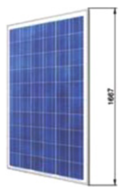
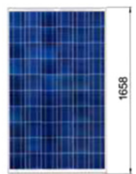
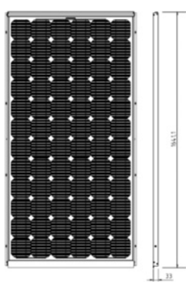
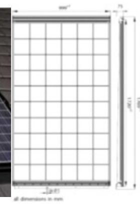
Abakus Solar AG Leithestraße 39 D-45886 Gelsenkirchen Germany; www.abakus-solar.de		Peak On P220-60	STC	13.2	36.77	8.22	220	0.73[a]	1667 × 1000 × 40	132.0	Polycrystalline silicon cells, IEC 61215 Ed.2, IEC 61730, http://www.abakus-solar.com/en/pv/modulescomponents/products/modules.html [16.01.2012]
		Peak On P220-60	NOCT	12.73	33.93	6.65	158	0.70[a]	1667 × 1000 × 40	94.8	
		Peak On P235-60	STC	14.6	37.21	8.48	235	0.74[a]	1630 × 1000 × 40	144.2	
		Peak On P235-60	NOCT	13.93	34.44	6.86	172.5	0.73[a]	1630 × 1000 × 40	105.8	
		ANT P6-60-230	STC	14.07	36.77	8.42	230	0.74[a]	1658 × 986 × 50	140.7	
		ANT P6-60-230	NOCT	13.57	33.91	6.93	170	0.72[a]	1658 × 986 × 50	104.0	
SOLON SE Am Studio 16 12489 Berlin Germany; T.: + 49 30 81879 0; F.: + 49 30 81879 9999; components@solon.com, www.solon.com	 	SOLON Black 160/05	STC	13.67	44.53	5.01	175	0.78[a]	1754 × 850 × 27	117.4	72 cells, monocrystalline silicon, IEC 61730, IEC 61215 Ed. 2, Inclination: 22–60°, http://www.abakus-solar.com/fileadmin/user_upload/Datenblaetter_Module/Solon/EN_DB_SOLON_Black_160_05_en.pdf [13.12.2011]
		SOLON Black 160/05	STC	13.28	44.28	4.97	170	0.77[a]	1754 × 850 × 27	114.0	
		SOLON Black 160/05	STC	12.89	44.03	4.93	165	0.76[a]	1754 × 850 × 27	110.7	
		SOLON Black 160/05	STC	12.50	43.78	4.89	160	0.75[a]	1754 × 850 × 27	107.3	
		SOLON Black 160/05	STC	12.11	43.53	4.85	155	0.73[a]	1754 × 850 × 27	104.0	
DuPont DuPont de Nemours (Luxembourg) S.à r.l. Rue Général Patton L-2984 Luxembourg; T.: +33 (0)1 41 97 45 00; www.gevity.dupont.com	 	Gevity	STC	17.7	24.20	8.77	160	0.75[a]	1332.5 × 929	129.36	Monocrystalline silicon cells, IEC 61215, IEC 61730-1, IEC 61730-2, http://www2.dupont.com/Photovoltaique_Integre/fr_FR/assets/downloads/DuPont_BIPV_flyer3.pdf [16.01.2012]
		Gevity	STC	17.7	24.43	8.87	165	0.76[a]	1332.5 × 929	133.4	

Table C1 (*continued*)

Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/ area (W/m^2)	Further information
SYSTAIC AG Kasernenstr. 27, D-40213 Düsseldorf Germany; T.: +49 211 828 559 0; F: +49 211 828 559 29; systaic@systaic.com, www.systaic.com	 	PV-laminate 215 W	STC			8.11			1674 × 984 × 5		Monocrystalline silicon cells, EN 61215, EN 61730-1, EN 61730-2, http://www.systaic.com/uploads/tx_sbdownloader/2010-02-10_systaic_PV-L_215-235W_EN.pdf [05.11.2010], http://www.systaic.com/uploads/tx_sbdownloader/2010-03-29_systaic_PV-M_215-235W_EN.pdf [05.11.2010]
		PV-laminate 220 W	STC			8.25			1674 × 984 × 5		
		PV-laminate 225 W	STC			8.31			1674 × 984 × 5		
		PV-laminate 230 W	STC			8.48			1674 × 984 × 5		
		PV-laminate 235 W	STC			8.60			1674 × 984 × 5		
		PV-module 215 W	STC			8.11			1680 × 990 × 50		
		PV-module 220 W	STC			8.25			1680 × 990 × 50		
		PV-module 225 W	STC			8.31			1680 × 990 × 50		
		PV-module 230 W	STC			8.48			1680 × 990 × 50		
		PV-module 235 W	STC			8.60			1680 × 990 × 50		
Suntech Mühlentalstrasse 36, 8200 Schaffhausen, Switzerland; T.: + 41 (0) 52 6320090; F: + 41 (0) 52 6320099; sales.europe@suntech-power.com, www.suntech-power.com	 	MSZ-190J-D	STC		45.2	5.62	190	0.75	1641 × 834.5 × 33	139[c]	Monocrystalline silicon cells, IEC 61215, IEC 61730, http://eu.suntech-power.com/images/stories/pdf/datasheets/English/suntech-justroof.pdf [12.12.2011]
		MSZ-195J-D	STC		45.4	5.69	195	0.75	1641 × 834.5 × 33	143[c]	
		MSZ-185J-C	STC		45.0	5.43	185	0.76	1641 × 834.5 × 33	136[c]	
		MSZ-190J-C	STC		45.2	5.62	190	0.75	1641 × 834.5 × 33	139[c]	
		MSZ-95J-DH	STC		22.6	5.62	95	0.75	879[b] × 834.5 × 33	132[c]	
		MSZ-90J-CH	STC		22.4	5.29	90	0.76	879[b] × 834.5 × 33	125[c] (given)	
Eternit AG CH 8867 Niederurnen, Switzerland; T.: +41 (0)55 617 11 11; info@eternit.ch, www.eternit.ch		Photovoltaic INTEGRAL PLAN					355				http://www.eternit.ch/en/products-and-solutions/roof/solar-force-systems/ [05.10.2010]
		SUNJOULE photovoltaic module					45		720 × 400	156.3	

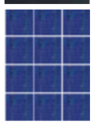
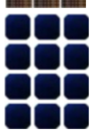
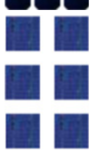
Schott Solar AG Hattenbergstrasse 10, 55122 Mainz, Germany; T.: +49 (0)6131/66-14105; F: +49 (0)6131/66 14105; solar.sales@schottsolar.com, www.schottsolar.de	 	InDax 214	STC	12.5	36.3	8.04			1769 × 999 × 75		Polycrystalline silicon cells, IEC 61730, IEC 61215, http://www.schottsolar.com/global/products/photovoltaics/schott-indax-185235/ [06.12.2011]
		InDax 214	NOCT		33.1	6.44			1769 × 999 × 75		
		InDax 225	STC	13.1	36.7	8.24			1769 × 999 × 75		
		InDax 225	NOCT		33.5	6.60			1769 × 999 × 75		
Kalzip/Corus Haydock Lane, Haydock, St. Helens, WA11 9TY Merseyside, United Kingdom; T.: +44 (0) 1942 295 500; F: +44 (0) 1942 295 508; enquiries.uk@kalzip.com, www.kalzip.com	 	AluPlusSolar PVL-136			46.2	5.1			5500 × 1000		Amorphous silicon cells from Uni-Solar, Inclination: 3–60°, http://www.kalzip.com/PDF/uk/Kalzip-Solar-Systems.pdf [10.12.2010]
		AluPlusSolar PVL-68			23.1	5.1			2850 × 1000		
Solar Century 91-94 Lower Marsh Waterloo, London SE1 7AB; T.: +44 (0)20 7803 0100; F: +44 (0)20 7803 0101; Your-Home@solarcentury.com, www.solarcentury.com	 	C21e Slate	STC	20/cell	12.0	5.55	52	0.78	1174 × 318 × 14[d]	139.3	Monocrystalline silicon cells, Active area same as C21e Tile, prEN 15601, BS 476-3:2004, http://www.solarcentury.co.uk/installers-and-roofers/products/solar-tiles/c21e-solar-roof-slates/ [14.12.2010]

[a] The values are calculated from $FF = P_{max}/(U_{OC} I_{SC})$.
[b] Half size—Applies to MSZ-95J-DH and MSZ-90J-CH.
[c] Stated by the manufacturer, other P_{max}/area-values are calculated from the stated P_{max} and area values.
[d] Active area.

Appendix D. Solar cell glazing products

See Table D1 below.

Table D1
Literature data for solar cell glazing products.

Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} [W]	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Further information
Sapa Building System Industrielaan 17 8810 Lichtervelde, Belgium; T.: +32 51 729 666; F: +32 51 729 647; info@sapagroup.com, www.sapagroup.com		Amorphous silicon thin film		5 per cell			32 per cell		576 × 976 per cell	50[a] (given)	The producer offers customized solutions. The options are opaque panels and see-through panels. Distances between cells can vary from 3 to 50 mm. http://www.sapagroup.com/Companies/Sapa%20Building%20System%20AB/Pictures/brochures/Solar_BIPV_low.pdf [06.12.2011]
		Polycrystalline		16 per cell			1.46–3.85 per cell		156 × 156/ 125 × 125 per cell	120[a] (given)	
		Monocrystalline high efficient		22 per cell			2.90–3.11 per cell		125 × 125 per cell	155[a] (given)	
		Amorphous silicon thin film 10% or 20% opacity		4 per cell			27 per cell		576 × 976 per cell	40–45[a] (given)	
		Monocrystalline semi-transparent		17 per cell			1.90–2.20 per cell		125 × 125 per cell	105[a] (given)	
		Monocrystalline high efficient 25 mm distance 36% transparency		22 per cell						135[a] (given)	
		Polycrystalline 50 mm distance 42.5% transparency		16 per cell						82[a] (given)	

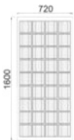
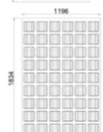
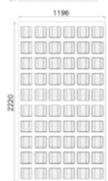
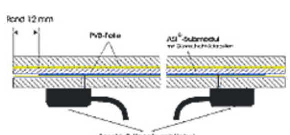
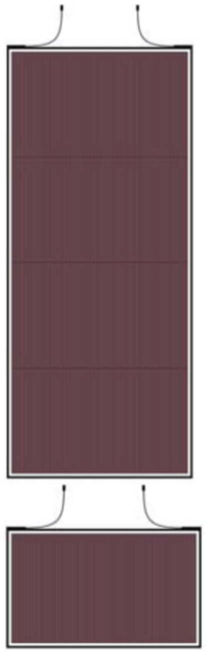
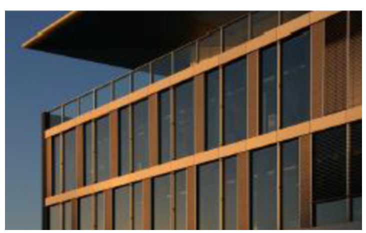
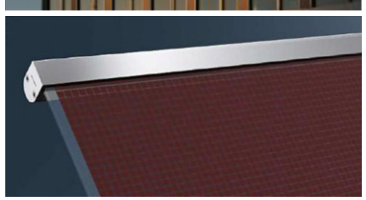
VIDURSOLAR Poligono industrial Bufalvent C/Edison, num 8-14 08243 MANRESA Barcelona Spain; T.: + 34 93 874 86 50; F: + 34 93 873 64 76; vidursolar@vidursolar.es, www.vidursolar.es		Model FV VS16 C36 P120 Transparency approx. 16%	STC	21.6	7.63			1600 × 720 × 11.5		Polycrystalline silicon cells Vidursolar also offers customized modules regarding shape, cell type, color and distance between cells, http://www.vidur.es/solar_predefinidos_detalle.php?id=1 [06.12.2011]
		Model FV VS16 C54 P180 Transparency approx. 16%	STC	32.4	7.63			1600 × 1056 × 11.5		
		Model FV VS36 C54 P180 Transparency approx. 36%	STC	32.4	7.63			1834 × 1196 × 11.5		
		Model FV VS41 C60 P200 Transparency approx. 41%	STC	35.7	7.63			2220 × 1196 × 11.5		
Abakus Solar AG Leithestraße 39 D-45886 Gelsenkirchen Germany; www.abakus-solar.de		Peak In P210-60, Transparency: 25%	STC	36.50	7.70	210	0.75[b]	2000 × 1066 × 11	98.5	Polycrystalline silicon cells Abakus also offers customized modules regarding shape, cell type, color and distance between cells. IEC 61215q, IEC 61730, http://www.abakus-solar.com/fileadmin/user_upload/Datenblaetter_Module/a2peak/PeakIn_P210_60_Factsheet_2010_english.pdf [17.01.2012]
Glaswerke Arnold GmbH & Co KG Neuseser Strasse 1, D-91732 Merkendorf, Germany; T.: +49 (0)9826 656 0; F: +49 (0)9826 656 400; SolAr@Glaswerke-Arnold.de, www.voltarlux.de		Voltarlux®-ASI-T-Mono 2x-fach, Transparency 10%	STC	49	1.80	48	0.54	2004 × 627 × 17	38.2	Amorphous silicon cells from Schott Solar (ASI®THRU) UL 1703, http://www.voltarlux.de/cms.asp?AE=1&IDN=60&Plugin=&H=%27157%27&T=0&Sprache=en [12.12.2011]
		Voltarlux®-ASI-T-Mono 4-fach Transparency 10%	STC	93	1.97	100	0.55	2358 × 1027 × 18	41.3	

Table D1 (*continued*)

Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} [W]	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Further information
Schott Solar Hattenbergstrasse 10 55122 Mainz Germany; T.: +49 (0)6131/66 14105; F: +49 (0)6131/66 14105; solar.sales@schottsolar.com, www.schottsolar.de		ASI® THRU-1-L	STC	6	111	0.55	48	0.79	1122 × 690 × 16	62.0	Amorphous silicon cells, ASI® THRU glass has a transparency of approx. 10%, *U*-value: 1.1 W/(m^{2}K) http://www.us.schott.com/architecture/english/download/asi_glass_brochure_us-2.pdf [01.12.2011]
		ASI® THRU-1-IO	STC	6	111	0.55	48	0.79	1122 × 696 × 34	61.5	
		ASI® THRU-2-L	STC	6	111	1.11	95	0.77	1122 × 1331 × 16	63.6	
		ASI® THRU-2-IO	STC	6	111	1.11	95	0.77	1122 × 1337 × 34	63.3	
		ASI® THRU-3-L	STC	6	111	1.66	143	0.78	1122 × 1972 × 16	64.6	
		ASI® THRU-3-IO	STC	6	111	1.66	143	0.78	1122 × 1978 × 34	64.4	
		ASI® THRU-4-L	STC	6	111	2.22	190	0.77	1122 × 2613 × 16	64.8	
		ASI® THRU-4-IO	STC	6	111	2.22	190	0.77	1122 × 2619 × 34	64.7	
PV Glaze 26 The Downs, Delamere Park Cuddington, Cheshire CW8 2XD, U.K; T.: +44 (0)1606 301847; info@pvglaze.com, www.pvglaze.com		EA1 Panel			196	2.8	340 ± 5%		2600 × 2200 single	59.4	SunFab™ amorphous technology, http://www.pvglaze.com/PVGD_Brochure.pdf [02.12.2011]
		PA1 Panel			289	2.46	450 ± 5%		2600 × 2200tandem	78.7	
Schueco UK Limited Whitehall Avenue, Kingston, Milton Keynes, MK10 0AL; T.: +44 (0)1908282111; F: +44 (0)1908282124; mkinfobox@schuco.com, www.schueco.com		Schüco Prosol TF							Various	50–70[a] (given)	Thin film technology, http://www.schueco.com/web/fassadenmodul_en/fenster_und_fassadenmodul [02.12.2011]

[a] Stated by the manufacturer, other P_{max}/area-values are calculated from the stated P_{max} and area values.
[b] The values are calculated from FF=$P_{max}/(U_{OC}I_{SC})$.

Appendix E. BAPV products

See Table E1 below.

Table E1
Literature data for some building attached photovoltaic products.

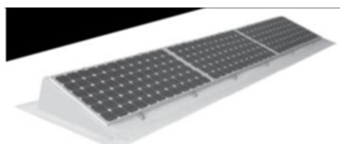
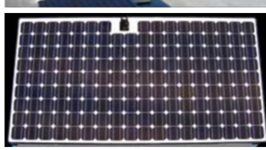
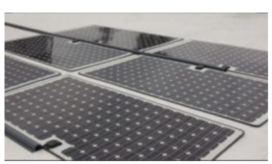
Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Further information
SolarFrameWorks Co 765 Moss Street, Golden, CO 80401, USA; T.: 1 888 90-SOLAR; www.solarframeworks.com	 	BIPV CoolPly™									Inclination < 2:12, http://www.solarframeworks.com/pdf/SFW_CP_BIPV_SS_web.pdf [13.12.2011]
Lumeta, Inc. 17182 Armstrong Ave. Irvine, CA 92614 USA; T.: 949.266.1990; F: 949.266.1960; www.lumetasolar.com	 	PowerPly	STC	13.8	98.9	5.33	400 ± 5%	0.76	2360 × 1230 × 10	137.8	Monocrystalline silicon cells, Inclination < 10°, UL 1703, IEC 61215, IEC 61730, http://www.lumetasolar.com/Resources/Documents/PowerPly%20400_093010.pdf [06.12.2011]

Table E1 (*continued*)

Manufacturer	Illustration	Product	Test	η (%)	U_{OC} (V)	I_{SC} (A)	P_{max} (W)	FF	Area (mm × mm)	P_{max}/area (W/m^2)	Further information
Hauptsitz Ernst Schweizer AG, Metallbau Bahnhofplatz 11 CH-8908 Hedingen Switzerland; T: +41 44 763 61 11; F: +41 44 763 61 19; www.schweizer-metallbau.ch	 	SunPower 220 Solar Panel	STC	17.7	48.6	5.75			1559 × 798		All-back contact monocrystalline silicon cells, IEC 61215, IEC 61730, http://www.schweizer-metallbau.ch/fileadmin/user_upload/00_Produkte/80_Sonnenenergie-Systeme/pdf_f/pdf_e/Sunpower_black_e.pdf [05.10.2010]
		SunPower 220 Solar Panel	NOCT		45.4	4.66			1559 × 798		
Uni-Solar Tour Albert 1er65, avenue de colmar92507 Rueil Malmaison Cedex France; T.: +33.1.74.70.46.24; F: +33.1.41.39.00.22; franceinfo@uni-solar.com, www.uni-solar.com		PVL-68	STC		23.1	5.1	68	0.58	2849 × 394 × 4	60.6	Amorphous silicon cells , Inclination: 3–60°, UL 1703, IEC 61646, IEC 61730, http://www.uni-solar.com/products/commercial-products/pvl/ [06.12.2011]
		PVL-68	NOCT 46°		21.1	4.1	53	0.61	2849 × 394 × 4	47.2	
		PVL-136	STC		46.2	5.1	136	0.58	5486 × 394 × 4	62.9	
		PVL-136	NOCT 46°		42.2	4.1	105	0.61	5486 × 394 × 4	48.6	
		PVL-144	STC		46.2	5.3	144	0.59	5486 × 394 × 4	66.6	
		PVL-144	NOCT 46°		42.2	4.3	111	0.61	5486 × 394 × 4	51.4	
Isofoton C/ Montalbán,9 28014 Madrid Spain; T.: +34 91 414 78 00; F: +34 91 414 79 00; isofoton@isofoton.com, www.isofoton.com		ISF-230	STC	13.9	36.6	8.36	230	0.75	1667 × 994 × 45	138.8	Monocrystalline silicon cells, 60 cells in serial (note that the photo to the left depicts 54 cells), Uncertainty regarding how the product is mounted, IEC 61215, IEC 61730, http://www.isofoton.com/technical/material/pdf/productos/fotovoltaica/modulos/grupos/ISF_230-240_ing.pdf [06.12.2011]
		ISF-230	NOCT		33.1	6.73	163	0.73	1667 × 994 × 45	98.4	
		ISF-235	STC	14.2	36.8	8.44	235	0.76	1667 × 994 × 45	141.8	
		ISF-235	NOCT		33.3	6.78	167	0.74	1667 × 994 × 45	100.8	
		ISF-240	STC	14.5	37.1	8.45	240	0.77	1667 × 994 × 45	144.8	
		ISF-240	NOCT		33.6	6.80	170	0.74	1667 × 994 × 45	102.6	

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Appendix B

B. P. Jelle and C. Breivik, “State-of-the-Art and the Path to the Building Integrated Photovoltaics of Tomorrow”, Lecture presented by C. Breivik at the *Renewable Energy Research Conference (RERC) 2012 - Technoport 2012 - Sharing Possibilities*, Trondheim, Norway, 16-18 April, 2012.

State-of-the-Art and the Path to the Building Integrated Photovoltaics of Tomorrow

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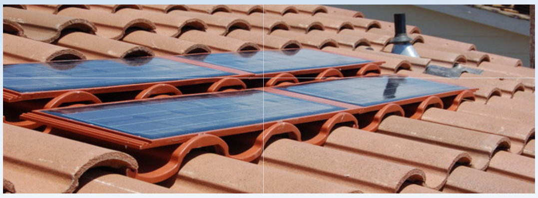
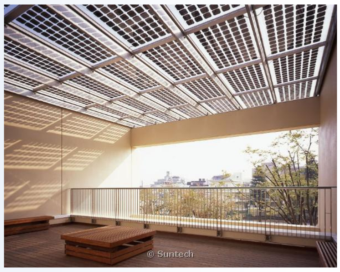




Renewable Energy Research Conference 2012 - Technoport 2012 - Sharing Possibilities, Trondheim, Norway, 16-18 April, 2012.

Building Integrated PhotoVoltaics (BIPVs)

- Today and Tomorrow

- Replace the outer building envelope skin, i.e. both a climate screen and a power source generating electricity.
- Reducing electricity costs.
- Savings in materials and labour.
- State-of-the-Art BIPV products.
- Possible future BIPV research paths.

Building Integrated PhotoVoltaics (BIPVs)

- Today and Tomorrow

- Architectural aspects.
- Test methods and standards.
- Economical aspects.

- For information on these and other aspects, including photo and figure references, it is referred to the literature and the references therein:

- B. P. Jelle and C. Breivik, "State-of-the-Art Building Integrated Photovoltaics", Submitted for publication in *Energy Procedia*, 2012.
- B. P. Jelle and C. Breivik, "The Path to the Building Integrated Photovoltaics of Tomorrow", Submitted for publication in *Energy Procedia*, 2012.
- B. P. Jelle, C. Breivik and H. D. Røkenes, "Building Integrated Photovoltaic Products: A State-of-the-Art Review and Future Research Opportunities", *Solar Energy Materials and Solar Cells*, 100, 69-96, 2012.

Buildings Experience Various and Changing Climate Conditions throughout their Lifetime

– Also BIPVs

Photos: Samfoto (left) and Scanpix (right).

Deterioration of Building Materials - Exposed to Several Climate Factors

- Solar radiation (UV-VIS-NIR)
- Ambient infrared (IR) heat radiation
  (the resulting elevated temperature increases the rate of chemical degradation reactions, and also the rate of growth of rot and fungus up to limiting temperatures)
- High and low temperatures
- Temperature changes/cycles
  (relative temperature movements between different materials, number of freezing point passes during freezing/thawing)
- Water
  (e.g. moisture, relative air humidity, rain (precipitation), wind-driven rain)
- Physical strains, e.g. snow loads
- Wind
- Erosion (also from above factors)
- Pollutions (e.g. gases and particles in air)
- Microorganisms (in general)
- Oxygen
- Time (determining the effect for all the factors above to work)

BIPVs – Building Envelope and PV Requirements

- Fulfil the requirements of both:
  - Building envelope.
  - PV solar cells.
- Durability in general and vs. climate exposure factors.
- Rain, air and wind tightness, various building physical aspects like heat and moisture transport, etc.

Photos: Solarcentury (left) and from Best Practice Catalogue of Solar Thermal and PV Integration in Roofs, WP A, Eur-Active Roofer, Cenergia, 2008 (right).

PV and BIPV Properties and Characteristics

- Solar Cell and Building Envelope

Solar Cell

- Solar cell efficiency $\eta = P_{max}/(\Phi A)$, where P_{max} is the maximum power point in W or Watt-peak (Wp), Φ is the input light irradiance in W/m² and A is the surface area of the solar cell in m².
- Quantum yield, φ = no. of photo-electrons / no. of photons.
- Open circuit potential or voltage U_{oc}.
- Short circuit electrical current I_{sc}.
- Maximum power point $P_{max} = (UI)_{max}$.
- Fill factor $FF = (UI)_{max}/U_{oc}I_{sc}$.
- Band gap E_g.

Building Envelope

- Durability in general and vs. climate exposure factors.
- Rain, air and wind tightness, various building physical aspects like heat and moisture transport, etc.
- Various mechanical properties.
- Any chemical changes.

Categorization of State-of-the-Art BIPVs

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

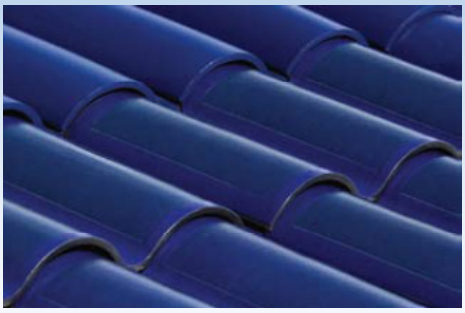
BIPV Foil Products

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

Example of a BIPV foil product from Alwitra GmbH & Co. using amorphous silicon cells from Uni-Solar.

BIPV Tile Products

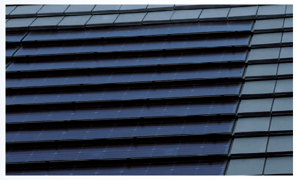
Manufacturer	Product*	η (%)	U_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Area (mm x mm)	P_{max}/area (W/m^2)
Solardachstein	STEPdesign		23.15	2.40	1.36 /cell	0.76	8 units 100 x 100	136
SRS Energy	Solé Powertile		6.3	4.6	15.75 /module	0.54	868 x 457.2	39.7
Lumeta	Solar Flat Tile		7.4	5.2	28 /module	0.73	432 x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



Example of BIPV tile products from SRS Energy (left) and Solar Century (right).

BIPV Module Products

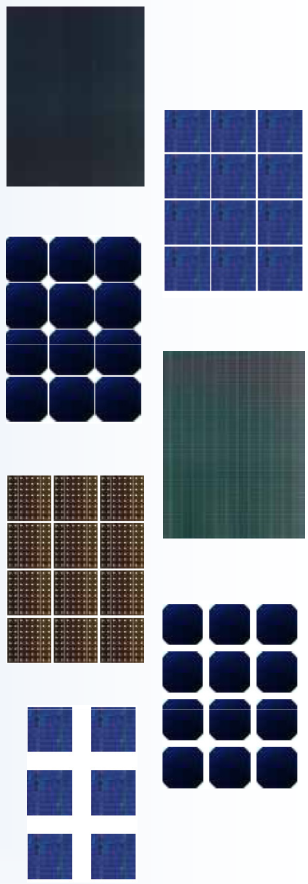
Manufacturer	Product*	η (%)	U_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Area (mm x mm)	P_{max}/area (W/m^2)
Creaton AG	Creaton Solesia		13.86	8.46	90/module	0.77	1778 x 355	142.6
Rheinzink	PV Quickstep		17.10	5.12	68/module	0.78	2000 x 365	93.2
Abakus Solar AG	Peak On P220-60	13.2	36.77	8.22	220	0.73	1667 x 1000	132.0
	Peak On P235-60	14.6	37.21	8.48	235	0.74	1630 x 1000	144.2
	ANT P6-60-230	14.07	36.77	8.42	230	0.74	1658 x 986	140.7
DuPont	Gevity	17.7 17.7	24.20 24.43	8.77 8.87	160 165	0.75 0.76	1332.5 x 929 1332.5 x 929	129.36 133.4
Suntech	MSZ-190J-D		45.2	5.62	190/module	0.75	1641 x 834.5	139
	MSZ-90J-CH		22.4	5.29	90/module	0.76	879 x 843.5	125
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



Example of BIPV module products from Creaton AG (top) and Rheinzink (bottom).

Solar Cell Glazing Products

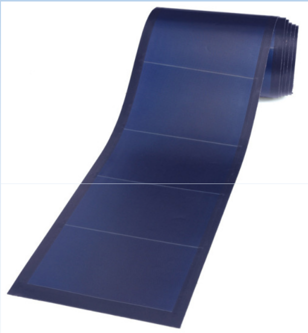
Manufacturer	Product*	η (%)	U_{oc} (V)	I_{sc} (A)	P_{max} (W)	FF	Area (mm x mm)	P_{max}/area (W/m^2)
Abakus Solar AG	Peak In P210-60		36.50	7.70			2000 x 1066	
Vidursolar	FV VS16 C36 P120		21.6	7.63			1600 x 720	
Glaswerke Arnold GmbH & Co KG	Voltarlux-ASI-T-Mono 4-fach		93	1.97	100/module	0.55	2358 x 1027	41.3
Schott Solar	ASI THRU-1-L	6	111	0.55	48	0.79	1122 x 690	62.0
	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



Example of various solar cell glazing products from Sapa Building System (to the right) using either amorphous, polycrystalline or monocrystalline cells with different distances between the cells.

Building Attached PhotoVoltaics (BAPVs)

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

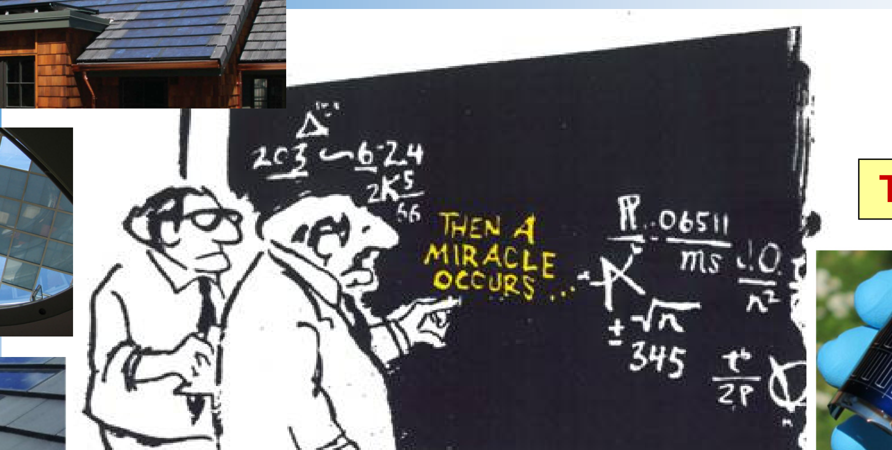



Example of BAPV products from Uni-Solar (left) and Hauptsitz (right).

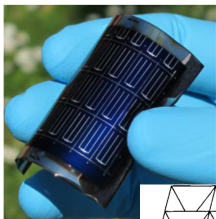
Beyond State-of-the-Art BIPVs ?



Today



Tomorrow ?



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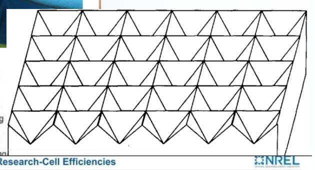
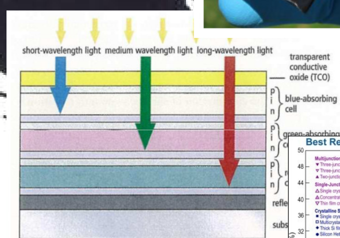
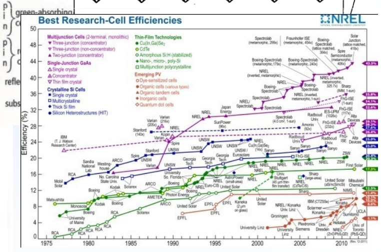
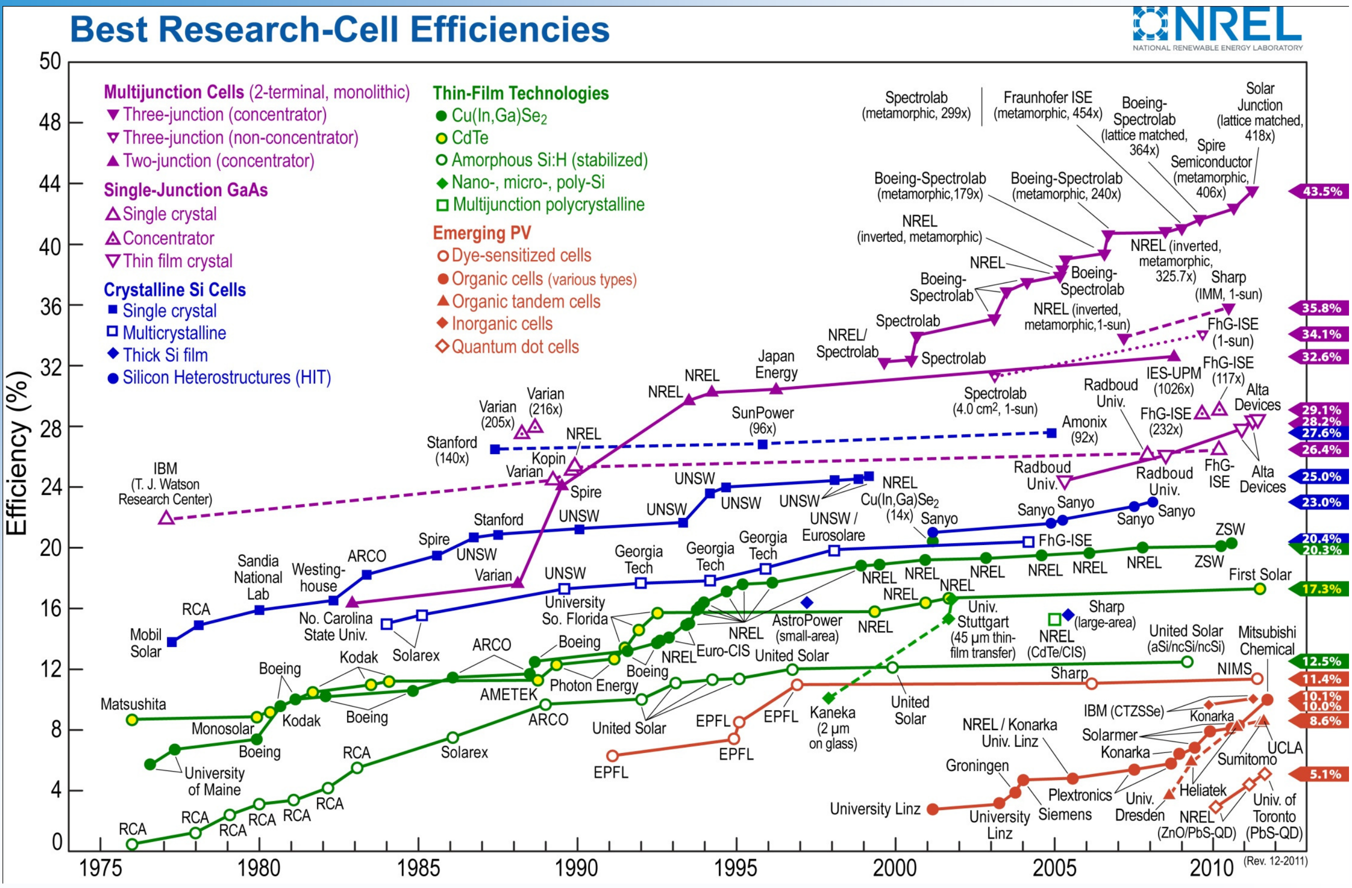





PV Development and Impact on BIPVs

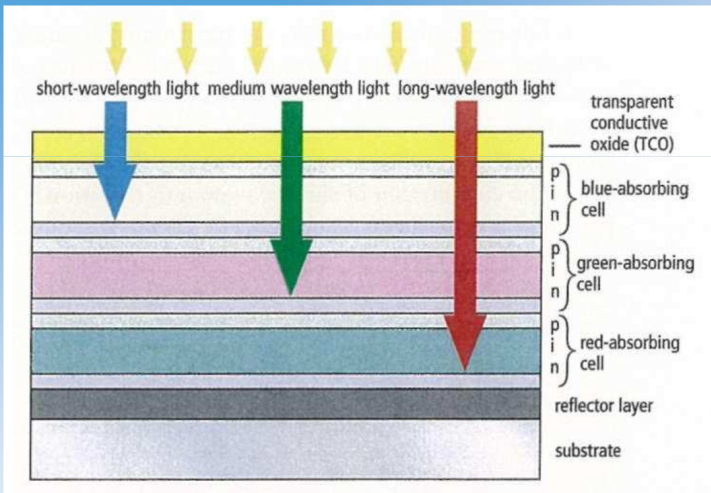


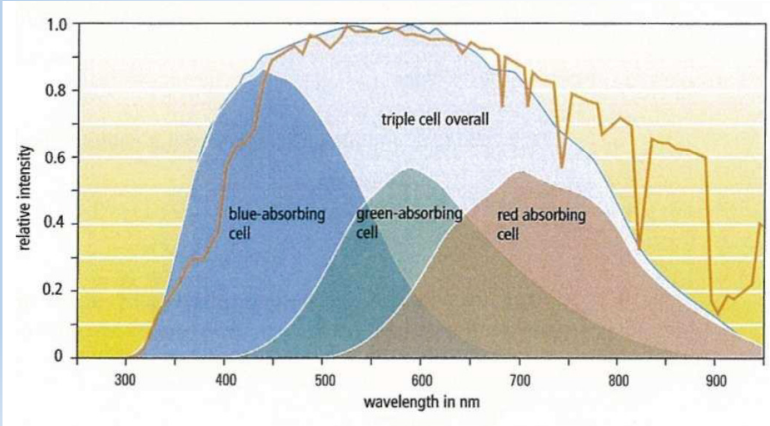
New Materials and Solutions for BIPVs

- May be found in miscellaneous fields, e.g.:
- Ultra-low cost and low-medium efficiency organic based modules.
- Ultra-high efficiency modules.
- Solar concentrator and/or solar trapping systems embedded in the solar cell surface and material beneath.
- Flexible lightweight inorganic thin film solar cells.
- Several others some of them yet to be discovered.

"think thoughts not yet thought of"
and
"the more we know the more we know we don't know"
(Jelle et al. 2010).

Sandwich or Stack Solar Cell



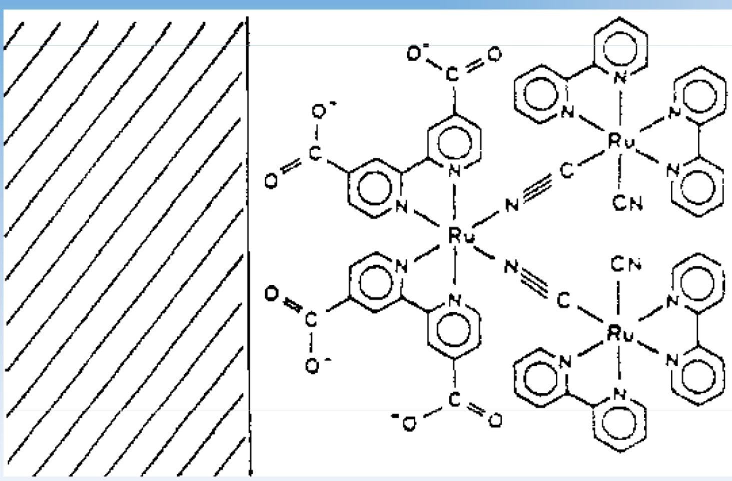


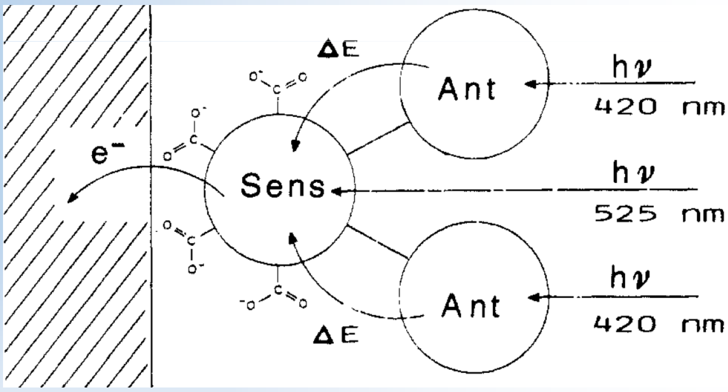
An amorphous triple solar cell with its configuration (left) and spectral responses (right) (The German Energy Society 2008).

Dye Sensitized Solar Cells (DSSCs)

The Grätzel Solar Cell

Applying ”Antennas”





Adsorption mode of the trinuclear complex on the TiO_2 surface applying an antenna-sensitizer molecular device (Amadelli et al. 1990).

New Solar Cell Materials and Solutions

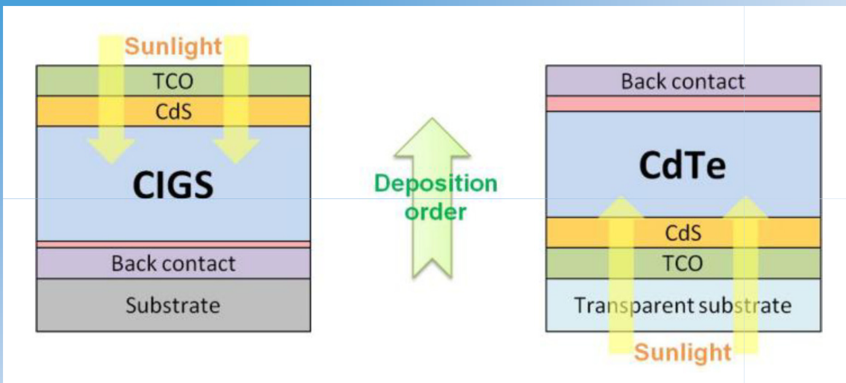
- Various examples, e.g.:
- Concentrated photovoltaic (CPV) cells.
- Flexible CIGS (copper indium gallium selenide) cells.
- Flexible CdTe cells.
- Crystalline Si on glass (CSG).
- Microamorphous Si cells.
- Hybrid solar cells (applying both organic and inorganic semiconductors).

New Solar Cell Materials and Solutions

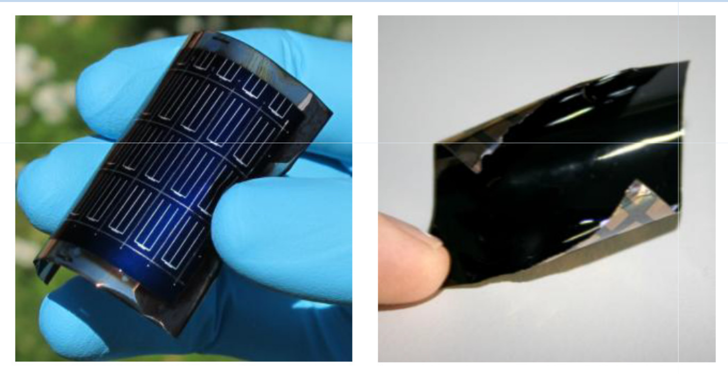
The German company PVflex Solar GmbH has said that *"thanks to flexible lamination, CIGS solar cells now have the ability to both realize their potential as the most efficient thin film technology and to dominate the building-integrated photovoltaics (BIPV) market in the future"* (Stuart 2010).

Moreover, "one might also envision incorporating solar cells or photovoltaics with electrochromic materials in completely new fenestration products, where the photovoltaic and electrochromic material or materials cover the whole glazing area" (Jelle et al. 2012a).

CIGS and CdTe Solar Cells

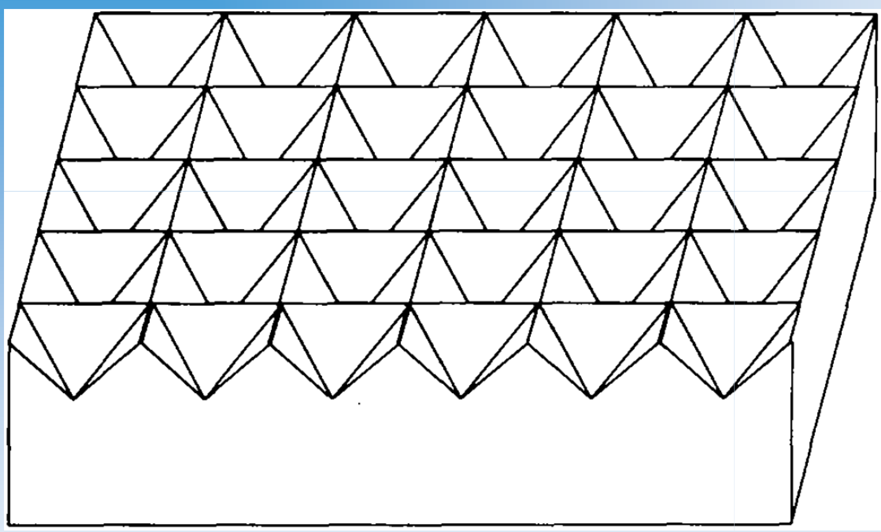


Schematic built-up of CIGS (left) and CdTe (right) thin film solar cells (Buecheler et al. 2011).



Flexible CIGS (left) and CdTe (right) solar cells on polyimide substrates (Buecheler et al. 2011).

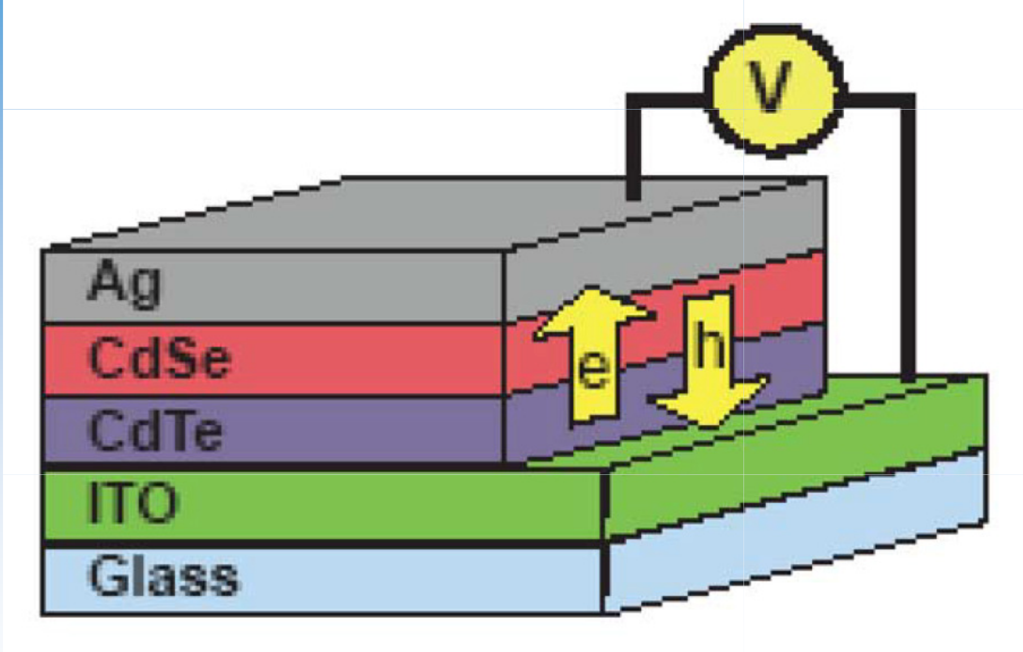
Inverted Pyramid Texturing of a Solar Cell



The inverted pyramids geometry utilized for light trapping on Si solar cells (Smith and Rohatgi 1993).

- Great light trapping properties due to:
- Reduced front surface reflectance by providing the opportunity for a portion of the incoming solar rays to undergo a triple bounce.
- Increase in path length of the solar ray through the cell, thus absorbing a larger fraction of the solar rays which has entered the cell before exiting the cell.
- Increase in amount of solar rays reflected from the back surface, by total internal reflection at the front surface/air interface by making the incident angle greater than the critical angle.

Fabrication of a Complete PV cell Applying a Handheld Airbrush



Fabrication of a complete PV cell using a handheld airbrush, dilute solutions of CdSe and CdTe nanorods, commercially available silver paint, and transparent-conducting-electrode-coated glass (Javier and Foos 2009).

Miscellaneous Other Aspects – Part 1

- Room for improvement in each specific system, e.g. regarding ventilation rate, positioning, removing of snow, etc.
- BIPV systems should be included early in the planning process to ensure a good integration.
- A well-established communication between the planners and manufacturers of BIPV products is important for the development of new BIPV solutions.
- For mono- or polycrystalline PV cells it is very important to achieve a sufficient ventilation rate, as the solar cell efficiency normally decreases with increasing temperature, and should thus be planned ahead of the construction phase.

Miscellaneous Other Aspects – Part 2

- Various solar radiation trapping mechanisms might be embedded in the surface.
- An idea may be to fabricate a "solar concentrator" at a microscopic material level embedded in the solar cell surface and beneath (Jelle et al. 2012b).
- Integrate PV cells in materials at an early stadium, e.g. in prefabricated concrete plates (Prasad and Snow 2005, SolarPower Restoration Systems 2011).
- Integrating PV with smart windows, e.g. electrochromic windows.
- Photocurrent quantum efficiencies exceeding 100 % in a quantum dot solar cell have been reported, being enabled by multiple exciton generation (MEG). The MEG process may occur in semiconductor nanocrystals or quantum dots where absorption of a photon with at least twice the bandgap energy creates two or more electron-hole pairs (Semonin et al. 2011).

Future Visions for BIPVs – Part 1

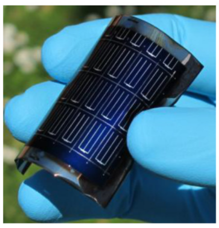
- BIPVs replacing conventional roof and facade materials already in progress, BIPV global market $\$1.8 \cdot 10^9$ in 2009, expected to grow to $\$8.7 \cdot 10^9$ in 2016 (Coons 2009).
- Low production costs, low environmental impacts and high efficiencies are key factors for the future BIPVs.
- Internal energy storage may also be envisioned in future solar cell materials, e.g. analogous to a photoelectrochemical solar cell (PEC) with internal storage. Various battery-technologies, e.g. metal hydrides, and nano technologies, could represent some of many possible ways to increase the energy storage density.
- The research and development of solutions regarding BIPVs for the retrofitting market are of great importance.

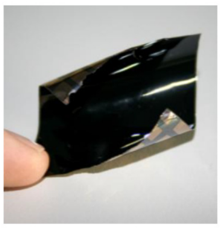
Future Visions for BIPVs – Part 2

- Great need for governmental subsidies in various countries.
- Necessary with a system for feeding the grid with PV electricity.
- BIPVs as solar cell glazing products provide solar shading, daylight transmission and electricity production.
- Forthcoming theoretical and experimental explorations may provide the PV and BIPV industry with several new and innovative materials and solutions.
- ”Future solar cell materials may also be envisioned as thin laminate or paint layers, hence also enabling application by paint brush or spray” (Jelle et al. 2012a).

Conclusions

- State-of-the-Art BIPVs
  - Numerous products on the market today
  - Improvements continuously being made
- The BIPVs of Tomorrow
  - Several research paths possible
  - Many new and flexible solutions expected
- BIPV Requirements
  - Solar cell
  - Building envelope






The Sun…
… an almost ever-lasting, renewable
and non-polluting energy source…

Appendix C

B. P. Jelle and C. Breivik, “State-of-the-Art and the Path to the Building Integrated Photovoltaics of Tomorrow”, Lecture presented by B. P. Jelle at the seminar *Supervarmeisolasjon og nye teknologier i bygningskroppen - Nytt i nær framtid* (High Performance Thermal Insulation and New Technologies for the Building Envelope - Emerging in the Near Future), Sandnes, Norway, 22 May, 2012. (Note that only the front page is included in this appendix as the lecture is identical to appendix B except the front page.)

State-of-the-Art and the Path to the Building Integrated Photovoltaics of Tomorrow

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Seminar "Supervarmeisolasjon og nye teknologier I bygningskroppen – Nytt i nær framtid" (High Performance Thermal Insulation and New Technologies for the Building Envelope – Emerging in the Near Future), Sandnes, Norway, 22 May, 2012.