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Review

Building Integrated Photovoltaics: A Concise Description of the Current State of the Art and Possible Research Pathways

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Abstract: Building integrated photovoltaics (BIPV) offer an aesthetical, economical and technical solution to integrate solar cells harvesting solar radiation to produce electricity within the climate envelopes of buildings. Photovoltaic (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, *i.e.*, the climate screen, hence serving simultanously as both a climate screen and a power source generating electricity. Thus, BIPV may provide savings in materials and labor, in addition to reducing the electricity costs. Hence, for the BIPV products, in addition to specific requirements put on the solar cell technology, it is of major importance to have satisfactory or strict requirements of rain tightness and durability, where building physical issues like e.g., heat and moisture transport in the building envelope also have to be considered and accounted for. This work, from both a technological and scientific point of view, summarizes briefly the current state-of-the-art of BIPV, including both BIPV foil, tiles, modules and solar cell glazing products, and addresses possible research pathways for BIPV in the years to come.

Keywords: building integrated photovoltaics (BIPV); solar cell; state-of-the-art; review; research pathway

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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 needs 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.

The BIPV systems replace parts of the conventional building materials and components in the climate envelope of buildings, such as the roofs and facades. According to Peng *et al.*, BIPV systems are considered as a functional part of the building structure, or they are architecturally integrated into the building's design [1]. Hence, the BIPV system serves as a building envelope material and power generator simultaneously [2].

This work summarizes first briefly the current state-of-the-art of BIPV, including both BIPV foil, tiles, modules and solar cell glazing products, also mentioning building attached photovoltaic (BAPV) systems. Thereafter, this work bridges the technologies of today and the scientific explorations of tomorrow by addressing and investigating several possible research opportunities and pathways for BIPV in the future. For further overview and elaborations within these aspects of BIPV, refer to the study by Jelle *et al.* [3].

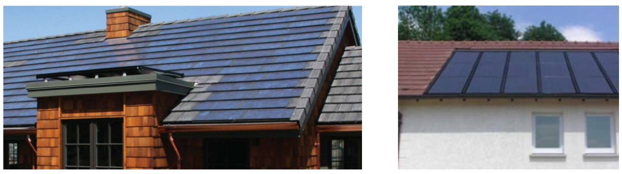
2. Building Integration of Photovoltaic Cells

Building integration of photovoltaic (PV) cells may be 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. On the other hand, BIPV systems replace the outer building envelope skin, thus serving simultanously as both a climate screen and a power source generating electricity. That is, BIPV may provide savings in materials and labor, in addition to reducing the electricity costs. As BIPV act as the exterior climate protection screen, it is of major importance to have satisfactory or strict requirements of rain tightness and durability. Although not part of the BIPV definition, one may also envision BIPV products incorporating larger parts of the building envelope like including e.g., thermal insulation, e.g., in sandwich sections or building blocks.

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 is the inclination of BIPV, 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 (exceptions may e.g., be different architectural integrations). 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.

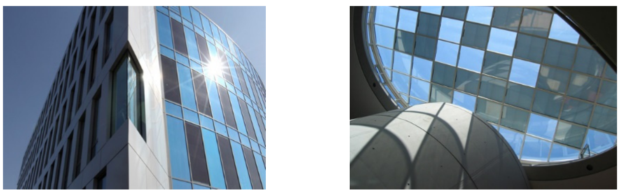
Hence, in short, BIPV systems have to fulfill all the requirements, with respect to several properties, of the building envelope skins they are substituting. Various building physical issues like e.g., heat and moisture transport in the building envelope also have to be considered and accounted for.

Examples of solar cells integrated as BIPV tiles and BIPV modules are shown in Figure 1. Furthermore, BIPV systems as solar cell glazing products in the facade and on the roof are depicted in Figure 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.



(**a**) (**b**)

Figure 1. Examples of BIPV tiles (**a**) and BIPV modules (**b**) (Applied Solar [4], DuPont [5]).



(**a**) (**b**)

Figure 2. Examples of BIPV as solar cell glazing products for facades (**a**) and roofs (**b**) (ASI Glass photovoltaic modules, Schott Solar AG [6]).

3. BIPV and Architectural Aspects

Opportunities for innovative architectural design, which may also be aesthetically appealing, are provided by miscellaneous BIPV systems, see e.g., Figures 1 and 2. BIPV 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 like 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 BIPV 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} (in V), short circuit electrical current I_{sc} (in A), fill factor $FF = P_{max}/(U_{oc}I_{sc}) = (UI)_{max}/(U_{oc}I_{sc})$, band gap E_g (in eV or J), quantum yield φ = number of photo-electrons divided by number of photons, solar cell temperature coefficient expressing the percentage decrease in solar cell efficiency (or another solar cell parameter like e.g., output power) for every degree Celsius the temperature of the solar cell rises above 25 °C (%/°C), and performance ratio (PR), which is the fraction of actual (measured) solar cell plant energy output (in kWh) divided by the calculated nominal solar cell plant energy output (in kWh), *i.e.*, PR then indicates all the losses due to solar cell array temperatures, system component inefficiencies and failures, and incomplete solar radiation utilization. The values reported by solar cell manufacturers are mainly obtained according to standard test conditions (STC, irradiance 1000 W/m^2, temperature of PV cell 25 °C, solar radiation distribution AM 1.5) or nominal operating cell temperature (NOCT, irradiance 800 W/m^2, ambient air temperature 20 °C, wind speed 1 m/s).

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], UL 1703 "UL standard for safety flat-plate photovoltaic modules and panels" [15], IEC 61724 "Photovoltaic system performance monitoring—Guidelines for measurement, data exchange and analysis" [16], and EN 50583 "Photovoltaics in buildings" [17]. For further and detailed information, it is referred to the standards themselves.

For rain tightness testing of BIPV products see the studies by e.g., Breivik *et al.* [18] and Fasana and Nelva [19]. Life cycle assessment (LCA) of PV systems [20] will also become more important.

5. State-of-the-Art of BIPV

5.1. BIPV Categorization

The range of BIPV products is very wide, and they may be categorized in 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 different BIPV products, the group building attached photovoltaic (BAPV) products should also be mentioned:

- BAPV products.

Building attached (applied/added) photovoltaics (BAPV) are regarded as add-ons to the buildings, hence not directly related to the building structures' functional aspects [1]. That is, BAPV are not BIPV, *i.e.*, BAPV are not integrated into the outer building envelope skin, thus not replacing the traditional building parts as BIPV are doing.

Some BIPV products exhibit a variety of properties, thereby making it more difficult to categorize them. Yet, in other cases, it might even be rather difficult to determine whether a PV product should be considered as a BIPV product or not, e.g., due to lack of information and uncertainty about how the product is mounted.

In the following, more details and some examples from each of the different BIPV product groups are given. For a comprehensive state-of-the-art review of these BIPV systems, including references and contact information, refer to Jelle *et al.* [3]. In the following, miscellaneous BIPV product properties are collected into tables. These tables provide the readers with valuable information concerning these products. However, unfortunately, it is often hard to obtain all the desired information from all the manufacturers. In general, many values (e.g., even the efficiency) 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, the 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 users to demand these values from the manufacturers.

Finally, the state-of-the-art BIPV products are part of setting the stage for the research pathways in the development of the future BIPV products.

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 Figure 3 present an example of one BIPV foil product.

Table 1. Literature data for one of the building integrated photovoltaics (BIPV) foil products [3].

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

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

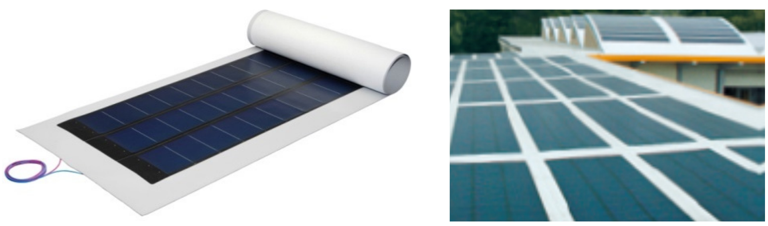


Figure 3. Example of a BIPV foil product from Alwitra GmbH & Co. using amorphous silicon cells from Uni-Solar [21].

PV foil products have a low fill factor due to both the low efficiency and the large solar cell electrical resistances of thin film cells. However, due to their flexibility and relatively low weight, these solar cell foil products may easily be applied to a lot of different building surfaces.

5.3. BIPV Tile Products

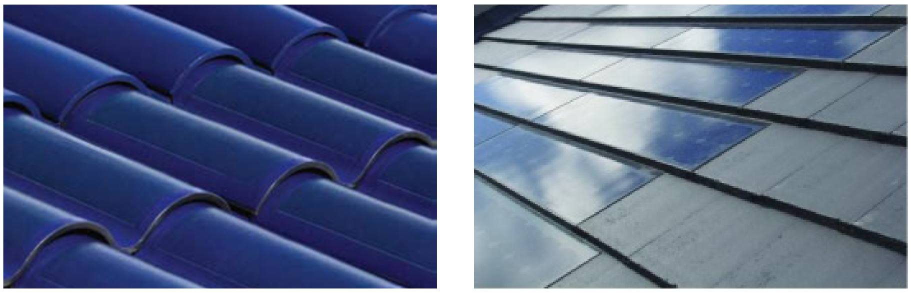
BIPV tile products may cover the entire roof or selected parts of the roof. They are normally arranged in modules with the appearance and properties of standard roof tiles and substitute a certain number of traditional roof tiles, thus also enabling easy retrofitting of roofs. The cell type and tile shape varies. Some tile products may resemble curved ceramic tiles 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 Figure 4.

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.

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 × mm)	P_{max}/Area (W/m^2)
Solardachstein	STEPdesign		23.15	2.40	1.36/cell	0.76	8 units 100 × 100	136
SRS Energy	Solé Powertile		6.3	4.6	15.75/module	0.54	868 × 457.2	39.7
Lumeta	Solar Flat Tile		7.4	5.2	28/module	0.73	432 × 905	71.6
Solar Century	C21e Tile	20/cell	12.0	5.55	52/module	0.78	1220 × 420	101.5

* Lumeta has also a Solar S Tile available.



(**a**) (**b**)

Figure 4. Example of BIPV tile products from SRS Energy (**a**) [22] and Solar Century (**b**) [23].

5.4. BIPV Module Products

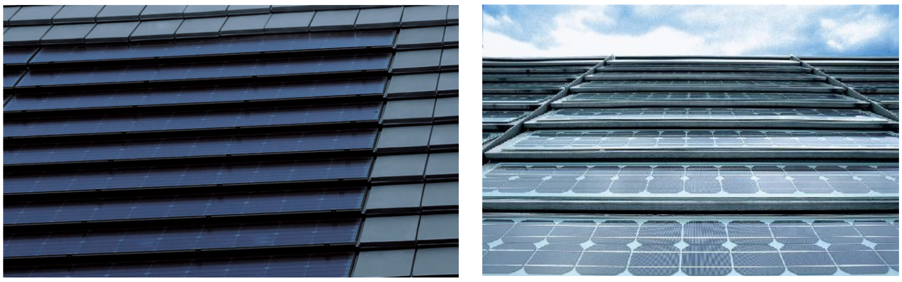
The BIPV module products presented are somewhat similar to conventional PV modules. The difference, however, is that the BIPV modules are made with weather skin solutions. Some of the products may replace various types of roofing, or they fit with a specific roof solution produced by its manufacturer.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

Several products are 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 BIPV or BAPV. 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 Figure 5.

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 × mm)	P_{max}/Area (W/m^2)
Creaton AG	Creaton Solesia		13.86	8.46	90/module	0.77	1778 × 355	142.6
Rheinzink	PV Quickstep		17.10	5.12	68/module	0.78	2000 × 365	93.2
Abakus Solar AG	Peak On P220-60	13.2	36.77	8.22	220	0.73	1667 × 1000	132.0
	Peak On P235-60	14.6	37.21	8.48	235	0.74	1630 × 1000	144.2
	ANT P6-60-230	14.07	36.77	8.42	230	0.74	1658 × 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 × 929, 1332.5 × 929	129.36, 133.4
Suntech	MSZ-190J-D		45.2	5.62	190/module	0.75	1641 × 834.5	139
	MSZ-90J-CH		22.4	5.29	90/module	0.76	879 × 843.5	125
Schott Solar	InDax 214	12.5	36.3	8.04			1769 × 999	
	InDax 225	13.1	33.5	6.60			1769 × 999	
Solar Century	C21e Slate	20/cell	12.0	5.55	52	0.78	1174 × 318	139.3

* Several models are available from various producers.



(**a**) (**b**)

Figure 5. Example of BIPV module products from Creaton AG (**a**) [24] and Rheinzink (**b**) [25].

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.

5.5. *Solar Cell Glazing Products*

BIPV as 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 aesthetically pleasing results possible. Some solar cell glazing product examples are given in Table 4 and Figure 6.

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

* Several models are available from various producers.

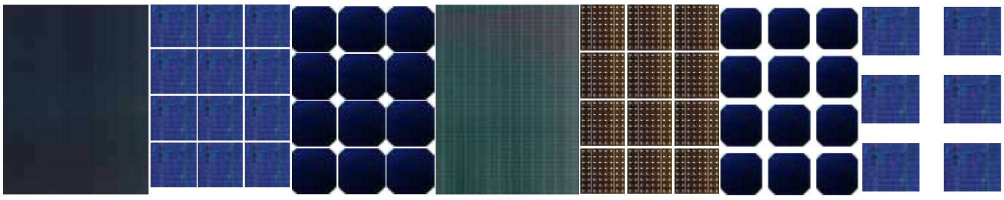


Figure 6. Example of solar cell glazing products from Sapa Building System [26] using either amorphous, polycrystalline or monocrystalline cells with different distances between the cells.

The solar cell glazing modules transmit daylight and serve as water and sun protection. The distance between the solar cells depends on wanted transparency level and the criteria for electricity production, but normally the distance is between 3 and 50 mm. The space between the cells transmits diffuse daylight. Hence, shading, heating and natural lighting are provided while producing electricity. Human comfort aspects related to solar cell glazing products are also important and being investigated [27,28].

The solar cell glazing manufacturers usually offer customized products for specific projects, regarding shape, cell material, color 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 Figure 6 are 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 Figure 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 building attached photovoltaic (BAPV) products [3].

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

* Several models are available from various producers.

(**a**)

(**b**)

Figure 7. Example of BAPV products from Uni-Solar (**a**) [29] and Hauptsitz (**b**) [30].

6. Economical Aspects of BIPV

The global market for BIPV is expected to grow from \$1.8 $\times$ 10^9 in 2009, to \$8.7 $\times$ 10^9 in 2016, according to consulting firm NanoMarkets, New York [31]. 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 BIPV volume will drop from 75% of the market to 33% by 2016 [31].

As PV panels occupy a large area for installation, the associated financial challenge could be best answered by space-saving technologies like BIPV [32]. 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 BIPV adds only a marginal extra cost (2%–5%) to the overall construction costs of a commercial building [33].

The BIPV technology is a growing technology and is still rather expensive. Furthermore, one may note that the building sector is rather price-sensitive. In addition, as BIPV is still far from being a mature technology, uncertainty about BIPV and their implementation is another crucial aspect to be considered. This uncertainty includes many factors, e.g., installation, electrical aspects, safety issues, integration aspects, building physical aspects, protection *versus* climate exposure, durability, maintenance, demolition, life cycle assessment, possible to sell surplus electricity to the grid or not, architectural aspects and others. Naturally, all these factors may also lead to increased costs.

Today, a maximum payback time for PV modules of ten years is generally expected in Europe. However, such a short payback time is normally not achieved without subsidies. Countries developed for electricity 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, *i.e.*, possible to sell the PV generated electricity to the grid, the PV industry may have a more promising 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 [34].

Over time, the cost of a PV system will decline with the improvement of technical advances, resulting into a lower price per kW installed [35], which is an important part of the development to make installation and building integration of PV products profitable without subsidies, thus setting the stage for the next step, *i.e.*, pursuing research opportunities and advances on the path to develop the BIPV of tomorrow.

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 [36]. For further studies of the energy payback time, refer to the literature [36–40].

7. The Path to the BIPV of Tomorrow

7.1. PV Development and Impact on BIPV

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

As for the advances in PV technology, in Figure 8, there is a timeline given 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 [41]. The experimental investigations range from the more pure materials science-focused ones, e.g., quantum dots [42], to the more device-focused ones, e.g., ceramic tiles [43]. The advances in these PV technologies and their increasing efficiencies will naturally be exploited in the coming BIPV products to be made.

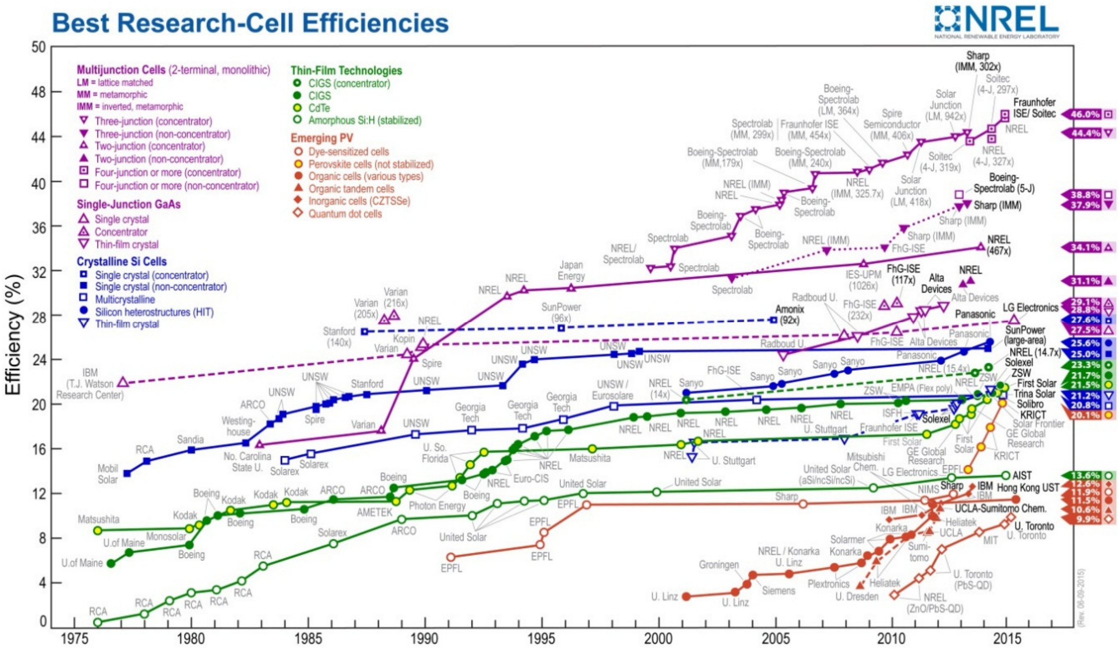


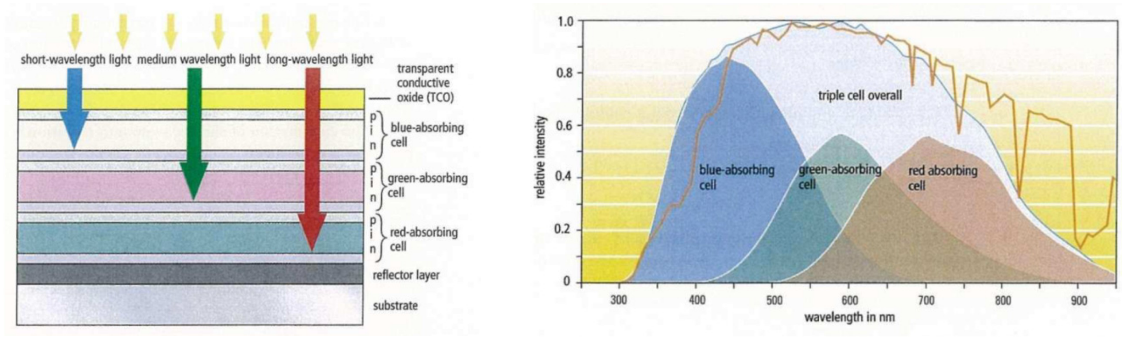
Figure 8. A timeline for reported best research-cell efficiencies, depicting all verified records for various PV conversion technologies like crystalline Si, thin film, single-junction GaAs, multijunction and emerging technologies [41].

7.2. New Materials and Solutions for BIPV

The research paths for possible new PV technologies that may initiate and advance into new innovations, and which may be developed into BIPV, 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. And the more we want to know... and that's the whole fun of it, scientific research included!*" [44], the latter one representing a modified extrapolation from a quote from Aristotle.

7.3. Sandwich Solar Cells

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 Figure 9 [38]. 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.

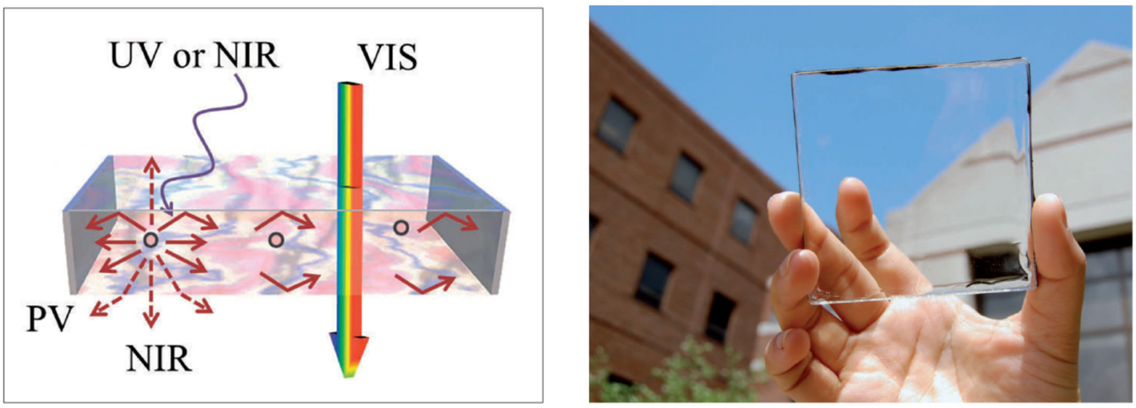


(**a**) (**b**)

Figure 9. An amorphous triple solar cell with its configuration (**a**) and spectral responses (**b**) [38].

7.4. Solar Cells Absorbing Non-Visible Solar Radiation

Another strategy is depicted in Figure 10, where researchers from Michigan State University have developed a solar harvesting system using small organic molecules that are tuned to absorb specific non-visible wavelengths (*i.e.*, ultraviolet and near infrared) of solar radiation and letting the visible solar radiation pass straight through, thereby resulting in a solar cell able to create solar energy while still allowing people to see through a clear glass with no color distortions [45]. Thus, solar energy may be harvested by windows that apparently look like normal and clear windows.



(**a**) (**b**)

Figure 10. A solar harvesting system using small organic molecules that are tuned to absorb specific non-visible wavelengths of solar radiation and letting the visible solar radiation pass straight through (**a**), hence resulting in a solar cell that creates solar energy while still allowing people to see through a clear glass with no color distortions (**b**) [45].

7.5. Polymer Solar Cells

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 [46]. The highest reported efficiency for an organic solar cell (with the exception of DSSC) was 6.5% in 2007 and has now reached 11.5% in 2015 (see Figure 8), and this makes them competitive with CO_2-producing technologies [47]. However, the polymer solar cells are more sensitive to degradation, where ultraviolet solar radiation 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 BIPV [48]. 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 [47].

7.6. Dye Sensitized Solar Cells

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" [49]. 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 [50–53]. 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. 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 one 10th of the Si based cells [54]. 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. The schematic structure and band diagram for DSSC are depicted in Figure 11 [55,56]. For further investigations on DSSC, see various studies given in the literature [50–52,55–59].

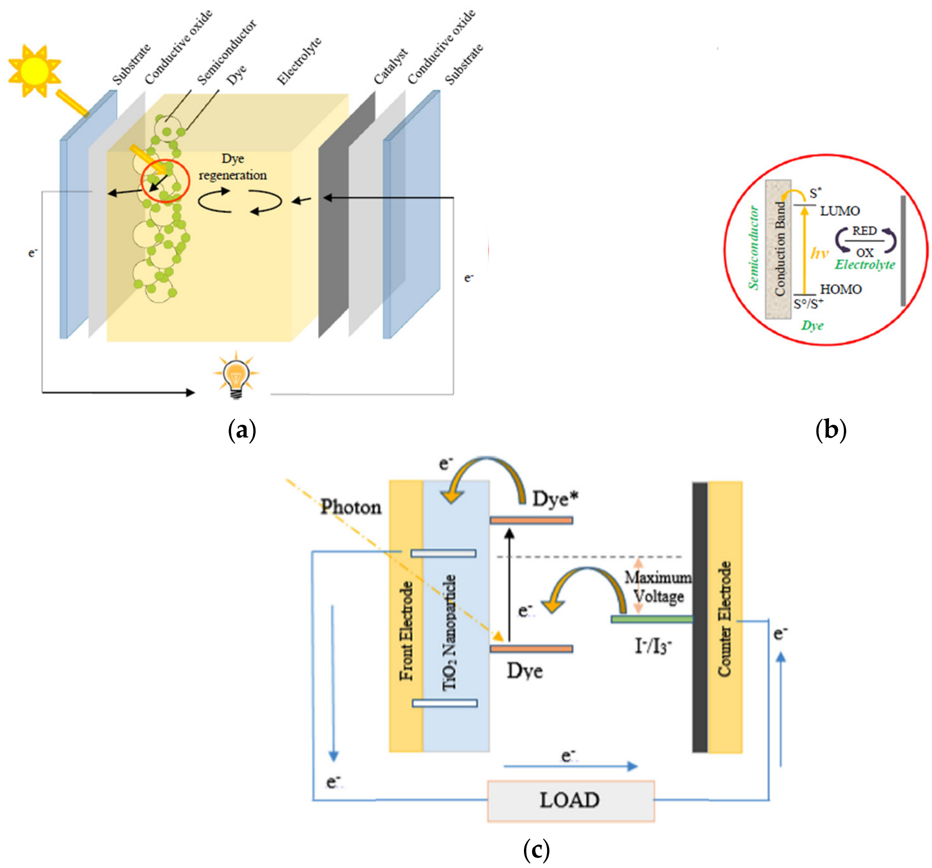


Figure 11. DSSC schematic structure ((**a**) [55]) and band diagram ((**b**) [55] and (**c**) [56]).

7.7. High-Performance Solar Cells

As noted in the above (Figure 8), research laboratories have for many years produced high-performance solar cells with efficiencies up to 25%–40% [38,60]. One approach is to use materials with higher purity and to eliminate the impurities along in the process. In addition, 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 making high-performance solar cells and increasing the efficiency may be solar cell concentrators or concentrated photovoltaic (CPV) cells. Efficiencies reaching 43.5% has been achieved for commercial-ready CPV cells [60]. These cells are typically applied in the concentrator modules based on a concept of the small-aperture refractive concentrators [61]. Currently, the highest solar cell efficiency for a CPV cell given in Figure 8 is 46.0%.

7.8. Antenna-Sensitizer Solar Cells

Yet another innovative option for more effective harvesting of solar energy is so-called "antennas" depicted in Figure 12, 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" [62].

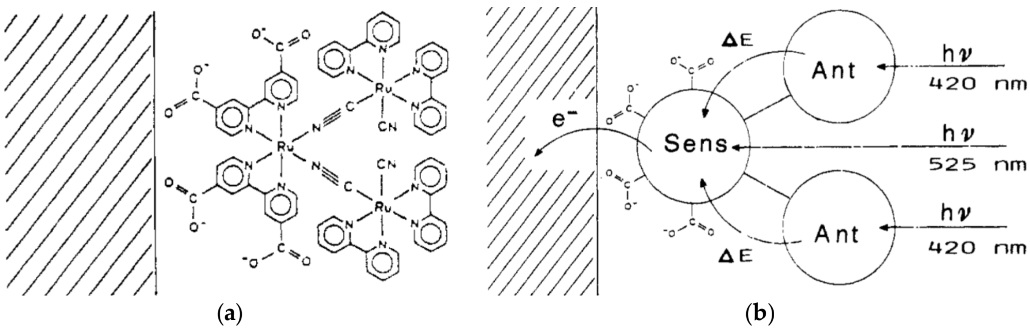


Figure 12. Illustrative representation of the adsorption mode of the trinuclear complex on the TiO_2 surface (**a**) and block diagram showing the function of the trinuclear complex as an antenna-sensitizer molecular device (**b**) [62].

7.9. CIGS and CdTe Solar Cells

Flexible CIGS (copper indium gallium selenide) and cadmium telluride (CdTe) solar modules are shown in Figure 13 (configurations) and Figure 14 (photos). In an experiment performed by Buecheler *et al.* [63], 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 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." [63].

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" [64]. Figure 15 shows an example of a bending test performed on a CIGS solar cell on flexible borosilicate ultra-thin glass substrate (100 μm) [65].

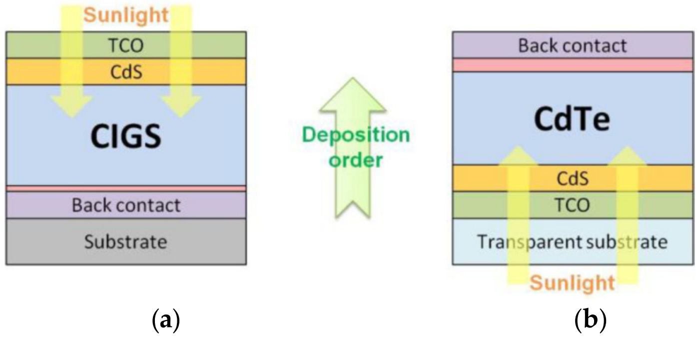


Figure 13. Schematic built-up of CIGS (**a**) and CdTe (**b**) thin film solar cells [63].

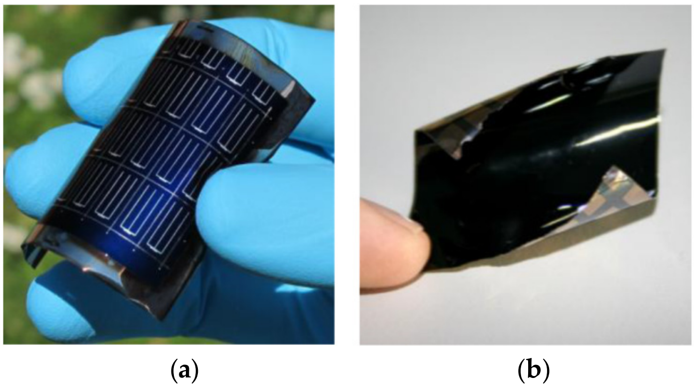


Figure 14. Flexible CIGS (**a**) and CdTe (**b**) solar cells on polyimide substrates [63].

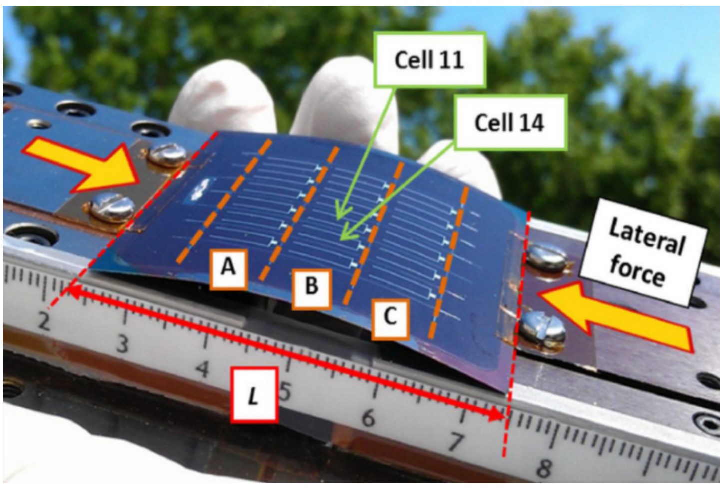


Figure 15. Bending test of a CIGS solar cell on flexible borosilicate ultra-thin glass substrate (100 µm) [65].

7.10. CIGS-Based Solar Shingles

New solar cell material technology includes crystalline Si on glass (CSG), copper indium gallium selenide (CIGS), microamorphous Si cells, concentrating systems and hybrid solar cells. Dow Chemical has introduced a line of CIGS-based solar shingles [66]. The BIPV solar shingle installs and performs like a standard asphalt shingle, has an expected lifespan of 15–20 years (like conventional asphalt shingles), and has received a GLOBE Foundation award for "Environmental Excellence in Emerging

Technology" [31,67]. 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.

7.11. Quantum Dot Solar Cells

In the recent experimental investigations carried out by Semonin *et al.* [42], 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. In Figure 16, there are shown scanning electron microscope images of TiO_2 nanorods and cadmium sulfide (CdS) quantum dots, for further details including charge transfer processes between CdS and TiO_2 in a quantum dot nanowire based solar cell, see the review by Badawy [68]. Thus, miscellaneous new and exciting discoveries within solar cell research will with time find their way into the PV and BIPV systems for the buildings of tomorrow.

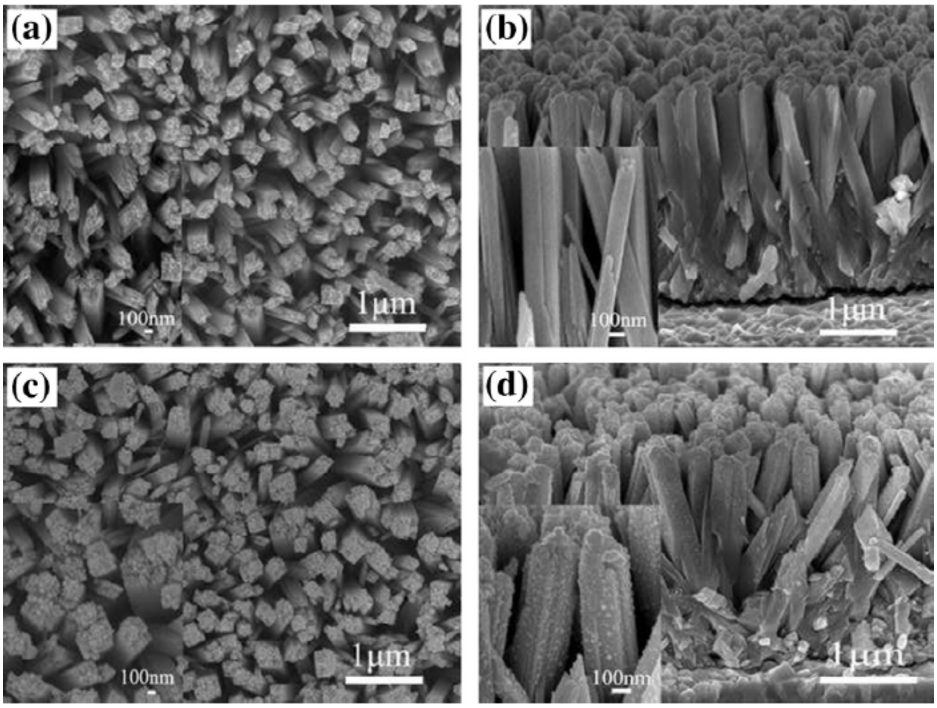


Figure 16. Field-emission scanning electron microscope (FESEM) images of (**a**) TiO_2 nanorod array (top view); (**b**) cross-sectional SEM image of TiO_2 nanorod array grown on FTO (fluorinated tin oxide); (**c**) top and (**d**) cross-sectional view of CdS quantum dots coated TiO_2 nanorod array [68].

7.12. From PV to BIPV

The PV industry offers many different 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.

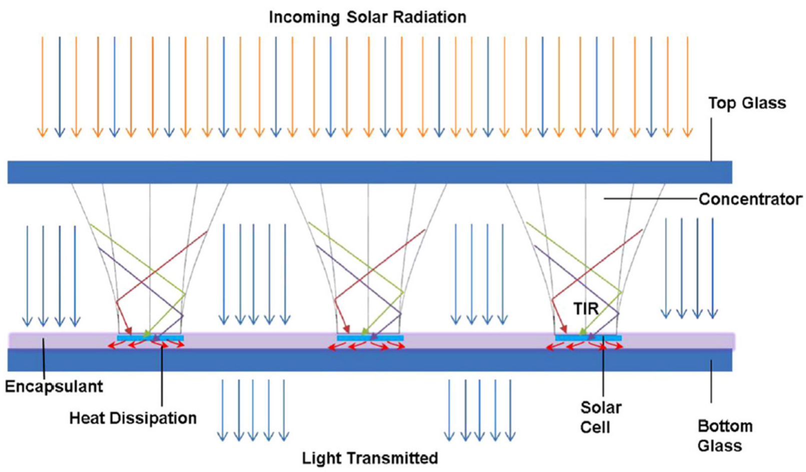
The BIPV systems are expected to improve in the near future regarding efficiency of both the product and the production phase, hence leading to decreased energy payback time. However, the payback time will be dependent on the market situation and/or subsidies.

As mentioned earlier, improvements for PV will also lead to improvements for BIPV. The BIPV products have to fulfill the requirements to the building envelope as well as the solar cell requirements, as compared to PV where only the latter requirements need to be fulfilled. Some specific aspects may be more important for BIPV and their application range than PV, e.g., the thickness and the flexibility or bending possibilities of the solar cells.

7.13. Solar Cell Concentrators

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. Classical solar concentrator systems are described as arrays of PV modules that are mounted onto large movable structures that are continuously aimed at the sun. Hence, one may envision to 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].

An example still at a macroscale, but nevertheless being part of the ongoing process of making the dimensions of solar concentrators smaller, is depicted in Figure 17 [69], where the height of the concentrator element is as small as 25 mm, thus entitling the authors to name their system as a building integrated concentrating photovoltaic (BICPV) system.



(**a**)

(**b**)

Figure 17. Schematics of a solar concentrator utilizing total internal reflection (TIR) in order to guide the incoming solar radiation to the active solar cell parts (**a**) and actual concentrator element array made of polyurethane (**b**) [69].

Another example of solar cell concentrators is given in Figure 18, in this particular case a luminescent solar concentrator (LSC), where first dye-doped polymethylmethacrylate (PMMA) plates were prepared by an *in situ* polymerization method and, thereafter, crystalline silicon solar cells were mounted to the as-prepared dye-doped PMMA plates [70].

Naturally, for solar concentrators to be applied as BIPV, it is crucial to make the concentrator dimensions as small as possible, e.g., with respect to the total thickness. For further details and information about solar concentrators, refer to the available literature [3,61,69–71].

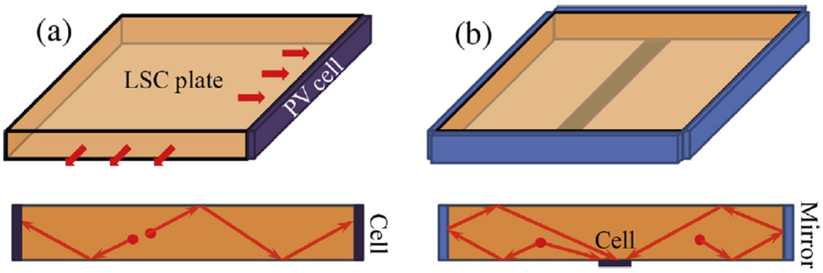


Figure 18. Illustration of a luminescent solar concentrator with (**a**) side-mounted and (**b**) bottom-mounted solar cells [70].

7.14. Inverted Pyramid Texturing

Inverted pyramid texturing of a solar cell as illustrated in Figure 19 is another option for more effective solar energy harvesting [72]. 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 [72]. In this respect, also note the work by Kang *et al.* [73] where they have designed an asymmetrically textured structure for efficient solar radiation trapping in BIPV.

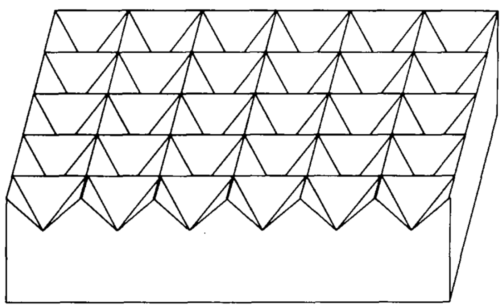


Figure 19. The inverted pyramids geometry utilized for light trapping on Si solar cells [72].

7.15. PV Integration in Concrete

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 [53,74]. 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. Note also the BIPV product DysCrete using an organic dye on a concrete surface to harvest solar radiation and generate electricity, the name origin from dye sensitized solar cells and concrete [75,76].

7.16. Solar Cell Paint

Thin laminate or paint layer solar cell materials represent another future option. Javier and Foos [77] fabricated a complete photovoltaic cell using a handheld airbrush, dilute solutions of cadmium selenide (CdSe) and cadmium telluride (CdTe) nanorods, commercially available silver paint, and transparent-conducting-electrode-coated glass, as depicted in Figure 20. 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 [77]. In this respect, see also the work by Lee *et al.* [78].

Schematics of a brush painting process to prepare brush-painted flexible organic solar cells are shown in Figure 21, where highly transparent and flexible Ag nanowire electrodes with low sheet resistance were utilized [79]. Furthermore, a patternable brush painting process for fabrication of flexible polymer solar cells was investigated by Heo *et al.* [80], their flexible polymer solar cell being depicted in Figure 22. Several other investigations have been carried out on brush painting (or spray coating) and flexible solar cells [81–85].

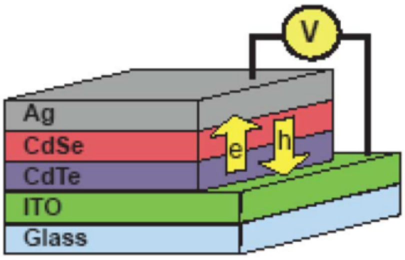


Figure 20. Schematic view of a PV cell composed of indium-tin oxide (ITO) coated glass, CdTe and CdSe nanorods, and silver paint. Electrons (holes) are preferentially pushed towards the Ag (ITO) electrode as depicted by the arrows [77].

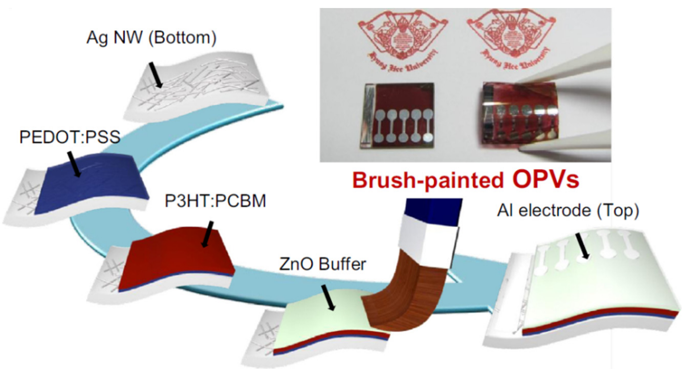


Figure 21. Schematics depicting a brush painting process of preparing brush-painted flexible organic solar cells. The inset photo shows the flexibility of the brush-painted flexible organic solar cells [79].

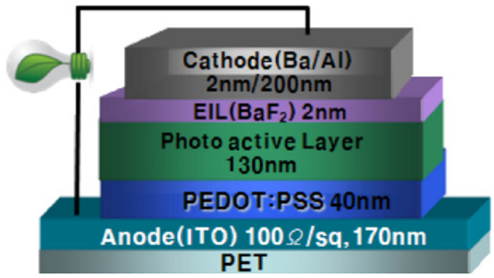


Figure 22. Device structure of a flexible polymer solar cell [80].

7.17. Hybrid Solar Cells

Hybrid solar cells are combining various properties of different materials. Typically, they consist of both organic and inorganic semiconductors, where the organics absorb the solar radiation and the inorganics function as the electron transporter. The structure and interface types are of crucial importance for the hybrid solar cells. Often, an increased interfacial surface area between the organic and inorganic materials is desired in order to facilitate charge separation and increase efficiency. Different nanoscale structures like mesoporous inorganic films mixed with organics, alternating inorganic-organic lamellar structures and nanowire structures may be made. Hybride solar cells exist in many variations and combinations and thus constitute a very broad group of solar cells, where e.g., nanoparticle, nanowire, quantum dot, graphene, carbon nanotube, conjugated polymer, silicon, cadmium telluride, cadmium sulfide, perovskite, titanium dioxide and dye sensitized materials among others are being applied [86–100].

7.18. PV Electrochromic Devices

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." [7].

Hence, 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 [101]. Thus, 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 (NREL) of Golden (USA) has built self-powered photovoltaic electrochromic devices up to 25 cm^2 [102]. 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." [102]. For further information it is referred to the available literature [57,101,103–105].

7.19. Various Aspects

The physical principles of losses in thin film solar cells and efficiency enhancements methods are addressed by Dhankhar *et al.* [106], where, in general, the investigations on thin film solar cells, including e.g., both amorphous and crystalline silicon, represent an important research field [106–110]. Studies on semi-transparent photovoltaics have also been conducted [28,103,111–115], likewise life cycle assessments (LCA) of photovoltaics [20,55,116,117]. Furthermore, note the study of screening-engineered field-effect solar cells by Regan *et al.* [118]. Other relevant studies on BIPV may also be found in the scientific literature [119–128].

For additional information on windows and glazing technologies, see e.g., the studies by Baetens *et al.* [102] for smart windows, Bellia *et al.* [129] for solar shading systems, Cuce and Riffat [130] for innovative glazing technologies, Gao *et al.* [131,132] and Ihara *et al.* [133–135] for aerogel-related glazing aspects, Grynning *et al.* [136] for windows as energy losers or energy gainers, Gustavsen *et al.* [137] for key elements and materials performance targets for highly insulating window frames, Hee *et al.* [138] for daylighting and energy savings in buildings, Jelle [139,140] for solar radiation glazing factor factors and electrochromics, and Jelle *et al.* [7,141] for fenestration of today and tomorrow and solar protection factors.

For continued, updated solar cell efficiencies in the above described materials and technologies, refer to the values given by NREL in Figure 8 [41]. Finally, see also further information in the reviews given by Badawy [68], Dhankhar *et al.* [106], Gerbinet *et al.* [117], Ikkurti and Saha [142], Jelle *et al.* [3], Rajesh and Mabel [143], Skandalos and Karamanis [144], and Sugathan *et al.* [56].

7.20. 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* 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 [145,146]. In general, investigating the durability of building materials and components, also newly developed ones, e.g., by carrying out accelerated climate ageing in the laboratory, is of major importance [146]. Thus, performing a robustness assessment of these materials and components may also be found to be beneficial [147].

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 [11], and for crystalline Si PV cells EN 61215 [12] 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 [15]. Naturally, some new materials and technologies will not be covered by these standards.

Thus, 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 BIPV.

7.21. Future Visions for BIPV

The main target of BIPV replacing conventional roof and facade materials is already in progress as the global market for BIPV was \$1.8 $\times$ 10^9 in 2009 and is expected to grow to \$8.7 $\times$ 10^9 in 2016 [3,31,148]. 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 BIPV [3,149]. 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 negative environmental impacts and high efficiencies are key factors for the future BIPV.

The research and development of solutions regarding BIPV 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 [150]. 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. Different battery technologies, e.g., metal hydrides, and nanotechnologies, 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.

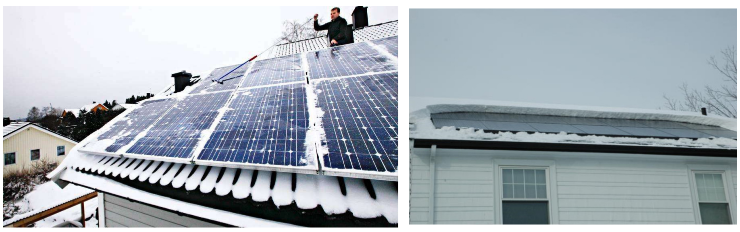
An almost unlimited range of opportunities is offered by BIPV as solar cell glazing products, providing both solar shading, daylight transmission and producing electricity. Combinations of PV with smart window technologies like e.g., electrochromics [7,57,101–103,139–141,151–171] may also be envisioned [57,101,103–105].

Self-cleaning aspects and how to avoid snow and ice formation on the solar cell surfaces will also be important issues to address [172–174]. Figure 23 illustrates this challenge as, depending on the climate conditions, snow and ice may stick to smooth glass surfaces for large inclination angles and even for vertical surfaces [173]. Then, the result may become manual and mechanical methods for removing snow from solar cell roofs as depicted in Figure 24 [175,176].

Thus, in order to find solutions for these challenges investigations on superhydrophobic and icephobic surfaces are being conducted [173], where some examples are shown in Figures 25 and 26 [177–179]. Several studies on superhydrophobic surfaces and icephobicity may be found in the literature [172,173,177–192], where ultimately these may lead to future solar cells able to avoid or minimize ice and snow formation on their surfaces.

(a) (b)

Figure 23. A snow/ice slab firmly sticking to the glass surface of an insulated window pane even at an inclination angle of 90° during a laboratory experiment (**a**). Snow covering a solar cell panel at an inclination angle of 70° (**b**) [173].



(a) (b)

Figure 24. Today, one often has to use manual and mechanical methods for removing snow from solar cell roofs as depicted in the (**a**) [175] and (**b**) [176] photos.

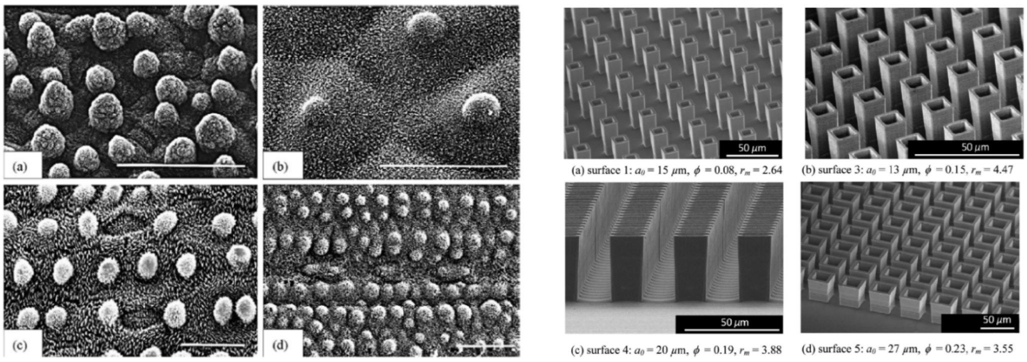


Figure 25. (left four photos) Examples of micromorphologies for water-repellent leaf surfaces of (**a**) Nelumbo nucifera and (**b**) Lupinuspolyphyllos (bars = 50 µm); and (**c**) Gladioluswatsonioides and (**d**) Sinarundinaria nitida (bars = 20 µm) (Hsu *et al.* [177]). (right four photos) Images of four representative hollow hybrid superhydrophobic surfaces fabricated (Dash *et al.* [178]).

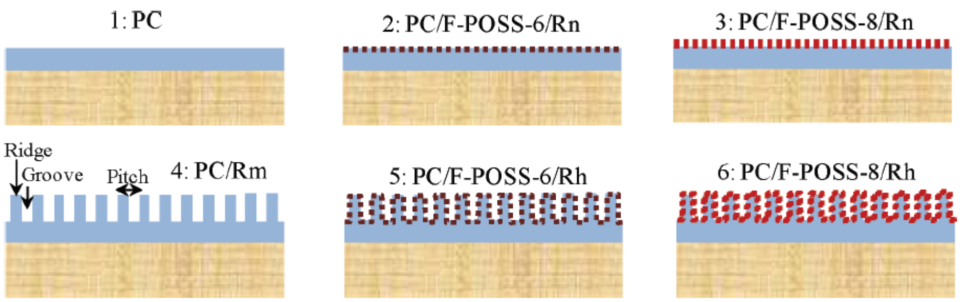


Figure 26. Anti-icing coating design cases where Rn denotes nanoscale roughness, Rm microscale roughness, and Rh hierarchical roughness (Xiao and Chaudhuri [179]).

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" [7]. A development towards higher solar cell efficiencies and building envelopes utilizing building integrated photovoltaics, smart window technologies [7,57,101–105,139–141,151–171], better thermal insulation [44,193–200], low-emissivity materials [201] and phase change materials [202], among others, may increase the energy efficiency and shorten the payback time of buildings and their applied technologies. We may end this with the following vision from Richard Lunt at Michigan State University: "*Ultimately, we want to make solar harvesting surfaces that you don't even know are there.*" [45].

8. Conclusions

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, environmental aspects, reduced production costs and improved building integration.

New and innovative solutions may reduce costs and increase the market share, e.g., in the retrofitting market. The chosen solutions should be easily applicable, where an 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. Furthermore, there is also a need for development of new standards and methods, e.g., regarding long-term durability *versus* climate exposure.

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Conflicts of Interest: The author declares no conflict of interest.

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