SolarEMR

Brochure mass-customized PV semi-fabricates

SolarEMR T1-partners

Facade of new R&D and production facility of SolarEMR-member Soltech is PV-active, and a very nice example of BIPV. 42 Patterned PV-panels form one total image which makes the integrated PV truly invisible!

Pictures front page

- *Left: Building Integrated PV (BIPV)-demonstrator at façade of building Heijmans Hive in Rosmalen (NL).*
- *Right: Infrastructure Integrated PV (IIPV)-demonstrator at Brightland Campus, Geleen (NL).*

The SolarEMR project, is being carried out within the context of Interreg V-A Euregio MeuseRhine, with funding from the European Regional Development Fund.

Contents

Introduction

Version history

2022-01-01: Living document to collect input from the broad range of aspects involved in the development of PV semi-fabricates as defined within the SolarEMR-project

2022-06-30: M6-version of brochure as described in the project plan as deliverable D.T1.1.1.

2023-01-24: M12-version of brochure as described in the project plan as deliverable D.T1.1.1

2023-06-12: M18 (and final) version of brochure as described in the project plan as deliverable D.T1.1.1

Glossary

PV semi-fabricates are also often called PV laminates or shortly laminates. These words are all used as synonyms in this brochure.

It should be possible to read this brochure without being an expert in the PV industry.

The target audience of this brochure are interested Small and Medium Enterprises (SMEs), companies and designers in the field of buildings and infrastructure.

This M18-version is the final version presented at the end of the project.

Figure 1: In the SolarEMR-project two very important Integrations of PV are developed; on the left some examples of Building Integrated (BIPV) and on the right some examples of Infrastructure Integrated (IIPV).

Scope and disclaimer

The authors of this brochure have done their best to describe the properties of the PV semi-fabricates extensively and as much as possible in a quantitative manner. However, depending on the specific aspect such a precise value can have a very different status. E.g. the maximum width of the pilot line for mass-customization as developed by TNO in Eindhoven is 0.7 meters at the moment. This is a hard criterion for the width dimension of laminates. But when we describe e.g. lifetime, it should be realized that the reliability is a very complex assembly of process settings and precise Bill Of Materials (BOM) used. Therefore we make an explicit disclaimer at this spot, that any value used in this brochure never can be used to ‘claim’ a specific performance.

On the one hand, values can be ambitions to be reached in the near future. On the other hand, values can be solid specification already today as being State of the Art (SOA). And everything in between these extremes is also possible. The authors do their uttermost best to give enough context in each paragraph for the reader to understand the status of the values. But on some occasions this cannot be defined precisely. E.g. it might be a realistic ambition to reach an overall efficiency of 18% for a specific laminate for a specific well-defined prototype. After assembling this prototype, it turns out that for unknown reasons the measured overall efficiency is e.g. 16%. This is intrinsic to Research and Development (R&D), and thus also for the R&D of the laminates within SolarEMR.

Abbreviations & definitions

- BOM: Bill of Materials
- c-Si PV Crystalline Silicon PV
- DH: Damp Heat
- DUT: Device Under Test
- Customer: company of xIPV product integrator that uses the SolarEMR-laminate
- EPT: Energy Payback Time
- End customer: final customer that buys the end product from the integrator company
- G-G: Glass-Glass
- GWP: Global Warming Potential
- IGU: Insulated Glass Unit
- MC: Mass Customization
- NZEB: Near-Zero-Energy-Buildings
- P_{mpp} [W]: Power at Maximum Power Point; unit [W]
- R&D: Research and Development
- SME: Small and Medium Enterprises
- SOA: State of the Art
- STC: Standard Test Conditions
- V_{mpp} [V]: Voltage at Maximum Power Point; unit [V]
- xIPV: Integrated PV in either x=**B**uildings or x=**I**nfrastructure

Integration type

The Energy Transition is now really speeding up in Europe. There is no discussion anymore about the abundant amount of solar energy that needs to be available in the short term (2030) and on the longer horizon (2050). For the Netherlands, most energy scenarios have defined a total capacity of at least 200 GWp solar PV to be installed by 2050. Especially in the densely populated EMR-region of the EU, there is a need for multi-function usage of area. A few years ago, various solar PV integration types might have sounded exotic, but at the moment they are already a serious working field for academics and technology companies. In general, PV is very well suited for “seamless” integration into the environment due to several generic reasons: first of all, a PV system does not contain any moving parts, and therefore it does not produce any noise. Second, the production of PV modules allows in principle to adapt the form factor, color and appearance to the environment in which these PV modules are to be integrated. This is true in principle, since today most production lines lack the flexibility to effectively realize this mass customization.

More specifically, “Integrated PV” includes a number of sub-domains which we briefly describe here.

Building Integrated PV (BIPV)

With BIPV, the PV system is incorporated into the building envelope and, in addition to its electricity generation function, it also has other functions: protection from wind and moisture, aesthetic improvement, especially if it is integrated into the façade of a building. This evolution is also stimulated by European legislation that makes it mandatory to strive for Near-Zero-Energy-Buildings (NZEB).

Infrastructure Integrated PV (IIPV)

In this field the PV system is integrated somehow in the infrastructure. This can be a noise barrier, road element, sideways of the road, dikes (especially in the Netherlands!), railway barriers, etc…

Floating PV (FPV)

The PV system is applied on water surfaces, another important element to make the most effective use of the surface in densely populated areas. In addition to generating electricity, these PV modules can also reduce the rapid evaporation of water, which can also be a problem for water reservoirs during dry summers. Clearly, for this application, PV modules and PV systems will have to meet many additional conditions, such as corrosion resistance.

Agricultural Integrated PV (Agri-PV)

Multifunctionality also plays an important role in Agri-PV. Besides electricity generation, the PV module can also fulfill other functions: lowering the temperature near the plant (photosynthesis will decrease if the temperature is too high) and preventing the soil from drying out or damage from hail. Both elements are essential in view of the effect of warmer and drier summers expected based on climate projections.

Vehicle Integrated PV (VIPV)

In VIPV, PV is embedded on the exterior surfaces of the vehicle. This integration allows the recharging of a hybrid or fully electric car, which will improve convenience and reduce “range anxiety”. Clearly, the integration of PV on the exterior surface of a vehicle should be as “seamless” as possible; otherwise, the aesthetic quality of the car will suffer, which practically means that the PV systems must also be curved. In addition, the PV elements should also have the highest possible conversion efficiency since the outer surface of a car is limited.

Figure 2: Various types of integrated PV. Within SolarEMR we target BIPV with a façade application and IIPV with a noise barrier application. Source picture: IMEC.

The SolarEMR project is targeting the first two: the BIPV and IIPV, which are the largest markets at the moment. And which are also the markets that have great opportunities with respect to new products. The product developers could benefit from this brochure that describes comprehensive aspects related to the semi-fabricates that produce PV-electricity and will be integrated in the new BIPV- and IIPV-final products. In some parts in this document, we will refer to xIPV in case a development is not depending on whether the final product will be a BIPV- or IIPV-product.

PV Technologies

Crystalline Silicon (c-Si)

The PV-market nowadays is dominated by PV-modules based on crystalline PV cells. These crystalline PV-cells are available in multiple technologies: mono/poly/PERC/IBC/half-cells/etc…

SolarEMR-partners involved in the research and development of this PV-technology are: Helmo (LCA-info), IMEC, SolTech, TNO. Abbreviation used in this document: c-Si.

The vast majority of these PV-modules are rigid and involve one or two glass plates. Some exotic products get their rigid character from a non-glass structure (e.g. Dutch start-up company Solarge [1])

Please note that there are very few players that make flexible PV-modules based on c-Si [2][3]. The claimed curvature goes down to 30cm. However, in principle c-Si-cells are fragile and not ideal for bending too extreme.

CIGS

The 'other PV-technology' is a thin-film PV-cell based either on Cd, amorphous-Silicon (a-Si), or CIGS. Within the scope of SolarEMR we will limit ourselves to thin-film CIGS solar cells.

PV-modules based on CIGS are normally flexible because they are applied on a flexible substrate. The cells can withstand much more bending than the c-Si. CIGS cells available from a couple of suppliers which all have their own specific 'flavor' of CIGS.

SolarEMR- partners involved in the research and development of this PV-technology are: Helmo (LCA-info), and TNO. Abbreviation used in this document: CIGS.

Please note that there are very few players that make rigid PV-modus based on CIGS; they use a glass plate to achieve that. For the applications with rigid PV-modules the c-Si cells have the advantage of being mass-produced and are therefore difficult to compete with.

		PV Technology	
		cSi	**CIGS**
Form	**rigid**	>95%	rare
	flexible	rare	>95%

Figure 3: The most common market combinations of Form and PV-technology.

Bifaciality

Classically PV-cells are oriented towards the sun and capture the light from that sunny frontside (only); they are so-called monofacial. The last couple of years, bifacial PV-cells are emerging and becoming affordable. In an application that allows enough light to enter from the other side or 'backside' of the product it makes sense to consider bifacial cells. One can even make the laminate semi-transparent with the purpose to have the light entering also from that backside. Moreover, in case of a vertical installation in which one side of the product faces pure East and the other side faces pure West, there is no frontside or backside anymore. Throughout each day a frontside converts into a backside, and vice versa. With these PV-cells in a vertical tilt, the orientation is of no importance anymore, which is of course very welcome for e.g. noise barriers that follow roads which have all orientations. For BIPV, a possible application for bifacial PV-modules can be balconies or terrace fences. In the Netherlands, recently one full year outdoor monitoring in research facility SolarBEAT [4] was finished with very promising performance results. See Figure 4 below for a picture of the mockup with a lot of additional sensors for the purpose of research.

Figure 4: Bifacial PV Terrace Fence in 4 different orientations (3 prototypes per orientation).Can also be implemented as a balcony.

Upcoming PV-technologies

Within the project duration of SolarEMR there will for sure no new technologies available. However, with a slightly larger horizon of around 5 years from now, there might be PV-modules based on Perovskites or Tandems. Therefore these promising upcoming technologies are mentioned briefly

Perovskites

The main advantage of Perovskites would be the fact that the materials needed for Perovskites are readily available. Moreover, the energy consumption to produce Perovskites is much lower than at the moment for c-Si or CIGS, leading to lower cost. Perovskite devices have already achieved high efficiencies:

- 25.8% for a cell [5]
- 16% for a mini-module, achieved by the Solliance in the InterReg-region(!) [6]

These devices can be adapted in order to form semi-transparent and/or flexible devices. Further research is required for the improvement of their durability and scalability.

Tandem

Each PV-technology uses a specific part of the spectrum. Two different cells of the same or varied PV-technology may be used, with the requirement of complementary usage of the spectrum.

Moreover, when the devices are stacked on top of each other, the upper cell needs to allow adequate light transmission towards the lower cell, so more photons can be transposed into electrons, using the same area. The theory behind this so-called tandem technology has been described in literature already for a long time (e.g. c-Si-Perovskite, CIGS-Perovskite and Perovskite-Perovskite). But to actually build a device of such structure is challenging, due to the combination of the11ifferrent layers required. Nevertheless, the future for tandems seems bright.

Electrical Specification and Power Rating

The transformation of light into electricity is called efficiency, with symbol η. Because the amount of sunlight is changing dynamically and spatially, the PV-industry defined a standardized way of defining efficiency. This has been called the Standard Test Conditions (STC) and these are described by the standard IEC 61215 [7]. To describe all aspects of STC and the way PV-modules are officially rated goes beyond the scope of this document. However, the most important boundary conditions of the STC are:

- Irradiance (full spectral) is 1000 W/m^2
- Spectrum is AM1.5
- Temperature of Device Under Test (DUT) is 25 ^oC

Cell and laminate efficiency

Performance of c-Si:

- Up to η=23% cell efficiency
- Up to η=21% PV-module or laminate efficiency (active area)

Performance of CIGS:

- Up to η=18% cell efficiency
- Up to η=17% PV-module or laminate efficiency (active area)

Power rating final product

One should realize that the laminate will be used by ‘integrator-companies’ to be integrated in the final product. The final power density of that xIPV-product is the power of the laminate divided by the total area. Hence the final power rating is always lower than the laminate efficiency. Strictly speaking, this is beyond the scope of the laminate specification and the SolarEMR-project, but to manage expectations we (as project) like to be very clear to this effect. E.g. if a laminate with η=17% is integrated in a BIPV-element that is occupying 4/5 of the area of that complete product (because the other 1/5 of the area are e.g. needed for clamping the product to the roof, façade, balcony, whatever), then the power rating of the final BIPV-element will be 4/5 * η * STC = 136 Wp/m^2. Sometimes this figure is presented also into the format of an efficiency through dividing by 1000 Wp/m^2. Hence, the final building product efficiency is η=13.6%. For clarity in this brochure, only the PV-cell and laminate efficiencies are presented in %. And the final building or infrastructure PV-product is presented in Wp/m^2.

Dimensions PV-modules and laminates

Historical background

For a very long time, PV-modules came in just a few versions; the overall majority of the market had standard sizes with either 60 of 72 PV-cells, with a fixed cell size. The 60 cells version is the version used in roof mounted application, and has a size of 1.0m x 1.6m. This was the most standard PV-module for ages. Recently (in the last couple of years) this has been changed.

c-Si

The laminate can now be supplied in virtually any size with a large freedom in output voltage-current combination. Upon customer request any design can be made within the following boundaries, imposed by the laminator w x l x h. The length of the individual strings of cells to be implemented in the laminate is limited by the tabber-stringer itself. Apart from the mechanical limitations, the number of cells that can be interconnected in series depends on the used cells' breakdown voltage. Typically, a value of 20-24 cells in series is used. Beyond that, bypass diodes have to be added for safety reasons to avoid local overheating/breakdown in partially shaded strings.

The most performant option, in terms of price and efficiency, is the use of standard sizes. For each type, SolarEMR-partner SolTech has 4 'predefined' laminate sizes, that are optimized in terms of solar cell covering and have the highest power over surface ratings. Within every 'predefined' size, the panel can be "stretched" to a certain level. This variation keeps the same number of cells in the panel. All these considerations lead to the 4 sizes in the table below. In combination with color, that gives a couple of most common panels, as given in Appendix A.

	WIDTH				**LENGTH**		
	number of cells	**basic size [mm]**	**maximum size [mm]**		**number of cells**	**basic size [mm]**	**maximum size [mm]**
size 1	6	994	1322		12	1984	2000
size 2	8	1323	1500		12	1984	2000
size 3	6	994	1322		8	1343	1662
size 4	6	944	1322		10	1663	1983

Figure 5: Table with basic and maximum dimension (in mm) and number of PV-cells, for 4 different module sizes.

Output voltage resp. current is typically in the range of 50 V resp. 10 A, although these can be tuned by changing the cell size (e.g. half-cut cells, shingles) and the (series-parallel) interconnection layout of the laminate.

CIGS

The laminate can be supplied in virtually any size with a large freedom in output voltage-current combination. Upon customer request any design can be made within the following boundaries:

- Width: from 20 to 2000 mm, please note that above 700 mm, at the moment stitching is needed
- Length: from 150 mm to >10000 mm

The BIC-TNO pilot line will have a width of 700 mm in the 'throughput'-direction. Therefore (manual) stitching of semi-fabricates will be needed in case the customer requirement in the width direction is larger than this 700 mm.

With respect to the length, some first trials off-line have shown that 10 meters are no problem. In 2020, manual stitching was still needed (see Figure 6 left). In 2022, a laminate with a length of 10 meters has been made in one uninterrupted run (see Figure 6 right).

Figure 6: Left: In 2020, for the 9.2 meter long laminate in the STAL-project, manual stitching was still needed. Right: In 2022, a 10 meter long laminate has been produced without stitching.

Curvature (or 2.5D dimension)

As briefly mentioned before, the large advantage of the flexible CIGS-technology is the fact that it can withstand bending. For the majority of the applications this bending into the final shape is done once. To be precise: the laminate is produced and put in stock either as sheets on top of each other or rolled up. Thereafter the integrator-company buys the laminate and bends it into the shape needed for the specific application in which it is kept permanent by e.g. gluing. The CIGS-laminate bent static in a radius of 4.5 cm shows no degradation in 200 thermal cycles of -40 to +85 °C.

Specific for the very common curved roof tiles in Europe, the resilience for bending is an enabler for the flexible CIGS-laminates (see Figure 7).

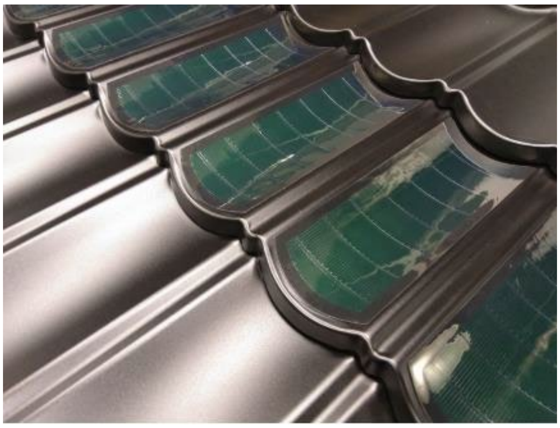


Figure 7: Curvature in the laminates is needed when the application with curved roof tiles is desired.

But also less obvious applications become realistic; see Figure 8.

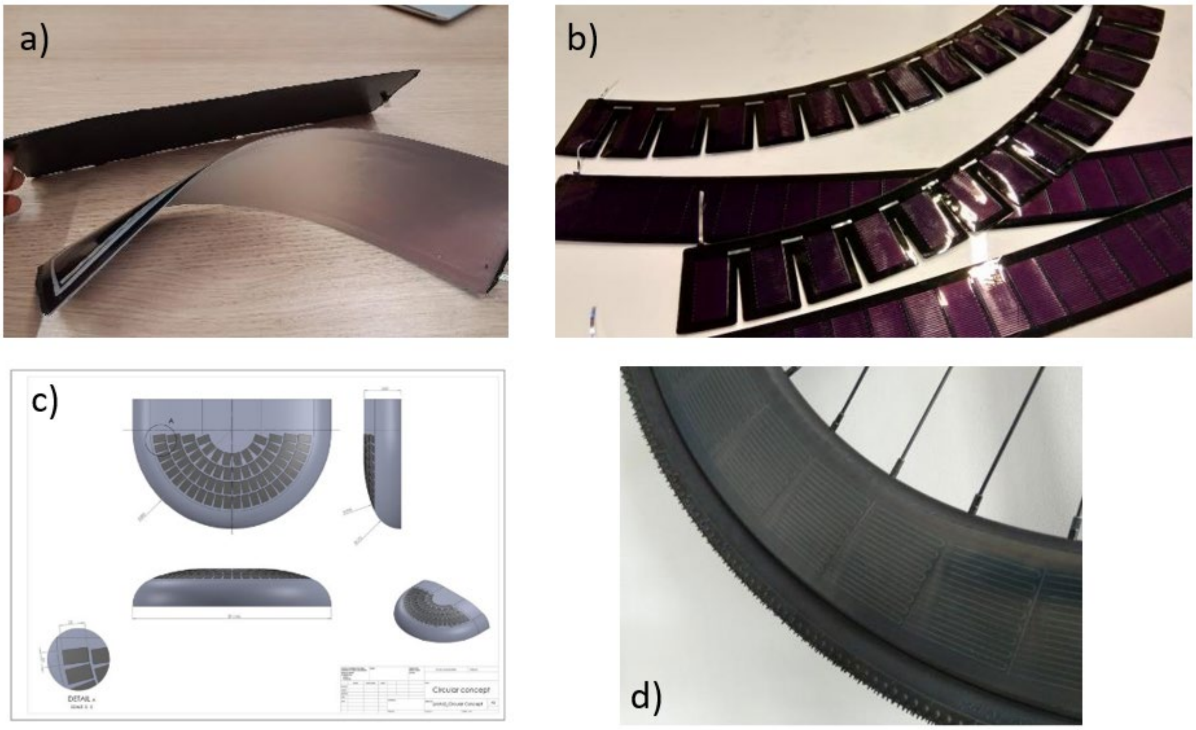


Figure 8: a) typical curvature of laminate (not maximum yet) b) option to create radius c) application in a dome-like appearance d) application in the rim of a bicycle wheel.

Dynamic bending

One could also think about applications in which the bending happens throughout the lifetime of the product. E.g. if the laminate would be integrated in a tarpaulin or sail of a ship. At the moment this is a very small nice market. But in case of interest, project partner TNO already has some knowledge on appropriate lifetime testing for such a 'dynamic' IPV-application.

Another application outside the horizon of the SolarEMR-project is the application of Floating PV. More specific, one product developer believes in an option in which the semi-fabricate PV is glued on floaters that stay on the waves. This application is actually tested at the moment. Analysis (and webcam video footage) shows the incredible tough dynamics at sea during a storm. The laminate should withstand those forces with an acceptable lifetime.

Figure 9: Application of flexible semi-fabricates in field of Floating PV. Prototype from project Solar@Sea [8].

The laminate of TNO (SOA configuration) can withstand multiple bends (>2 million) in bending or even torsion mode (dynamic) with a bending diameter of 50 cm without observable power loss or visual degradation.

Electrical Specifications

Although not all readers might be familiar with electronics, we do mention the range of the most important electrical characteristics. For more detailed information, the interested reader should get into contact with the SolarEMR-partners, to further discuss which electrical requirements should be met by the laminate to be able to be integrated in the application of the integrator-company.

General

The following electrical parameters are useful to describe laminates:

- Voltage at Maximum Power Point: V_{mpp} [V]
- Current at Maximum Power Point: I_{mpp} [A]
- Power at Maximum Power Point: Pmax [V], which is defined as $P_{max} := V_{mpp} * I_{mpp}$
- Voltage at Open Circuit: V_{oc} [V]
- Current at Short Circuit: I_{sc} [A]
- Fill Factor: FF [%], which is defined as $FF := P_{mpp} / (V_{oc} * I_{sc})$

Depending on the length, the voltage and current of the complete laminate can have quite a range of output:

- Voltage output 0.65 V to 700 V
- Current output 0.1 A to 8 A

Diodes

Diode functionality can be included based on optimal bypass diode design for intended application.

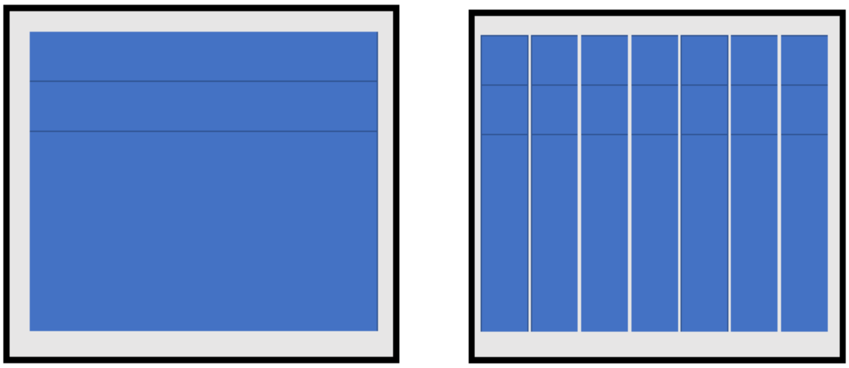
Multi-level bypass diode design is also possible on request.

The position of the diodes is very much related to the specifics of shade-mitigation.

Electrical Characteristics as function of Cell-topology

A solar laminate can be built up of small cells giving low current and high voltage, or otherwise big cells giving high current and low voltage. Example calculations for a 310 mm x 350 mm laminate :

- Option 1 (left): 6 cells of 312 mm wide in series
- Option 2 (right): 7 strings of 6 cells of 45 mm wide in series



	Option 1	**Option 2**
Voc	4,35 V	30,45 V
Isc	4 A	0,58 A
Vmpp	3,52 V	24,64 V
Impp	3,68 A	0,53 A
Pmax	13 Wp	13 Wp

Figure 10: Electrical parameters of 2 designs that have exactly the same outer dimension, but have different cell topology.

Note: Figure 10 contains calculation examples. The solar laminates are not limited to these electrical design configurations. Options look endless, but due to the practical limitations within the mass-customization pilot-lines of the SolarEMR-partners (or other parts of the process), the options are of course not endless. During the design phase, meetings between the customer (xIPV product developer) and the SolarEMR-laminate developers will make clear which options will be the most logical options, given the application.

BIPV-example

Within the SolarEMR-project, a small BIPV-demonstrator is built with the purpose to show the flexibility of the CIGS-laminates with respect to size and electrical characteristics[1]. SolarEMR-partner ZigZag Solar is already an established player in the market of BIPV (see e.g. Figure 11) [9], but was always limited to the very few options of PV-modules on the market that fit into their unique ZigZag cassettes.

Figure 11: ZigZag solar has a regular product that is already custom-made with respect to the color and paterns on the downward facing parts of the facade. The PV-panels are integrated in the upward facing part and therefore invisible from ground level.

With the new option to order the CIGS-laminates custom-made, a real nice market proposition is emerging. To prove the freedom of size, we demonstrate 10 different sizes in this one demonstrator (see Figure 12).

[1] And also with respect to shade mitigation of this specific ZigZag structure in the façade. See separate paragraph on shade mitigation later in brochure.

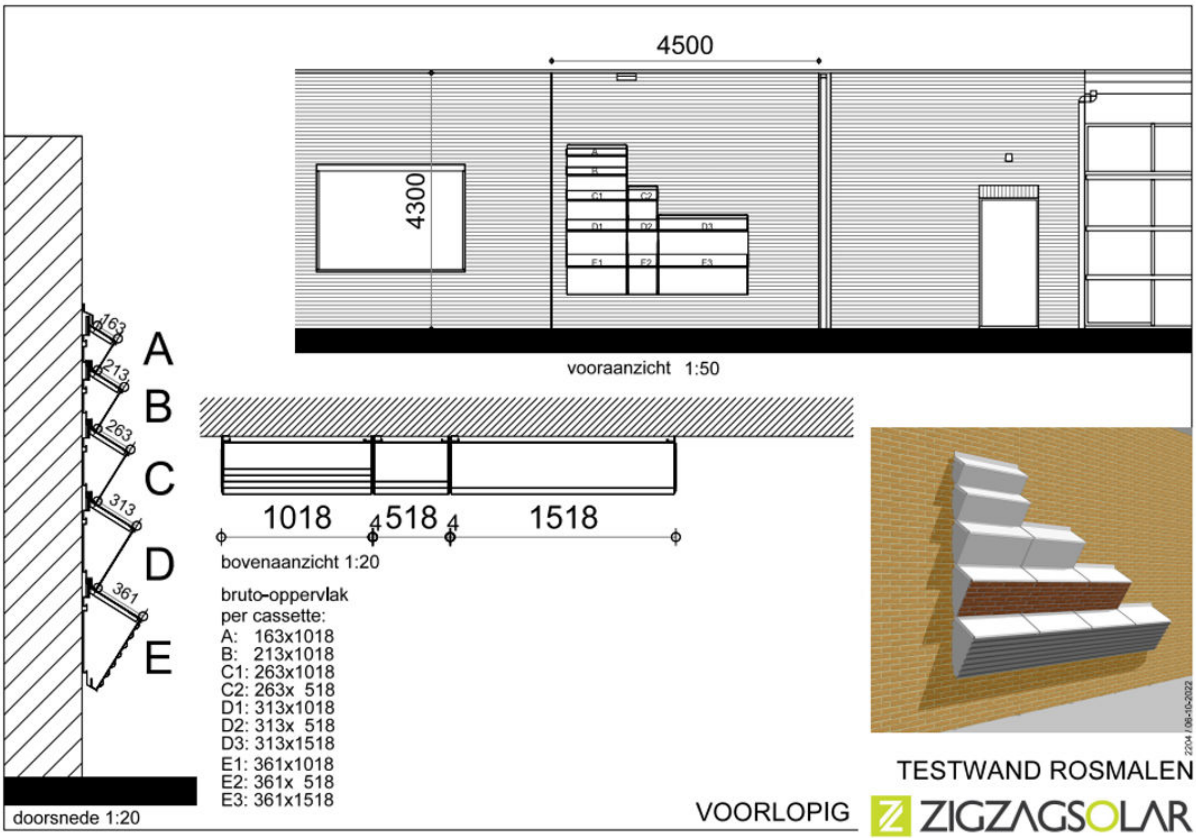


Figure 12: BIPV-demonstrator in SolarEMR-project shows freedom of shape for the ZigZag Solar façade: 10 different sizes (labeled A till E3) are requested from the integrator company (ZigZag Solar) and assembled by the supplier of the laminates (TNO).

This BIPV ZigZag-façade demonstrator acts as a teaser for developers and integrators to contact SolarEMR with their specific requirements from their applications.

Thermal effects

Absolute temperature boundaries

The highest and lowest temperature that a PV module may survive highly depends on the bill of materials utilized. In case of c-Si PV modules, the highest temperature achieved is the melting point of the encapsulant (e.g. 110 ˚C for EVA). For the lowest temperature, to the best of our knowledge there are no good references. Probably because very low, arctic, temperatures have not been a problem for PV-installations on Antarctica and North pole [10][11].

Temperature effect on performance

For someone not familiar with solar PV, it might sound strange that a PV-module- or PV-cell performs less when heated up, which happens when the sun is shining. This effect is intrinsic in the fundamental physics of the PV absorber, which is a semiconductor. When the temperature of a PV cell increases, the energy bandgap is reduced, affecting the V_{OC} of the PV device [12][13]. Every PV-technology ‘suffers’ from this effect, but there are differences in the magnitude of the effect. Moreover the effect is always a second order effect, and should not be a major hurdle for the integrator company.

c-Si

Depending on the type of cells (Al-BSF, PERC, Topcon, heterojunction) the temperature coefficients on electrical power P_{mpp} range between -0.45 and -0.26%/˚C. One should note that this is a relative percentage on the efficiency of the PV-cell (not absolute efficiency change).

CIGS

For the CIGS cells in the SolarEMR-project the temperature coefficient on electrical power P_{mpp} is -0.37 %/˚C. Temperature Coefficients of V_{OC} and I_{SC} are also well known, but go beyond the scope of this document.

For completeness and openness we mention this negative temperature effect on performance per PV-technology, but to our opinion it will never be a showstopper when implementing PV semi-fabricates in BIPV- and IIPV- applications.

Physical build-up (BOM)

c-Si

A c-Si PV-module typically consists of:

- Frontsheet : high-strength tempered low iron glass with thickness between 2mm and 10mm, or polymer transparent frontsheet (e.g. PET, ETFE) with thickness ~200-400 µm and adequate gas barrier properties
- Encapsulant: typically EVA (Ethylene-vinyl acetate)
- Strings of cells and strips for interconnections
- Backsheet: high-strength tempered glass with a thickness between 2mm and 12mm, or polymer backsheet (e.g. PET, Tedlar, PVF, PVDF) of various colors with thickness ~200-400 µm and adequate gas barrier properties.
- Junction box
- Aluminum frame (edge sealant may be added)

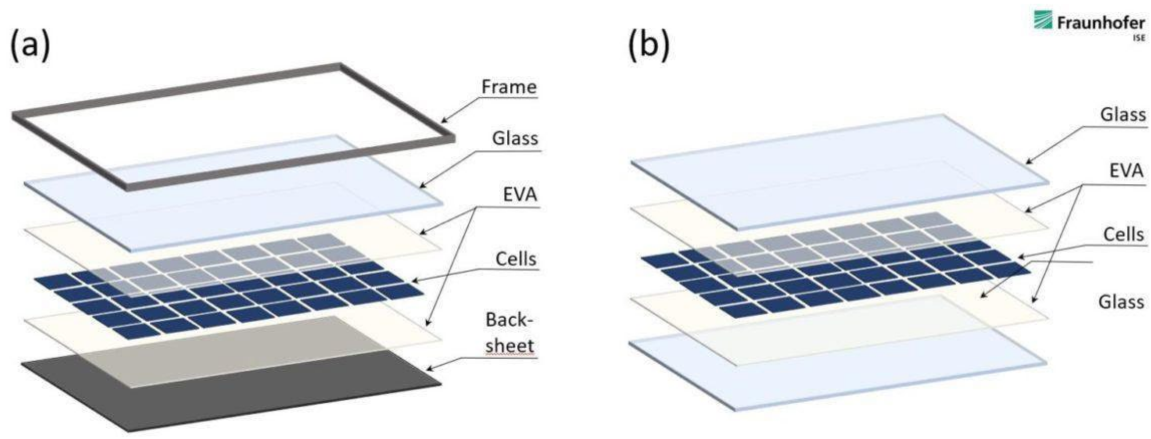


Figure 13: Artistic impression of build-up of c-Si laminate/panel. Source: Fraunhofer ISE.

CIGS

Solar laminates based on CIGS can be supplied in various configurations. A state of art (SOA) laminate contains commercially available and certified solar materials; front sheet, encapsulant, backsheet, edge seal etc.

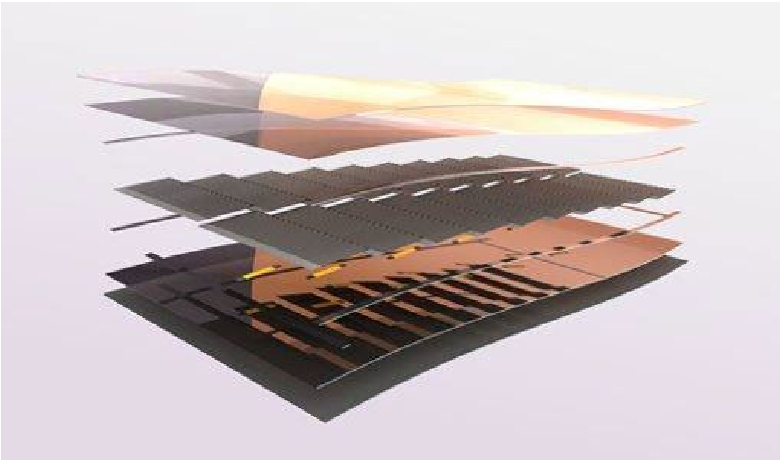


Figure 14: Artistic impression of build-up of CIGS laminate. Source: TNO.

On request the solar laminate can be supplied with different front- and/or backsheet in order to make the laminate more flexible, easily integrated or even optimized for cost and/or lifetime.

	SOA	Configuration options for better flexibility or integration and optimized on cost and/or lifetime					
Alternative front layer							
Frontsheet							
Encapsulant							
PV cell							
Encapsulant							
By pass diodes							
Backsheet							
Edge seal							
Alternative back layer							

Figure 15: Table that shows the numerous options that one has in the BOM.

All the layers of Figure 4 are relative small. Quantitative, the thickness varies between: ~2.5 mm for SOA materials and down to 0.5 mm for the thinnest configuration possible.

Weight: ca 2.5 kg/m^2 (to 1 kg/m^2 for the thinnest configuration)

Any form of the laminate can be supplied (within maximum sizes above) with some loss due to ineffective use of area.

BOM

Special request from the application will lead to a specific choice in Bill of Materials (BOM). As an example, in the BIPV-façade example (Figure 16, left picture) the front sheet of the laminate has been chosen in such a way that it will have a very good adherence with the cover layer that gives the façade a very nice look. And in the IIPV-road example (Figure 16, right picture) the front sheet of the laminate has been chosen in such a way that it will have a very good adherence with the cover layer that gives mechanical robustness towards the traffic driving over this road.

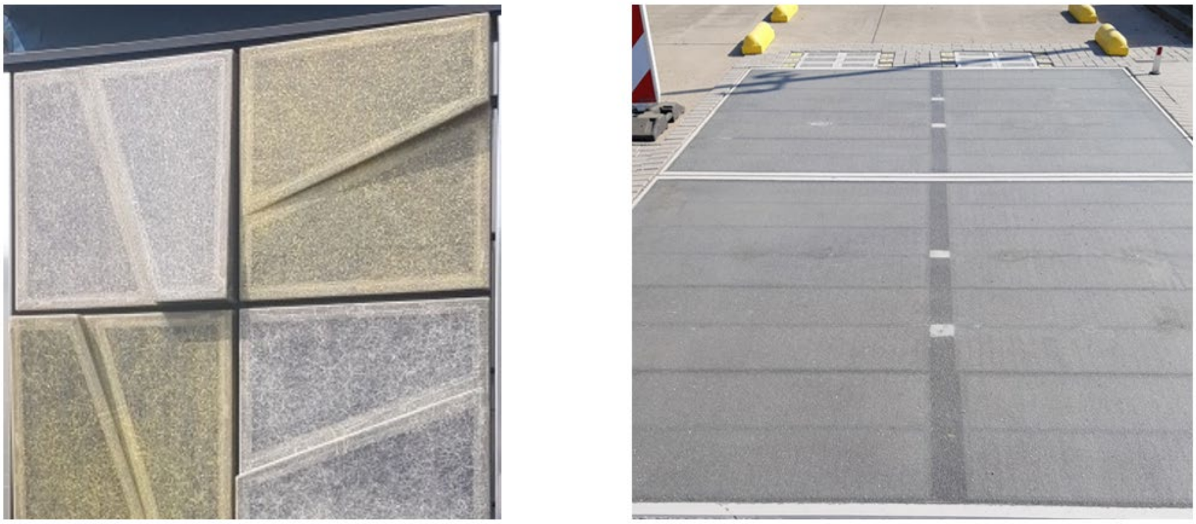


Figure 16: Front sheet adheres to the cover layer. In the left BIPV example the cover layer has a light weight façade cladding functionality. In the right IIPV example mechanical robustness is needed from the cover layer.

Connectors

There is always at least one positive and one negative point of contact on the laminates. These contact points are normally realized via a junction box. This junction box can be MC4 compatible or from other suppliers. The laminate can also be supplied with open lead (for ease of integration), in which situation the customer (integrator) should take care that these points of the laminate will not destroy the reliability (by potential water/humidity ingress). The position of the leads can be chosen on various positions of the laminate (front/back, top, middle, bottom, left, right).

Mechanical stress

c-Si

While crystalline Si (c-Si) intrinsically has a high fracture strength, cells can be quite fragile, as the overall strength will highly depend on the surface quality, determined by the wafering process (dicing) and surface treatments (polishing/etching). As they exhibit a brittle fracture, the crack will easily propagate along low-energy cleavage planes determined by the crystal orientation.

To minimize the impact of the fragility of the cells, first of all the encapsulation plays an important role in protecting the cells against e.g. thermomechanical stresses and mechanical loads (static or impact). Usually this is achieved by laminating glass panels at the front- and/or backside, and an additional Al frame around the laminate. Currently though, considering the strong interest in further integration of PV for dual-use applications, there is an increasing number of options being explored for alternative encapsulation, that are targeting light-weight and/or curved panels.

Next to minimizing the impact of mechanical stresses on the cells by way of encapsulation, the impact of such a crack can be mitigated depending on the cell (metallization) design and module layout (electrical interconnection) and is significantly reduced with multi-wire interconnection that is rapidly becoming standard in PV modules. Nevertheless, a cell crack that reduces the active area and thus the current will affect the whole string of (series-connected) cells, similarly as the impact of shading (cf. chapter 'Shade mitigation').

Other Features (not mentioned above)

After showing the many aspects in previous paragraphs, there are still a couple of features that are worthwhile briefly mentioning. All these features are specific for CIGS laminates:

- Laminate can withstand high pressures (>10 bar)
- Laminate can withstand injection molding temperatures and pressures

With:

- 2D shapeable during or after lamination
- 2.5D shapeable during or after lamination with special module design
- 3D shapeable only for the configuration without front- and backsheet

Reliability and Safety

c-Si

All the c-Si based PV modules are certified under the IEC 61215 standard, in order to ensure more than 25 years of operation outdoors with less than 20% degradation of power output. The sequences that the modules undergo consist of multiple aging tests such as:

- Damp-Heat at 85% RH and 85°C
- Thermal cycling of -40 to +85 °C
- Humidity freeze at -40 to +85 °C and 85% RH
- UV test at 15 kWh/m^2
- Outdoor testing at 60 kWh/m^2
- Mechanical load
- Hail test
- Wet leakage current test
- By-pass diode thermal test
- Hot-spot endurance test

CIGS

On top of the above mentioned test sequences, the following additional certification aspects/loads are being prepared or tested at this moment.

- Passes >3000h (up to 5000h) of damp heat testing while maintaining > 95% P_{max} initial
- Passes > 600 thermal cycles of -40 to +85 °C while maintaining > 95% P_{max} initial
- Passes insulation test

It goes beyond the scope of this brochure to dive into the details of these tests and their correlations towards lifetime in the application. The integrator company should always discuss with the SolarEMR-partners, the details of these test with respect to the lifetime of the specific application of interest.

Outdoor

The outdoor performance for a laminate with SOA build-up is proven on various test-sites [4][16] and in several demonstrators (pitched roof, noise barrier, curved tiles) for more than 2 years continuous monitoring. The correlation between the indoor standard tests as described in IEC 61215 and the outdoor realistic lifetime is very complicated to quantify. In general, when passing the tests of IEC 61215 an outdoor lifetime of 25 years is to be expected, as shown in the paragraph above. There is continuous effort from the complete PV-industry to improve the knowledge on the correlation between outdoor lifetime and indoor reliability testing.

Fire-resistance

A standard PV-module should withstand fire as described by test in the IEC 61730-2:2016.

However, after integrating the PV-module – which in our case is a PV semi-fabricate – it is more difficult to refer to a general standard.

BIPV

There is a worldwide standard for BIPV since 2020: the IEC 63092 [17]. It contains 2 parts. Part 1 is about the modules and Part 2 is about the BIVP-system. This standard is heavily based on the European standard which was composed in 2016, which is not a secret but mentioned honestly at the IEC-page: '*This document is based on EN 50583*.'

The European EN 50583 [18] refers for fire safety to the EN 13501 'Fire classification of construction products and building elements'.

Because the European Construction Product Directive (CPR) EU 305 is non-harmonized, the local building codes always overrule European standards. To our knowledge there is no specific standard for fire-safety of BIPV-systems in Germany and Belgium. But there is for the Netherlands, the NEN 7250:2021 'Zonne-energiesystemen – Integratie in daken en gevels – Bouwkundige aspecten' [19]. Also this standard refers to the single item burning test of EN 13501 with respect to fire safety. The requirement to meet a specific fire class is dependent on the height of the installation. For:

- Height till 13m: fire safety class D according to NEN-EN 13501-1:2019
- From 13m and higher: fire safety class B according to NEN-EN 13501-1:2019

Discussion amongst expert might lead to a more stringent A2 for the highrise-buildings of 13m and higher. However, A2 is very difficult (impossible) to reach because of the organic content of PV-modules. With an organic backsheet it is very difficult to meet A2 according to SolarEMR-partner ZigZag Solar.

IIPV

For the IIPV-demonstrator, SolarEMR has chosen to build a noise barrier. At the moment we have not (yet) a good reference with respect to fire safety of PV-noise barriers in Netherlands, Belgium, and Germany. This will have our attention in the upcoming period.

Shade mitigation

The effect of shade on performance and reliability of PV is a very complicated topic, which best can be handled by experts. Therefore in this brochure, we just briefly mention that the SolarEMR partners have the option to choose the best design of the semi-fabricate for the specific application. As an example one can see in Figure 17 to the right the complicated roof structure, and to the left two example cell-topologies that will behave differently for each location in that roof.

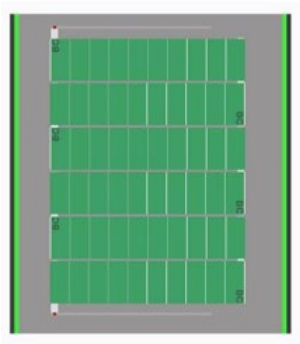
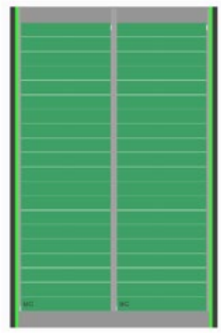




Figure 17: Left two different cell-topologies that have a different level of shade mitigation. Right: example of complicated roof structure, in which each part of the roof can be optimized with respect to shade.

Aesthetics

Many xIPV-products are much more in view than PV-panels in ground-mounted solar PV-parks or flat roof installations. Therefore the aesthetics are of much importance. Although aesthetics is a subjective topic, one can still quantify many aspects related to aesthetics. To be considered are:

- Transparency
- Color
- Texture
- Patterns

Transparency

Can be reached by multiple ways. One of the ways to achieve it with 'classical' PV-cells is shown below in Figure 18. Of course, the cell pattern is prominently visible. But this is not an issue in many applications. The product has great light effects when installed as a canopy.

Figure 18: Canopy with transparency achieved by alternating classical c-Si PV-cells.

But if this effect is to be found to prominent, then it is also possible to work with cells cut into cell-strips with a quite small width (typical 10mm, but going down to 3 mm). SolarEMR-partner SolTech could be contacted in case of interest for a transparent IPV-application based on these small cell-strips. As an example how this works out in a GU (Insulated Glass Unit) in e.g. an office building, see Figure 19.

Figure 19: IGU with transparency achieved by using small c-Si PV cell-strips. © Pilkington Sunplus™ BIPV [20]

Color

The property of color is going to a next level the last couple of years. Whereas in 2018, red and grey colored PV-façade elements where proudly presented [21], nowadays the color specification goes beyond calling it 'kind of red'. Some xIPV-producers define color already in RAL-code, just like in e.g. the car-industry or the paint-industry. The color does not have to come from the laminate, but it can be achieved by adding an additional foil, or coloring the encapsulant. For the MC pilot line developed by TNO, the ambition is to have an option of integrating an aesthetical foil (left option of Figure 8). It is not clear yet on which time scale this will be fully operational.

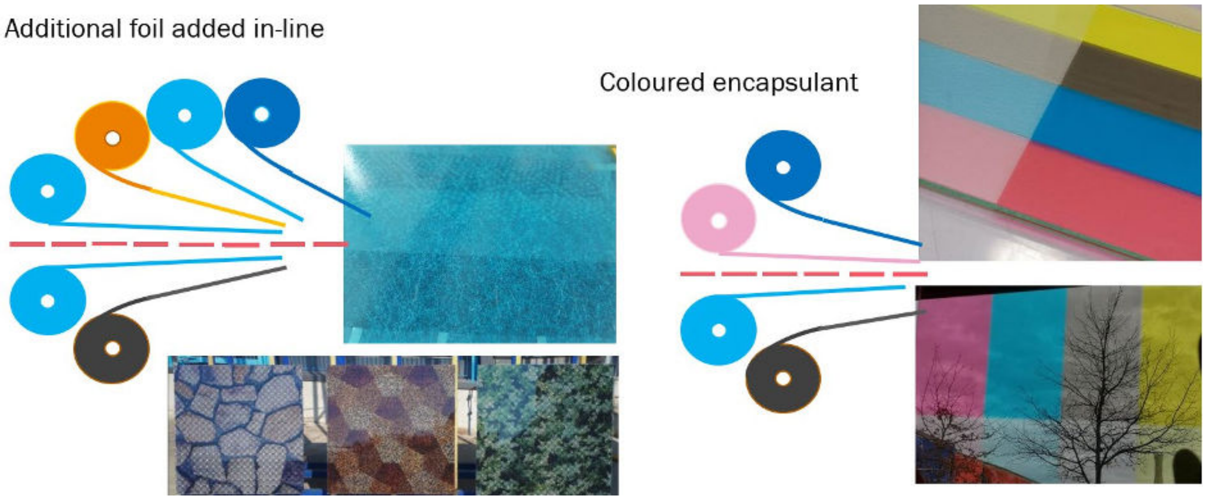


Figure 20: Schematic graph of how a colored foil or encapsulant can be used to give the end-product the desired amount of color.

For the c-Si panels, there are already many commercial options as shown in the table below:

		Wp/m²
Vision Square	semi-transparent	150
Clear Black	basic black	180
Mat Black	aesthetic black	170
Stopray Active	glass facade look	150
Clear Print	any design	130
Mat Grey	aesthetic grey	130
White	white	100

Figure 6: Color options for c-Si PV laminates and corresponding power rating (as produced by SolTech).

A good academic article on many coloring options has been published recently by Martina Pelle et.al [22].

As an example to show the option of color in the façade, please see Figure 21, which contains PV-active façade elements from the company Avancis. The coloring technology is by interference coating. The PV-technology is gals-laminate (hence rigid) CIGS.

Figure 21: Avancis Skala at Westspitze, © Avancis, Albrecht Voss. Source: https://www.skalafacade.com/en/

Texture

Texture might lead to more dirt accumulation. However, some earlier projects have demonstrated that this effect is surprisingly limited [X PVopmaat] Texture can even lead to an enhanced performance. The same as for the aspect of color, texture does not have to come from the laminate itself. A non-aesthetic effect of texture of the laminate, is the effect on the adhesion with the 'front-material' that the customer is processing in the xIPV product line. In general, texture is giving a more matt-like appearance to a PV-façade which is appreciated by many architects and end-customers.

Patterns

Also with respect to patterns, the architect and/or xIPV-product develop is in the lead to quantify over here. Patterns can be either i) wanted, or ii) mandatory, or iii) to be avoided. This aspect of patterns is very subjective to the wishes of the integrator or end-customer. To show what is possible nowadays, please see Figure 22 below.

Figure 22: PV panels based on c-Si cells, with a custom-made pattern. Source: Soltech.

Environmental aspects and circularity

A comparison between c-Si and CIGS with respect to environmental aspects and circularity is quite complicated and topic of many research groups all over the world. In this brochure we touch upon the most important aspects. For a detailed LCA-analysis specific for an IPV-application, the interested integrator company can contact SolarEMR-partner Helmo for more information.

Assets of c-Si technology

cSi technology remains the most matured technology on the PV market. Its production process has been continually improved during the past decades and offers the most optimized lines, reducing the energy consumption and the amount of raw material required and waste generated. This technology still offers the highest energy conversion efficiency, one of the key parameters to assess its environmental impact.

In contrast with these aspects, the cell production process for cSi technology remains intrinsically very energy intensive: the carboreduction implied in the upstream production (to produce the metallurgical grade silicon) and the following processes (polysilicon grade, Czochralski process, etc…) requires a lot of electricity and heat. Despite its small thickness (around 170 µm), a silicon cell can contribute between 60 to 81% of the total module carbon footprint, depending on the module design and location of production (implying different electricity mixes).

The next component causing the biggest impact, when present, is the aluminum frame, participating at a share of around 9% of the global share of CO2 emission during the production process. Double glass modules do not require frame, offering sufficient mechanical stability on its own, and leading to cost reduction as well.

The third element causing the biggest impact is the glass used in the front and/or backsheet layer with around 6 to 14% (when using frameless module). Despite that, the higher glass usage in a glass-glass (G-G) design is compensated by not using a polymer backsheet. As an example, ETFE is one of the most problematic materials causing harmful effect in CO2 emission but also for ozone depletion. Therefore, frameless glass-glass modules is one of the most interesting design in terms of GWP score.

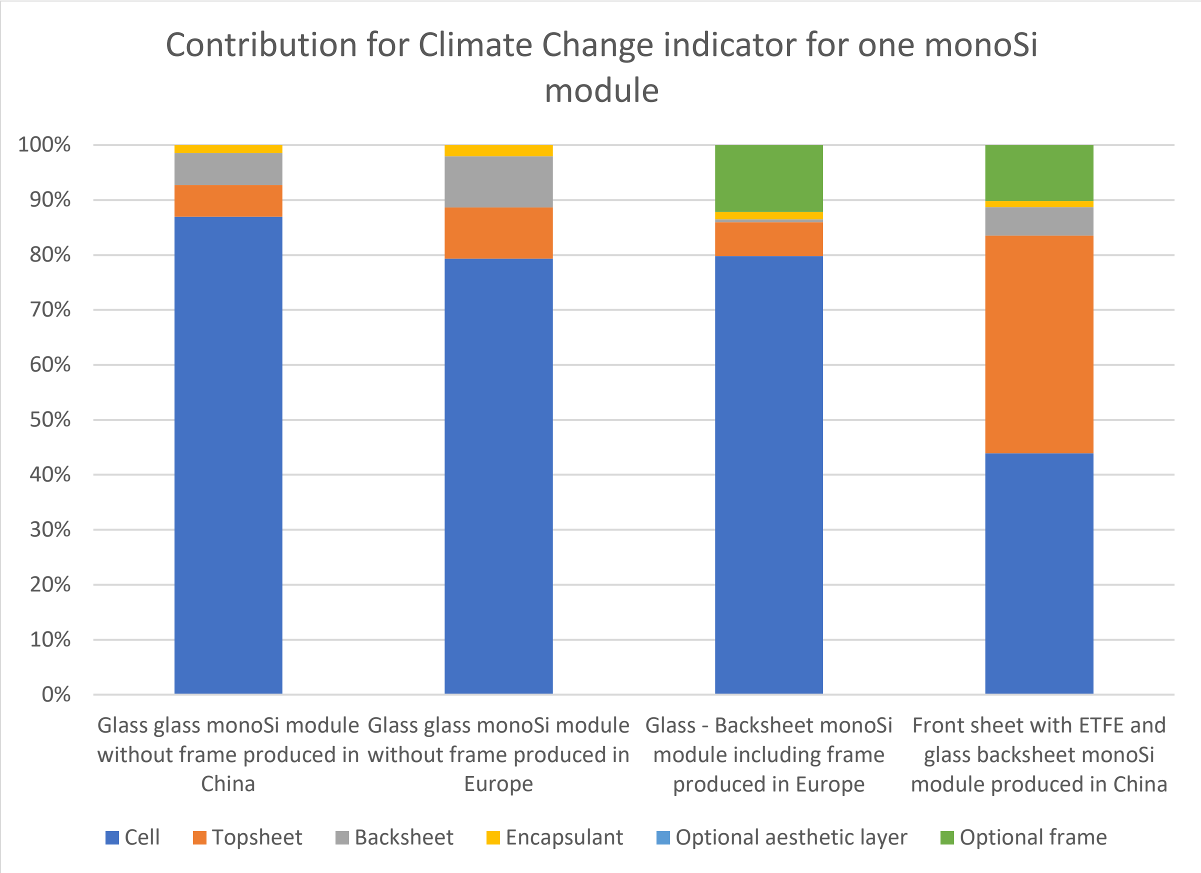


Figure 23: Comparison between several scenarios of modules with different composition and location of production. Aesthetic layers are not shown yet because of the lack of information regarding its composition. Backsheet of third scenario is composed of PVF,PET and LLDPE (surrogates of real elements composing the backsheet).

The Energy Payback Time (EPBT), which is the length of time a PV system must operate before it recovers the energy invested to produce it, can be evaluated between less than 3 years (for CIGS, even less than a year) for this type of module, depending on the module design, the average cell efficiency during its lifetime, the irradiance, etc… This number can highly change If we also account for the infrastructure energy demand cost as well as the balance of system, which is normally the case.

Assets of CIGS technology

Because it is a thin film technology, CIGS modules require a significant lower energy production compared to classical cSi technology, which is a clear advantage in terms of environmental impact. Its energy efficiency is now able to compete with classical technology (reaching up to 17%) and thus decrease its environmental burden by producing more decarbonized energy. CIGS technology can propose a broad variety of flexible modules, widening the possibilities of solar harvesting on divers surfaces employed for other purposes, and thus allows a local CO2-free electricity production.

Regarding the resource uses, most specifically for metal depletion, the Indium and Gallium present in the absorber layer are classified in the list of critical raw materials for the supply risk and the high economic importance by the European Community. However, the quantification of this scarcity is still a debated subject, and several indicators exist. In the context of the CIGS cells developed by

TNO, the main hotspot for the Resource use, minerals and metal (quantified in kg Sb eq) remains the molybdenum used in the back contact layer, followed by Indium and only in fifth position gallium. This can be explained by the quantity implied in the cell architecture. For comparison, the main hotspot in this category for cSi technology is the silver used for the metallization paste, silver being one of the most resource-constrained element in the PV feedstocks. Copper also account for a large share, being the second or third hotspot, depending on the type of CIGS cell.

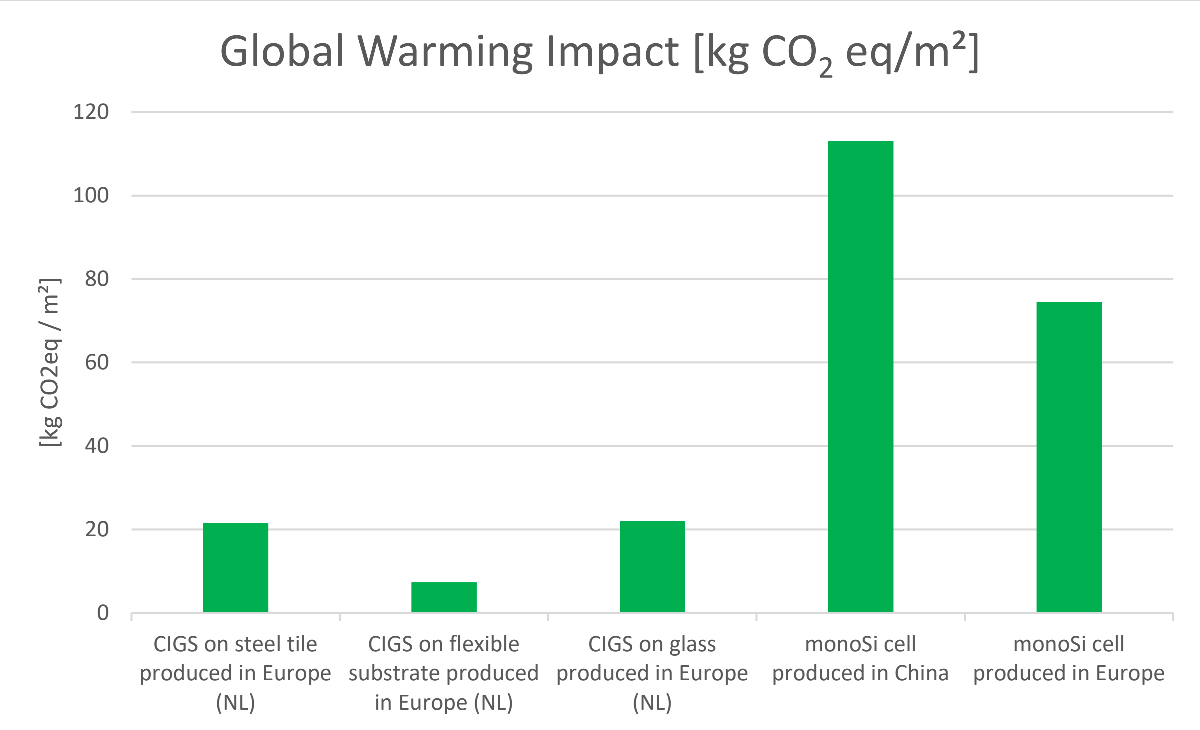


Figure 24: Comparison per square meter of the two technologies. CIGS includes lamination where mono-SI accounts for the cell production. Higher numbers are expected if lamination is taken into account.

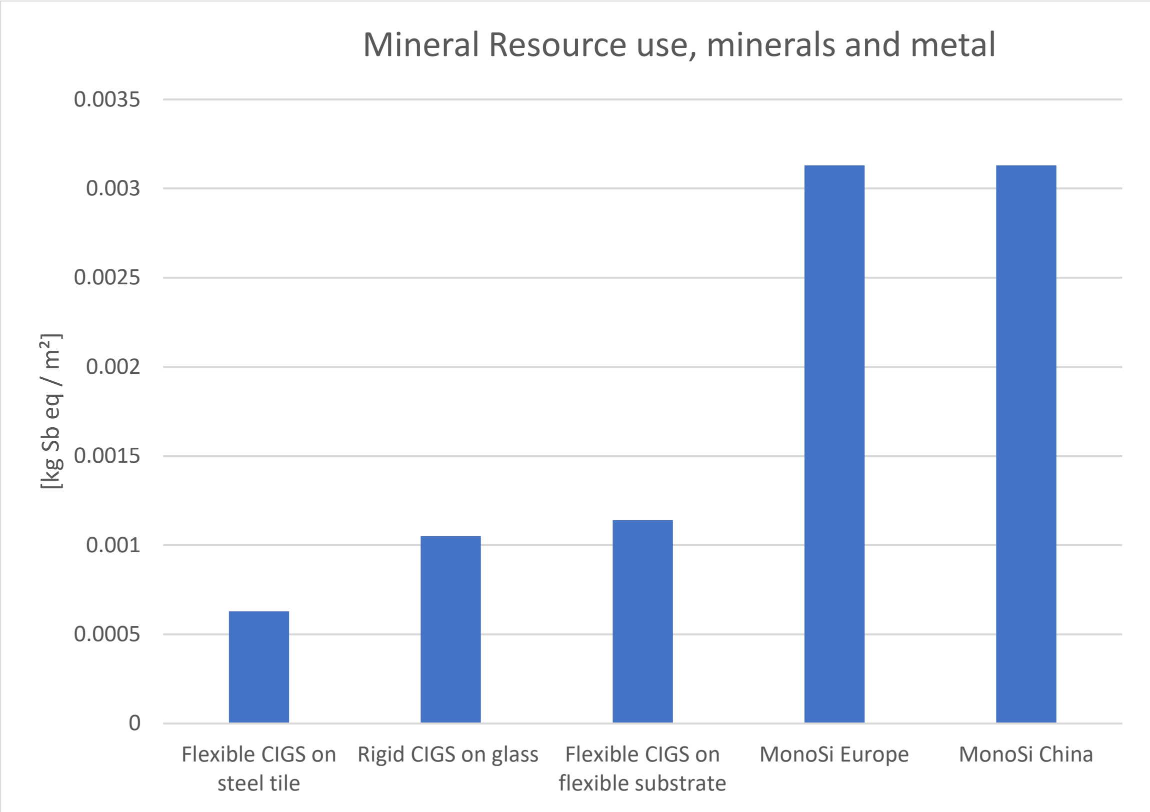


Figure 25: Comparison per square meter of the two technologies. Higher score for mono-Si are explained by the quantity of silver used for the metallization paste, Location does not impact the scores.

Comparison with national electricity production mix and benefits

A first comparison can be shown between the electricity produced through solar modules implied in the BIPV and IIPV solutions developed in this project and the electricity mix of the EuroRegioMeuse countries. Theses results are not definitive, as they do not take into consideration the carbon cost of the infrastructure and balance of system, which is normally the case for the national electricity mixes.

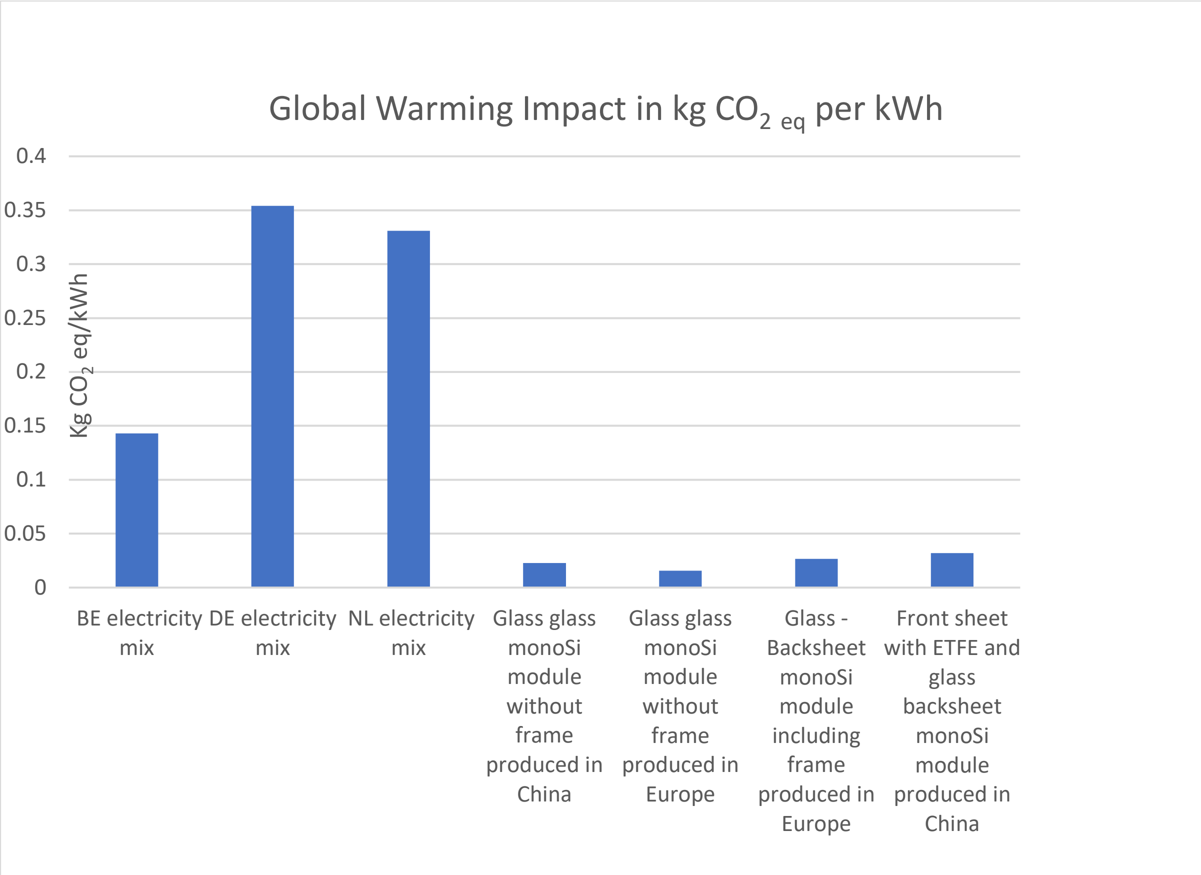


Figure 26: Comparison with national electricity mixes and electricity generated by solar modules. Higher scores are expected for modules when adding share of infrastructure and balance of system. National electricity mix data from https://ourworldindata.org/grapher/carbon-intensity-electricity?tab=table (data of 2021).

Comparison with foreign manufacturing (China) scenario vs European scenario

Most of the PV production is now based in China, as the vast majority of electronic devices. A comparison can be made to see the benefit to produce the PV feedstock in Europe.

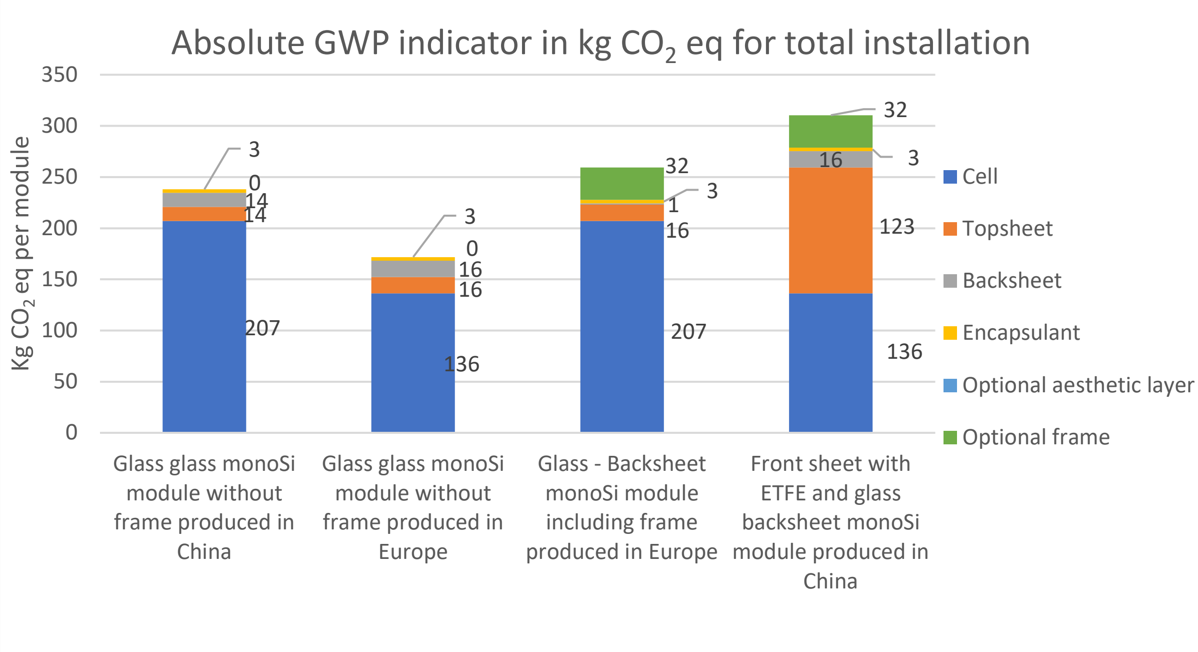


Figure 27: Comparison with several cSi modules and different compositions.

Given that electricity is one of the major drivers for carbon emission for the cell production (regarding cSi technology), the location of the production site has an immediate influence on it. It pertains to compare these numbers based on kWh produced, which depends on the specific location where the solar electricity is generated (hence correlated to the location irradiance).

On the other hand, transport has a very low impact on the carbon intensity, and only contribute to 3% for cSi modules. For CIGS, this number is even lower given the lighter weight of the module, leading to more products transported in one container for the same distance.

Despite that, it is currently impossible to choose between a European-manufactured cell with a Chinese-manufactured one, but these results clearly indicate the interest to relocate the laminate production in Europe, especially in countries where the electricity mix is based on decarbonized energy production, such as in Norway with a majority of hydropower electricity. Metallurgical grade silicon from Europe usually comes from this country, explaining the strong decrease of carbon intensity when considering this location of production compared to China.

Global share of each component in the noise barrier designed in the SolarEMR project

Infrastructure Integrated PV (like noise barriers) are always very specific, depending on each configuration and project. It is then difficult to indicate which element of the system has the biggest impact. In the context of the SolarEMR project, a noise barrier demonstrator has been analyzed. It shows that the infrastructure, made out of concrete, is the biggest contributor. These results are also based depending on the lifetime of each element, which is illustrated in the following figure.

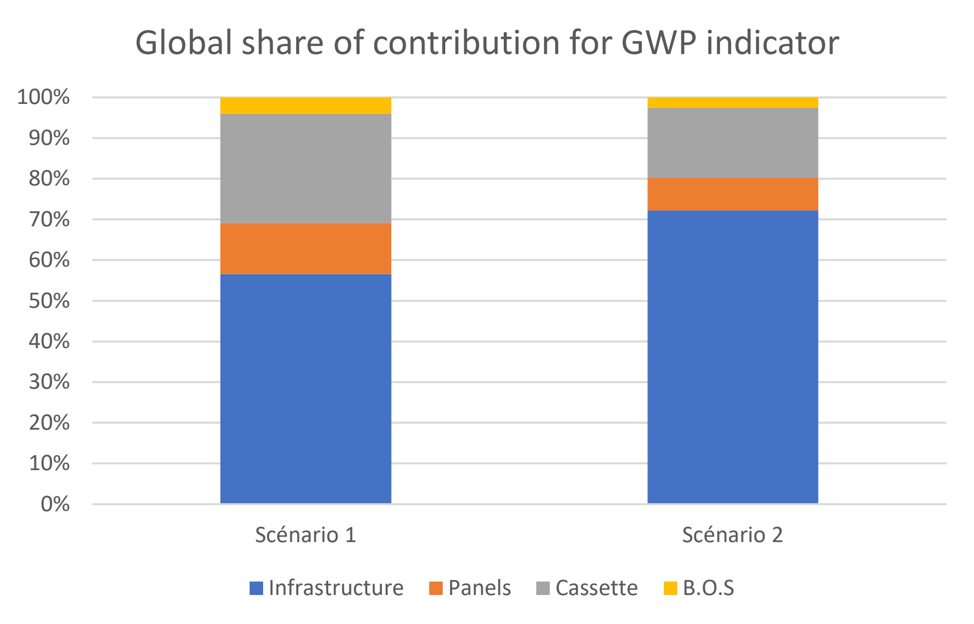


Figure 28: Global share of contribution for the noise barrier prototype developed in the frame of the Solar EMR project. First scenario depicts a 60-year old lifetime for infrastructure, second scenario depicts a lifetime of 30 years for infrastructure.

In the first scenario, the lifetime of the infrastructure (concrete walls) is based on a 60-year duration, which can be assumed for a typical noise barrier installation. In scenario 2, the lifetime is reduced to 30 years, giving another allocation factor and increasing the impact from the infrastructure. Solar panels are developed to work during roughly 30 years old, depending on the environmental condition and situation. The longer a solar panel work, the better its environmental footprint will be through the decarbonized energy it will produce. Generally, a tradeoff must be operate to choose between materials that allow to lengthen the lifetime and on the same time, cause harmful effect with their intrinsic composition.

Employing cassettes (which are the mounting systems of the PV panels) that can be clipped on already existing noise barrier infrastructure could also help to significantly decrease the environmental impact for GWP indicator.

Finally, the balance of system, including all the electronics devices such as inverters, cablings, power optimizers, batteries, etc… are simplified in this study and should be taken into consideration, giving that they are expected to burden the total carbon footprint score, as well as the Mineral Resource Depletion score, employing many electronics components and hence rare metals.

Recyclability and circularity

in Europe, PV modules falls under the EU WEEE directive which requires to treat PV waste such as electronics waste. Since August 2018, 85% of panels should be recovered and 80% prepared for reuse and recycled

cSi technology: Organisations such as PV cycle [23] work in Europe to collect, disassemble and recycle most of the components present in the modules. The recycling rate can reach very high value (above 90%), but this rate depends on how easy each element (glass layer with encapsulate layer for instance) and hence, the complexity of the module, are aggregated to each other. More guidelines regarding design of modules are proposed in the design document.

CIGS Technology: CIGS panels have not reached the same market share compared to cSi panels, and the recycling sector for this technology is not yet fully prepared. Also, because of the inner architecture of these thin film modules, varying more compared to cSi technology, there is no specific industrial scale process that allow a steady recycling path, and research are still ongoing on this topic. The best economical value that could arise from CIGS recycling process are specific to the Indium and Gallium recovery. These elements, as already mentioned above, are classified in the list of critical raw materials and many effort should be put into their recollection.

Additional Reading / Inspirational

Figure 29: International School, Copenhagen (DK), © Adam Moerk / C. F. Møller Architects. Source: https://iea-pvps.org/wp-content/uploads/2021/03/IEA-PVPS-Task-15-An-international-collection-of-BIPV-projects-compr.pdf

To stimulate the uptake of BIPV, within the International Energy Agency PVPS-program there has been a Task dedicated to develop and disseminate BIPV since 2016. This Task 15 is called: ‘Enabling Framework for the Development of BIPV’. Many reports on various aspects of BIPV have been published and are freely accessible [24].

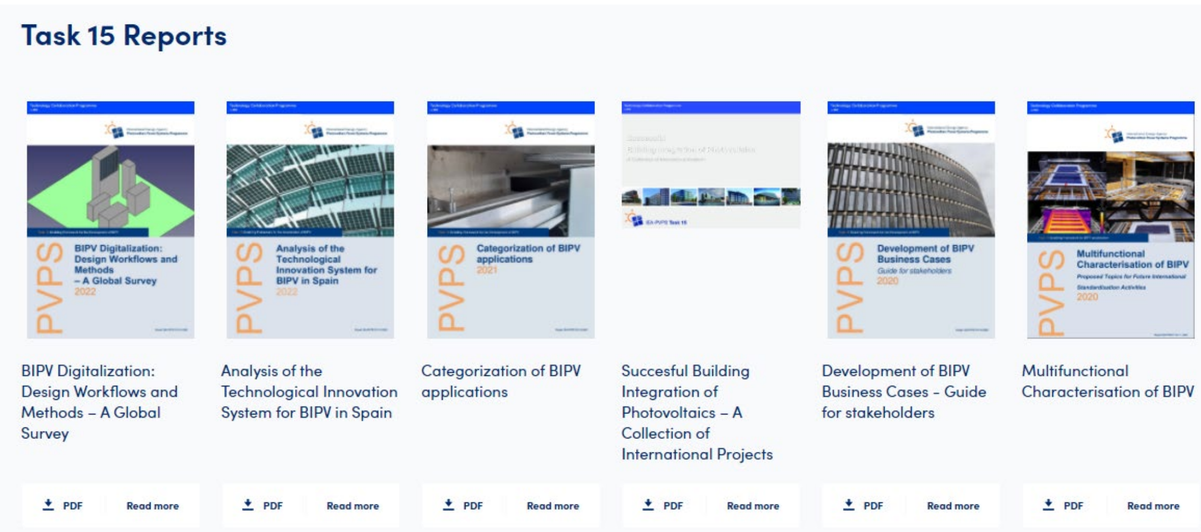


Figure 30: Overview of Task 15 reports that can be downloaded from: https://iea-pvps.org/research-tasks/enabling-framework-for-the-development-of-bipv/#contacts

For inspiration, especially the beautiful book of subtask 15A is highly recommended. Also this ebook version is for free download at: https://iea-pvps.org/key-topics/succesful-building-integration-of-photovoltaics-a-collection-of-international-projects/ See Figure 29 and Figure 31 just as beautiful examples from that book.

Figure 31: Solsmaragden Offices, Drammen (NO), © Enova. Source: https://iea-pvps.org/wp-content/uploads/2021/03/IEA-PVPS-Task-15-An-international-collection-of-BIPV-projects-compr.pdf

Last but not least, a very good academic review article of BIPV was written recently (2021) by Kuhn et.al from Fraunhofer ISE [25].

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[18] EN 50583 has 2 parts. Part -1 is about the modules and Part-2 is about the BIVP-system, https://www.nen.nl/nen-en-50583-1-2016-en-215685

[19] NEN 7250:2021 'Solar energy systems – Integration in roofs and façades – Building aspects', https://www.nen.nl/nen-7250-2021-nl-287757; please note this standard is in Dutch language only.

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[23] https://pvcycle.org/

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Appendix A: Most common geometries and colors in the c-Si laminates

	Basic Panel Dimension		Max Panel dimension		Cell/ panel	Wp/panel
SolSky Clear White	994 mm	1984 mm	1322 mm	2000 mm	72	195 Wp
SolSky Mat Grey	994 mm	1984 mm	1322 mm	2000 mm	72	258 Wp
SolSky Clear Black	994 mm	1984 mm	1322 mm	2000 mm	72	362 Wp
SolSky Mat Black	994 mm	1984 mm	1322 mm	2000 mm	72	342 Wp
SolSky Clear Print	994 mm	1984 mm	1322 mm	2000 mm	72	258 Wp
SolSky Clear White	1323 mm	1984 mm	1500 mm	2000 mm	96	260 Wp
SolSky Mat Grey	1323 mm	1984 mm	1500 mm	2000 mm	96	343 Wp
SolSky Clear Black	1323 mm	1984 mm	1500 mm	2000 mm	96	483 Wp
SolSky Mat Black	1323 mm	1984 mm	1500 mm	2000 mm	96	456 Wp
SolSky Clear Print	1323 mm	1984 mm	1500 mm	2000 mm	96	343 Wp
SolSky Clear White	994 mm	1343 mm	1322 mm	1662 mm	48	130 Wp
SolSky Mat Grey	994 mm	1343 mm	1322 mm	1662 mm	48	172 Wp
SolSky Clear Black	994 mm	1343 mm	1322 mm	1662 mm	48	241 Wp
SolSky Mat Black	994 mm	1343 mm	1322 mm	1662 mm	48	228 Wp
SolSky Clear Print	994 mm	1343 mm	1322 mm	1662 mm	48	172 Wp
SolSky Clear White	994 mm	1663 mm	1322 mm	1983 mm	60	163 Wp
SolSky Mat Grey	994 mm	1663 mm	1322 mm	1983 mm	60	215 Wp
SolSky Clear Black	994 mm	1663 mm	1322 mm	1983 mm	60	302 Wp
SolSky Mat Black	994 mm	1663 mm	1322 mm	1983 mm	60	285 Wp
SolSky Clear Print	994 mm	1663 mm	1322 mm	1983 mm	60	215 Wp

Appendix B: Color options

Clear Black

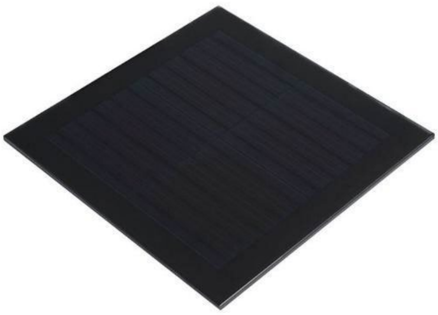
This is the panel with the highest performance as the extra clear glass that covers the front of the solar cells lets pass almost all of the daylight straight to the solar cells. The high efficiency black cells on a black background give a nice appearance. The big electrical interconnections are covered and only the small cell interconnections can be observed.

- Black basic panel
- Cell interconnections visible
- Best performance (power and cost)

Mat Black

The mat surface of the glass avoids reflections and makes the cell interconnections invisible from a certain distance whilst having a very little impact on the performance.

- Aesthetic black panel
- No cell patterns visible
- Mat surface



Mat Gray

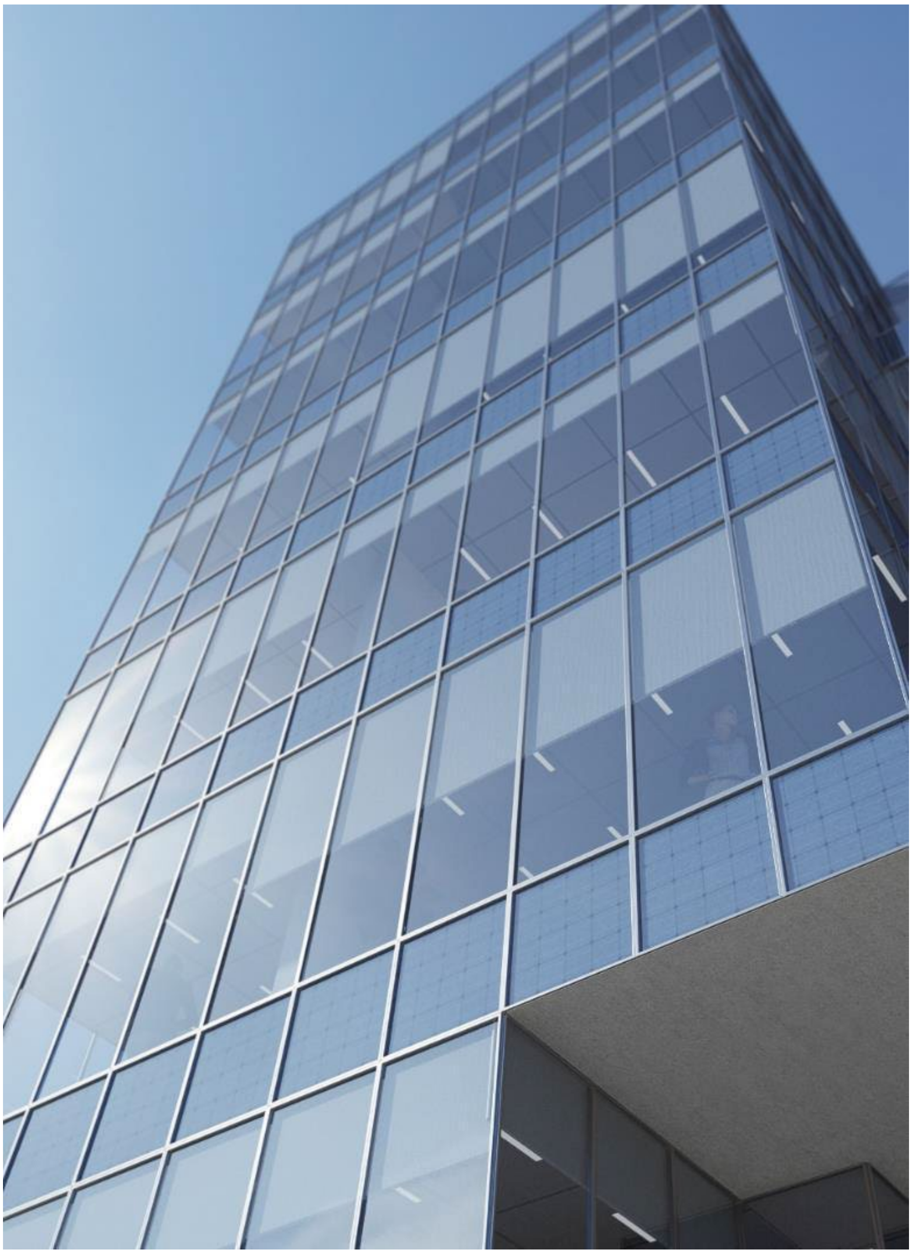
The panels have a 100% uniform grey appearance. The cells are totally invisible and the mat surface avoids reflections. This solution leads to a building element that has no visual reference to a solar panel at all anymore.

- Full uniform grey panel
- No cells visible
- Mat surface

Clear White

The panel that has the least 'solar panel feeling'. It is 100% bright white. It is the brightest solution in the range but comes with the lowest performance as white is of course a naturally reflecting colour.

- Full uniform white panel
- No cells visible
- Power losses due to white color



Soltech Stopray Active is a non-transparent, integrated PV product, with no cell patterns visible. Can be installed as IGU (Insulated Glass Unit)