BIPV Design Handbook

for practising architects

ETH zürich

A / S Architecture and Building Systems

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Introduction

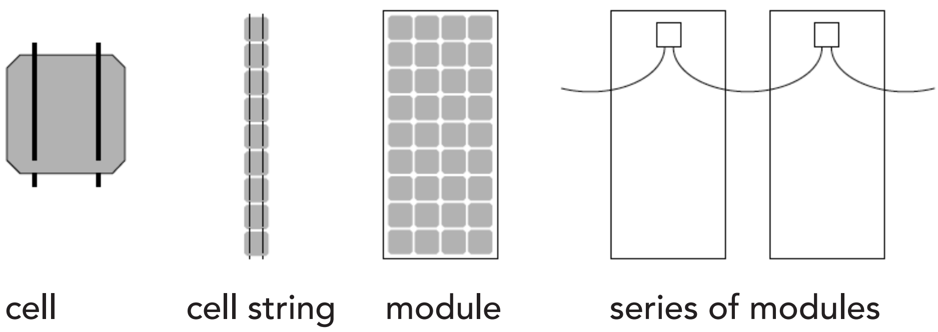
A contemporary building must produce energy. From an architect's point of view, solar technology can seem intimidating. However, after familiarizing with the basics, one can design with solar materials just like with any other material. Solar cells and modules come in lots of different shapes and sizes and it's still a fast-evolving industry. In principle it is often like building with glass, especially when designing a custom module.
From a technical, economical, and ecological perspective, building integrated photovoltaics (BIPV) make a lot of sense. This handbook aims to help architects integrate solar materials into their design workflow. It shows the wide spectrum of possibilities and gives the architects the necessary knowledge to start the planning process. In this way widespread adoption is possible with the same level of architectural integration as with any other material.
The solar industry is a rapidly evolving market. Efficiencies and durability increase yearly. The fundamental building blocks of the modules don't change that drastically.

A series of solar cells are put together to a string of cells and the strings are connected to form a module. The module has to be protected to ensure durability. A module basically consists of 3 main layers:

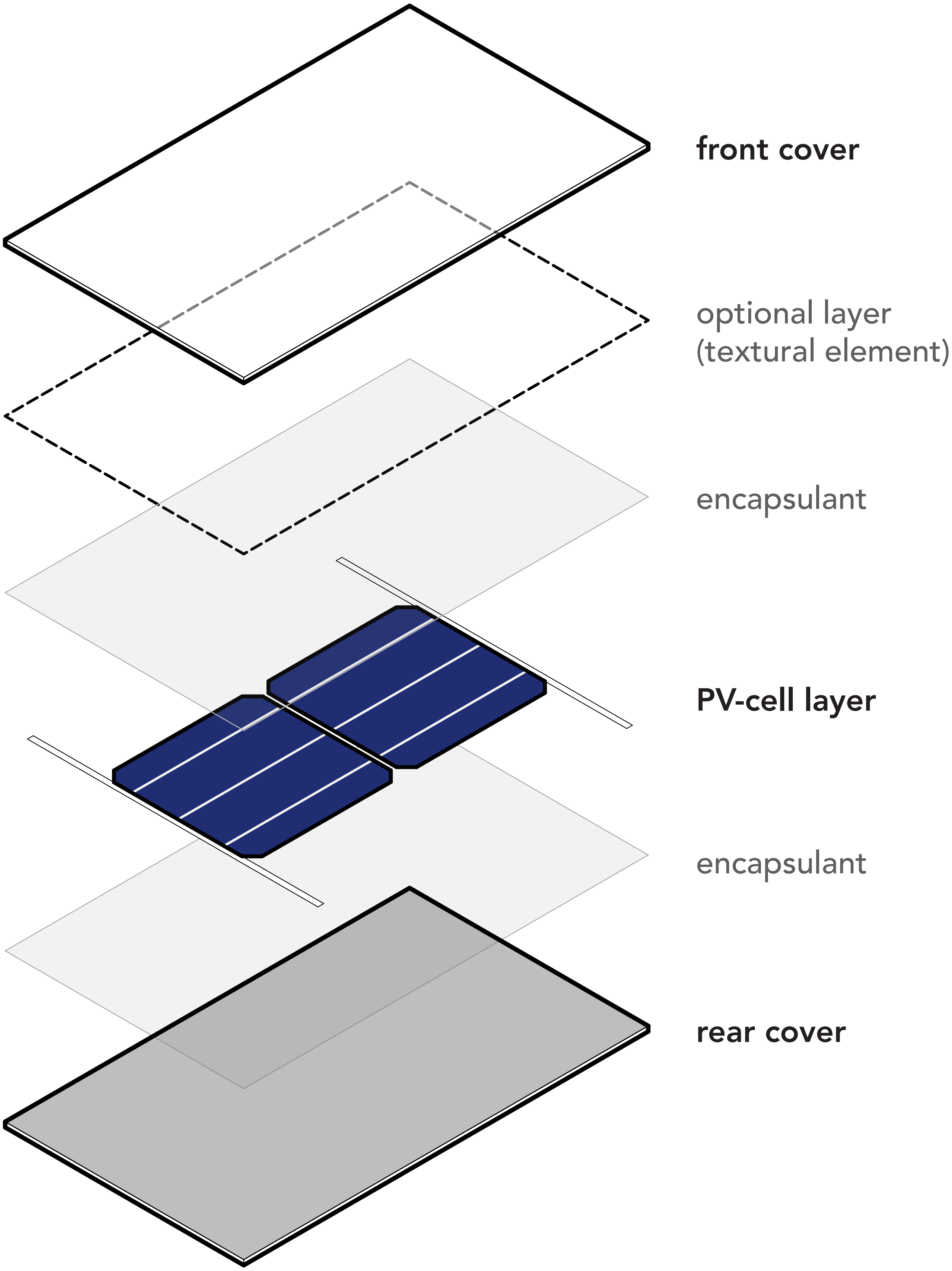
- Front cover
- Solar cell layer
- Rear cover

The materiality of these 3 layers affects the visual appearance and the technical performance of a solar module. When designing a custom module, architects can be in control of these layers and select the materiality best suitable to the project. The handbook shows in different chapters the technical basics about each layer. There are traditionally two encapsulation layers in between these layers to hold everything together. This configuration is called a laminate. Other configurations are also possible. To alter the appearance and texture of the module, additional layers may be introduced.
Lastly, the mounting system has to be considered. Different options are shown in a seperate section in the handbook.

PV-Module



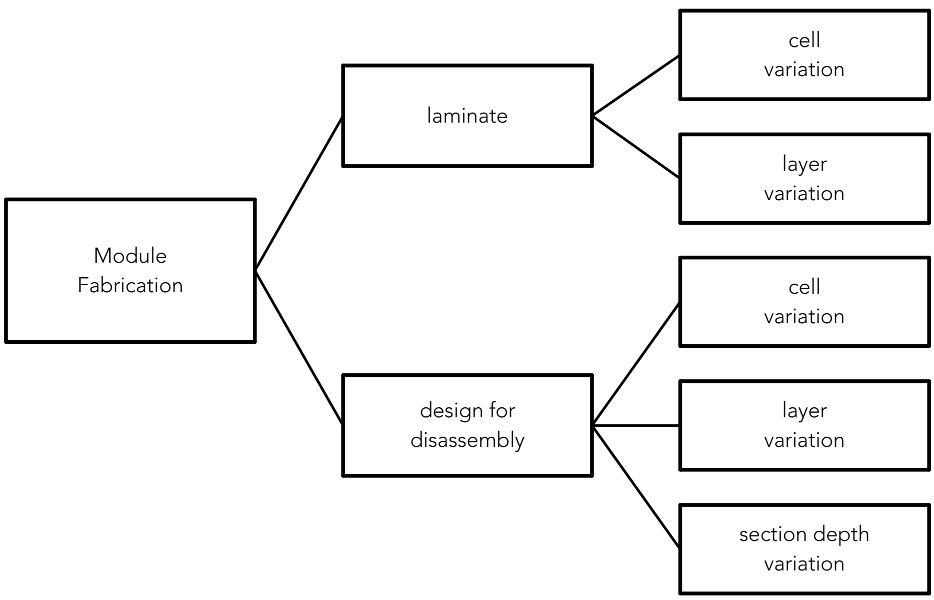
Source | 01

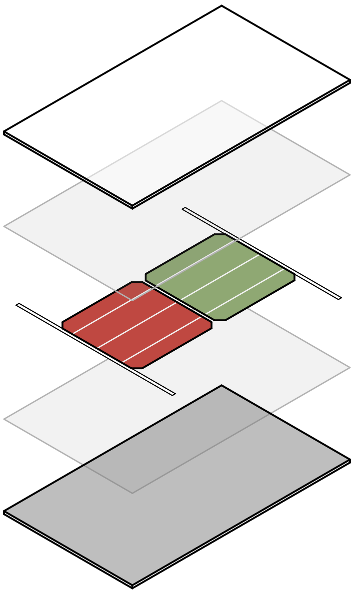


layers in a solar module

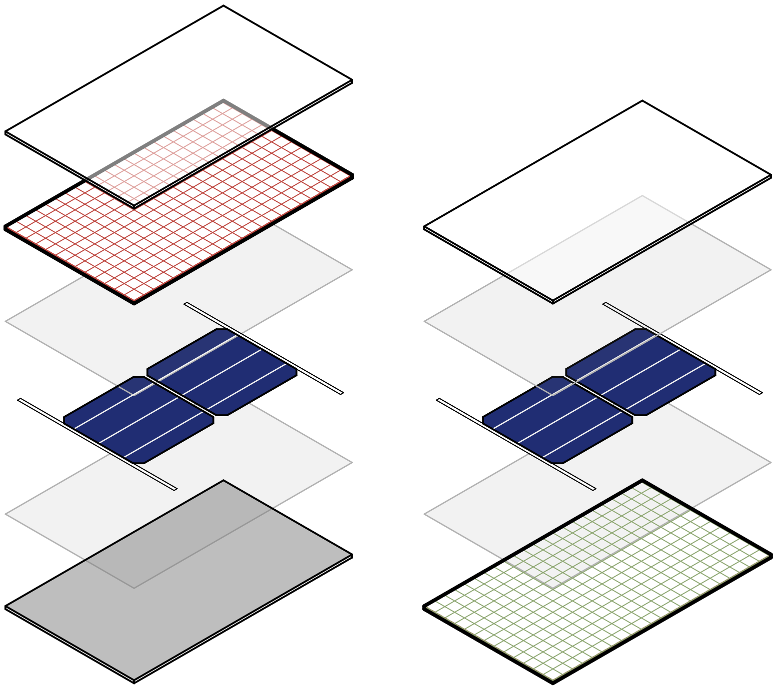
Module Fabrication

At first the module fabrication should be considered. As mentioned in the introduction, the standard way to produce a module is to laminate all the layers together (laminate). A lot of variation and design decisions can still be made with this approach.
The PV-cells can be varied (cell variation). PV-cells are available in various colours, shapes and with different efficiencies. This can already alter the appearance of the module substantially.
The other Layers can also be changed (layer variation). The materiality of the front and rear cover as well as an additional layer can also alter the colour and texture of the module.
A different strategy would be to design a module for disassembly (design for disassembly). The aim of this strategy is to plan the eventual reuse at the end of a module's life span. The longest guarantees of manufacturers today are 30 years. PV-cells energy yield degrades over time. Additionally, the cell technologies available on the market improves every year. This means a reuse of parts of the module during the lifetime of the building is almost inevitable. Different assembly tactics can be used, for example a sealing band. Laminated modules are almost impossible to disassemble.
Another strategy is to give the module more depth (section depth variation). Additional depth can give the module a different look and disguise the electricity production. A surface with more texture is often visually more pleasing than clean flat surfaces.

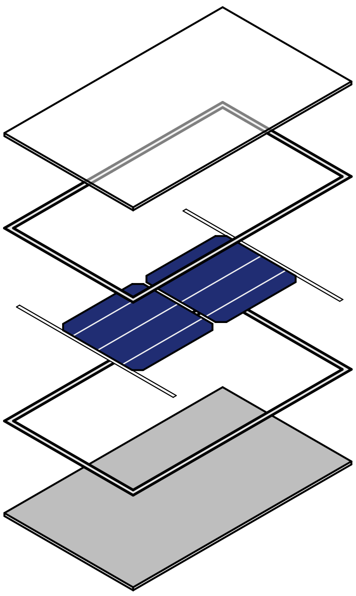




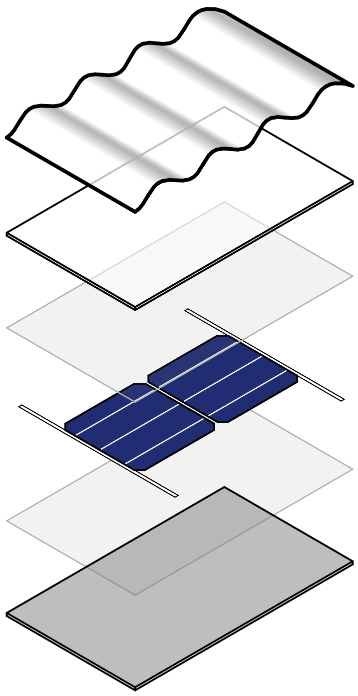
cell variation



layer variation



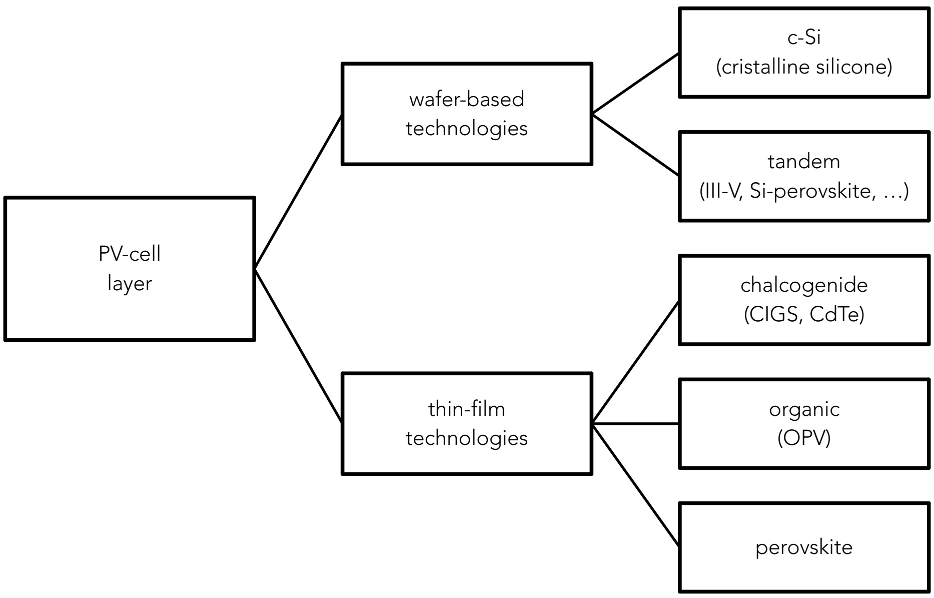
desgin for disassembly



section depth Variation

PV-Cell Layer

For the PV-cell layer there are 2 core technologies to choose from. Wafer-based technologies and thin film technologies. Both have sub-technologies and variants.
The technologies differ in a few key factors. They vary in efficiency, cost, long term stability, and appearance. Some contain hazardous components.
The wafer-based PV-cells, especially the crystalline silicone based ones, are currently the most common used PV-cells. The widespread adoption has brought the cost down and improved their efficiency. Lots of colours and shapes are available. There are also less established wafer-based cells available. Due to their cost, they are typically used for more specialized applications, for example in satellites.
Thin-film technologies include chalcogenide cells (CIGS, CdTe), organic cells (OPV) or dye-sensitized cells, and perovskite solar cells. Thin-film technologies in general are not yet as common as wafer-based ones. Still, the CIGS cells represent the second-most relevant technology after the crystalline silicone-based cells and offer a few exciting advantages. CIGS cells can be glued to a bigger range of geometries and their homogenous black appearance is very discret. Current available products contain hazardous elements in small quantities (Cd and lead). They can reach a similar level of efficiency as crystalline silicone based cells.
OPV and perovskite solar cells are still upcoming new cell technologies with a high potential. Especially the lack of hazardous materials is promising. In terms of efficiency, they still lack behind the other technologies.



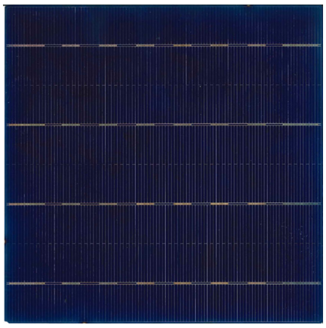
Wafer-based Technologies

When designing with wafer-based technologies it's important to consider, that a standard module will always be much cheaper than a custom one. Crystalline silicone-based cells are currently the most common in the market and the most developed. The manufacturer warranty normally is 25 years or more. The degradation rate of approx. 0.5% per year is also lower than with other technologies. The silicone-based cells are best suited for well oriented building surfaces with direct radiation. However, in Zurich BIPV is economically viable in all orientations.

The individual cells can be connected with conventional visible wires or with conducting foils and edge connectors for a more even appearance.

The following pages show a selection of wafer-based cells to give a first improession.

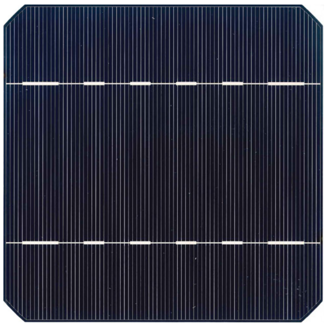
Crystalline silicone cells



Polycrystalline
Sillicon

Efficiency: 18 - 20%

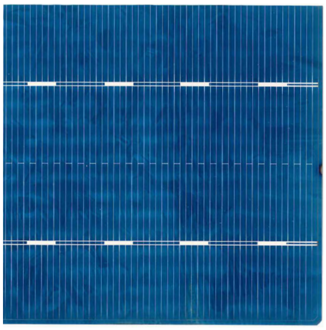
156 x 156 mm



Monocrystalline
Sillicon

Efficiency: 20 - 24%

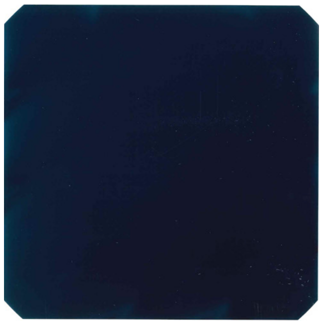
125 x 125 mm
161 x 161 mm



Polycrystalline
Sillicon

Efficiency: 18 - 20%

76 x 76 mm



Monocrystalline
Sillicon
(with conducting foil)

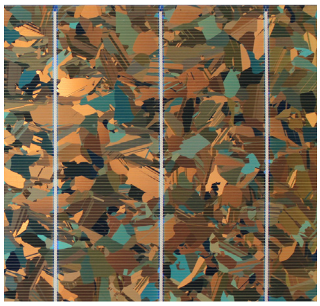
Efficiency: 20 - 24%

125 x 125 mm
161 x 161 mm

Coloured Cells

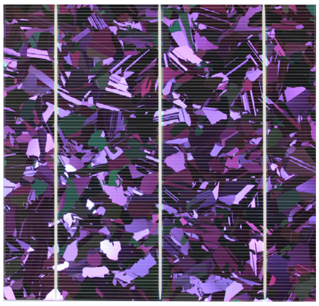
Polycrystalline Sillicone
(Metallic Gold)

Efficiency: 16.8%



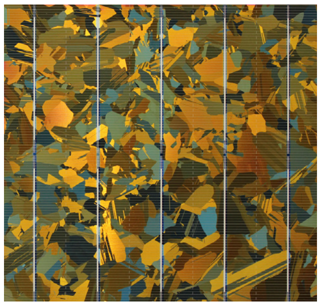
Polycrystalline Sillicone
(Emerald Green)

Efficiency: 17.8%



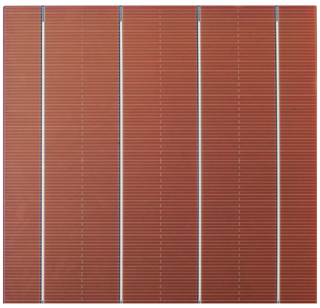
Polycrystalline Sillicone
(Disco Pink)

Efficiency: 17.4%



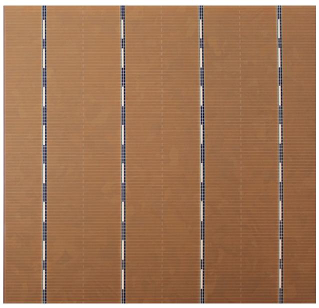
Polycrystalline Sillicone
(Modern Bronze)

Efficiency: 18.6 - 18.8%



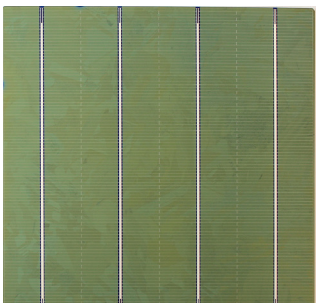
Polycrystalline Sillicone
(Tile Red)

Efficiency: 16.6%



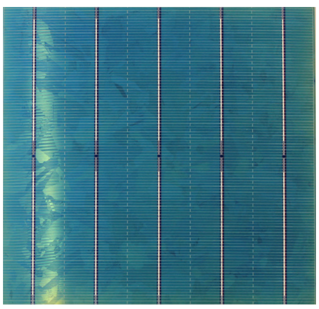
Polycrystalline Sillicone
(Terracotta 4.0)

Efficiency: 14.4%



Polycrystalline Sillicone
(Forest Green)

Efficiency: 17.4%



Polycrystalline Sillicone
(Turkish Blue)

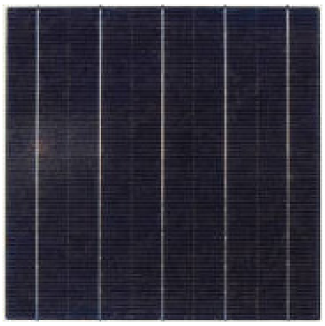
Efficiency: 17.8%

Thin-film Technologies

Thin-film technologies have some advantages for façades. A lot of the radiation on façades is diffuse radiation (even on sunny days). Thin-film solar cells respond very well to diffuse radiation. They are also lighter and therefore use less raw material which makes them more environmental. Their materiality also makes them flexible, which makes them more suitable for adaptive solar configurations.
At the moment they are not as common as the wafer-based cells, which is why they have a shorter life expectancy and a degradation rate of approx. 1% per year. Obviously, the figures change from product to product and will change rapidly in the future.

CIGS

Efficiency: 15 - 19%



CdTe

Efficiency: 15 - 19%

OPV
bidirectional
solar tape

Efficiency: 10 - 12%

Perovskite

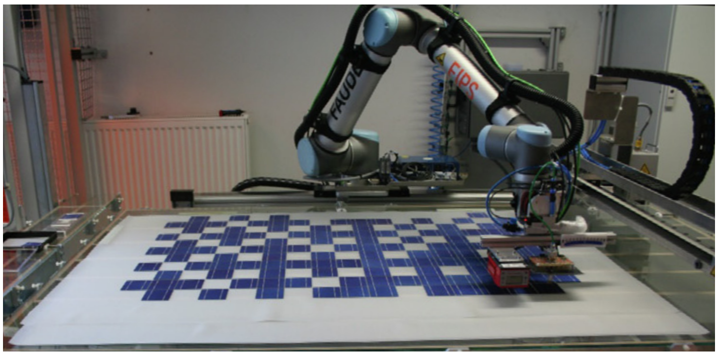
Efficiency: 15 - 18%

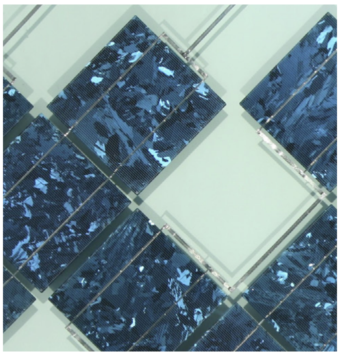
Design Possiblities | PV-cell Layer

Patterns

The spacing and arrangement of the individual cells can be changed. The only requirement is that the individual cells still have to be connected to fotm strings and modules.

Obviously, more space between the cells negatively affects the module efficiency, but shading, natural light and passive solar gains can more than compensate these losses.

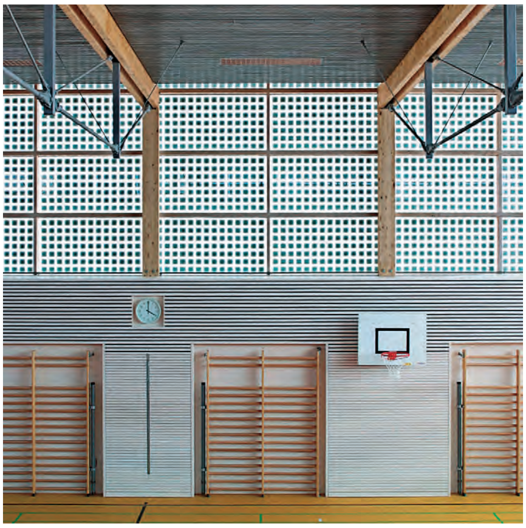




irregural arrangement

Source | 02

Source | 03

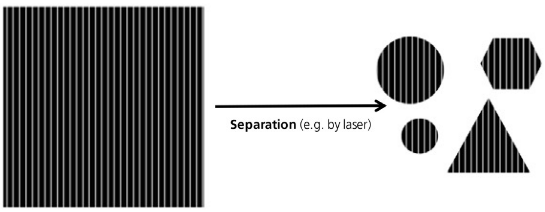


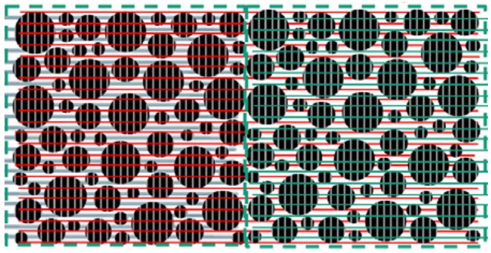
Source | 04

spacing between cells

Separation

Another possibility is to cut the individual cells into various shapes. The cells can be cut with a laser and then arranged in clusters. The only requirement for such clusters is that all the segments are correctly contacted and that the total area of the segments in the clusters is the same. Connection between the segments can be achieved with parallel wires.





Source I 02

PV-cell seperation

PV-cell cluster

Source I 05

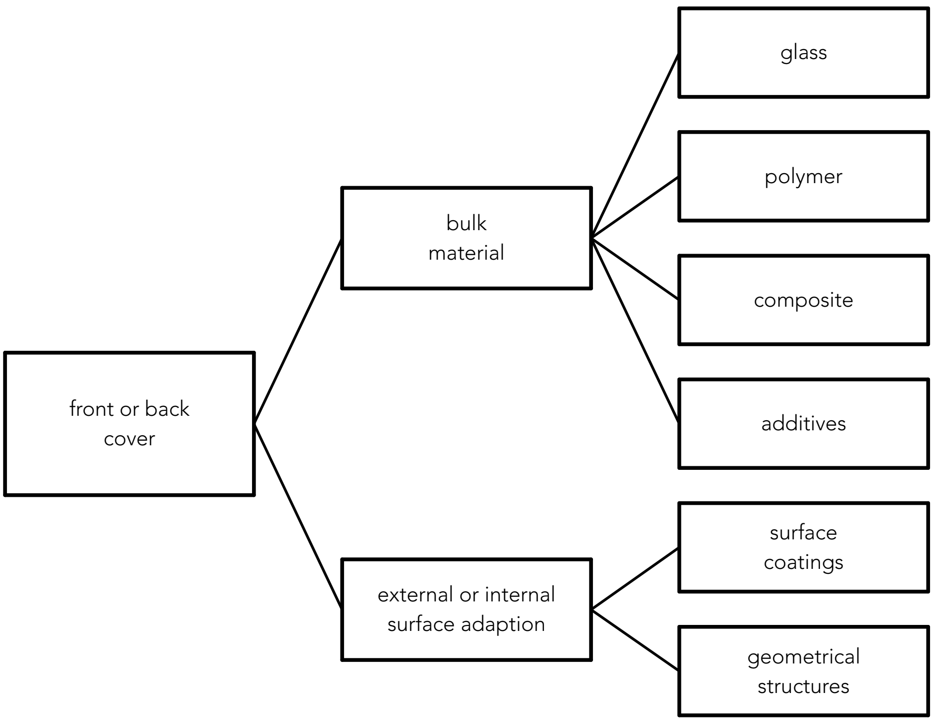
Module with custrom wafer shape

Front/Rear Cover

Like all parts of the module, the front and the rear cover fulfill functional as well as aesthetical functions. The front and sometimes the rear cover are directly visible and therefore play a huge role in the appearance of the module. They also have to withstand environmental forces. In certain applications they even need to fulfill fireproofing regulations. They must fulfill these functions at a reasonable cost and yield the maximum possible amount of electricity.

Therefore, the most commonly used material for BIPV is glass. Glass is highly transparent, mechanically stable, non-combustible, and well known within the building industry. In simple terms, building with BIPV is like building with glass. When using a glass front and back cover, a BIPV module can be classified as laminated safety glass. Similarly to other applications with glass, it's surface can be structured, coated, or finished with various effects. For example, structured glass is great to reduce glare and reflections.

Even though glass can be recycled, it needs a lot of energy to produce, which harms it's environmental footprint. Polymers offer a great alternative. Various sorts of polymers or polymer compounds can also provide enough protection from environmental impacts, but are much lighter and with less embodied emissions. Polymers are currently hard to use when strict fireproofing regulations apply. Additives can be used to achieve certain properties, for example to increase the module's protection against wear and tear. Additionally, there are pigments which are used to achieve a coloured impression.



Bulk Materials

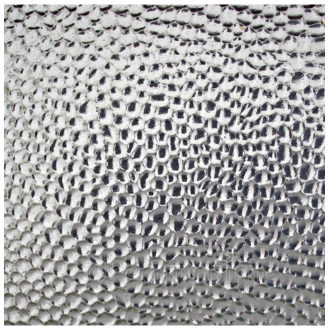
glass

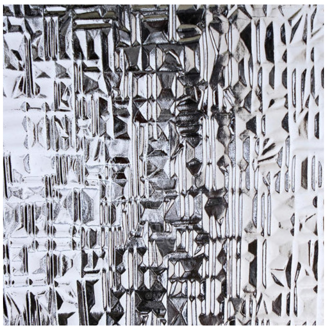
Source I 06

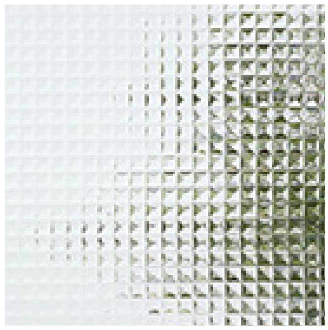
normal floatglass

low iron floatglass
(higher transparency)

structured glass







Source I 07

polymer

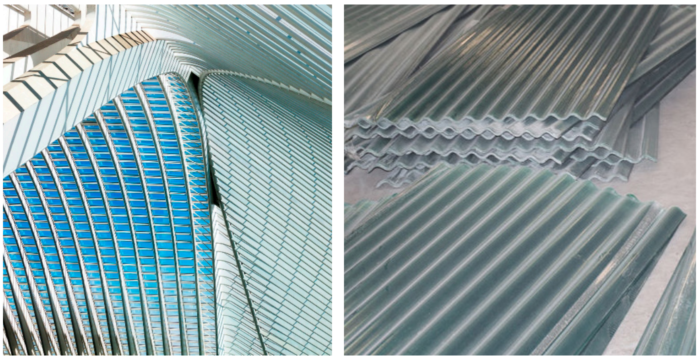
- ETFE
- PA
- PP
- PET
- PVF

Source I 08

ETFE front cover

composites I additives

- fibre glass reinforeced plastics
- polymer and thin alu foil compound
- pigments (colours)
- TiO_2 (higher reflectance)

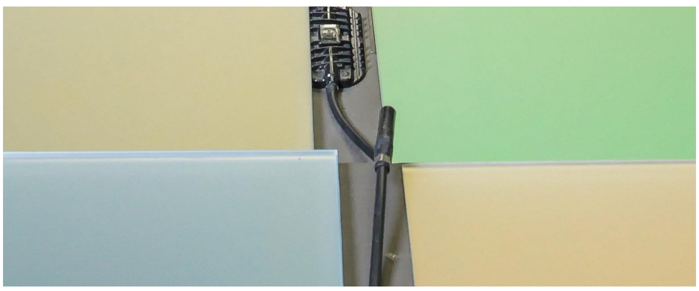


Source I 09

fibre glass plastic

Surface adaptions

- surface coatings
- geometrical structures
- printing

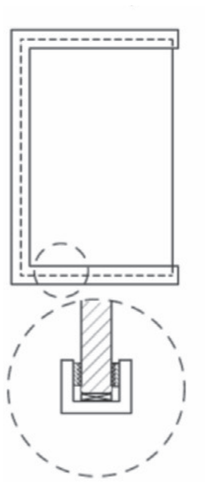


Source I 10

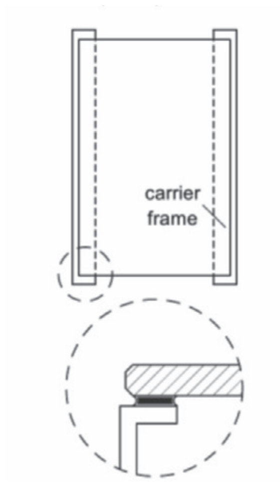
coloured PV-modules

Mounting Systems

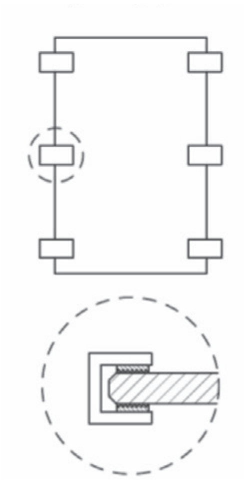
Solar modules can be mounted in lots of different ways. Most importantly, the mounting system has to provide ventilation from the back to prevent efficiency loss caused by overheating. Battens and counter battens are commonly used to achieve this.
The connections between modules can also be made in the ventilation space. The visible fixtures can be project specific. In general, the more complicated, the more expensive it will be. Four possible mounting systems for modules are shown below.
More construciton examples can be found at *https://solarchitecture.ch*



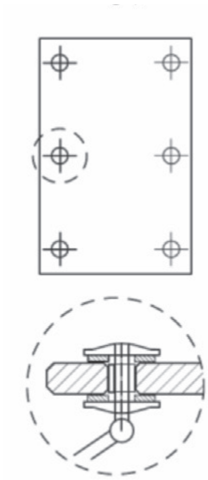
lineary supported
(two, three or four sided)



structural silicone sealant



local edge supports



local point supports

Source | 02

Electricity Yield

At an early design stage, the exact electricity yield might not be very important. To get a rough estimate, there are a few things to consider. Firstly, the global radiation (G), which is 1200 kWh/m^2 per year for Zurich. Secondly the orientation of the surface of the modules (F_F). Thirdly, the module Surface (A) and fourthly, the module efficiency (η_{PV}). The module efficiency is manly dependent on the cell technology, the cover materials used and the spacing of the individual cells. Lastly, everything gets multiplied with the performance ratio (PR). It accounts for losses within the entire system, such as reflection losses, module contamination, snow coverage, shading, and distribution losses. Well planned roof systems achieve a performance ratio of app. 75%. Façade systems normally realize a performance ratio bellow 70% due to unfavorable conditions. For a more detailed calculation go to PV-GIS (*https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html#PVP*).

Electricity Production:

$$E = G \cdot F_F \cdot A \cdot \eta_{PV} \cdot PR$$

E	Electricity production [kWh]
G	Global horizontal radiation [kWh/m^2]
F_F	orientation factor [-]
A	total PV area [m^2]
η_{PV}	efficiency of PV module [-]
PR	Performance Ratio [-]

Module Efficiency:

$$\eta_{PV} = \eta_{cell} \cdot f_{cover} \cdot (A_{cell}/A_{module})$$

η_{PV}	efficiency of PV module [-]
η_{cell}	efficiency of PV cell [-]
f_{cover}	optical efficiency of cover [-]
A_{cell}	Total area of cells per module [m^2]
A_{module}	Area of one module [m^2]

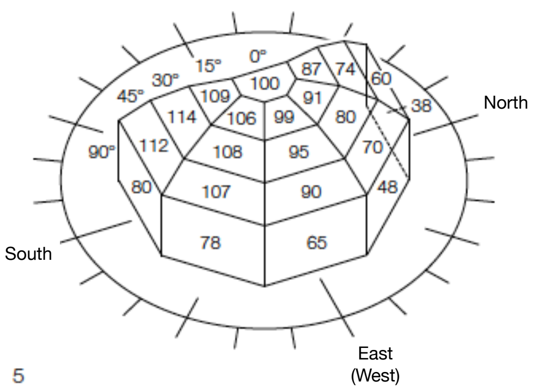
Monocristalline silicone	Polycristalline silicone	GIGS CdTe
20 - 24 %	18 - 20 %	15 - 19 %
Amorphous Silicon	Perovskite	OPV
5 - 9 %	15 - 18 %	9 - 11 %

typical efficiencies of PV-technologies (η_{cell})

https://www.nrel.gov/pv/module-efficiency.html

normal glass	low iron glass	structured glass
70 - 85 %	80 - 95 %	70 - 85 %
polymer	fibre glass	colour layer
80 - 95 %	75 - 85 %	50 - 70 %

typical optical efficiency of covers (f_{cover})



relative annual irradiation on surfaces with different orientations in relation to the horizontal axis in Zurich (F_F)

Source I 01

Cost Calculation

The cost is always a key factor in the building industry. Solar systems are always connected with higher investment costs, but when the location is good, the investment will be amortized within 5 to 10 years. A solar system usually is profitable.
If a solar installation is cost effective is dependent on location and orientation of the modules. The better the orientation, the faster the amortization. The swiss government does subsidize the cost of a solar system and there are tax savings as well. A great first cost estimate, especially for renovations, can be done at *www.sonnendach.ch.*

Key factors

amortization: 5 - 10 years (with good orientation)

net investment cost:	200 - 300 CHF/m^2	roof system (standard)
	350 - 700 CHF/m^2	facade system (custom)

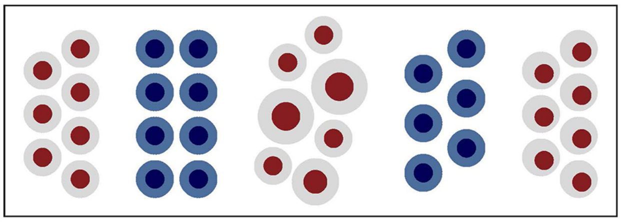
Examples from the BIPV Workshop

Team 2 | Josien de Koning & Lucas Lamberti

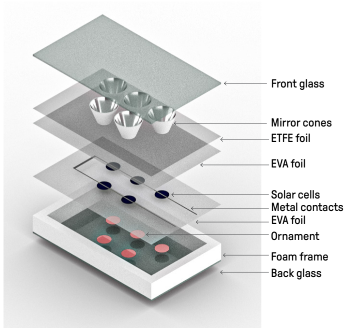
$$E = G \cdot F_F \cdot A \cdot \eta_{PV} \cdot PR$$

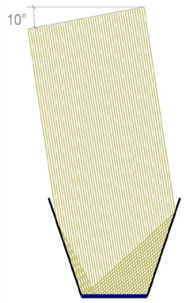
E	Electricity production [kWh]	**1137**
G	Global horizontal radiation [kWh/m²]	**1'200**
F_F	orientation factor [-]	**0.67**
A	total PV area [m²]	**41**
η_{PV}	efficiency of PV module [-]	**0.069**
PR	Performance Ratio [-]	**0.5**

E/A = **Area Specific Yield (KWh / m^2) = 27.7**

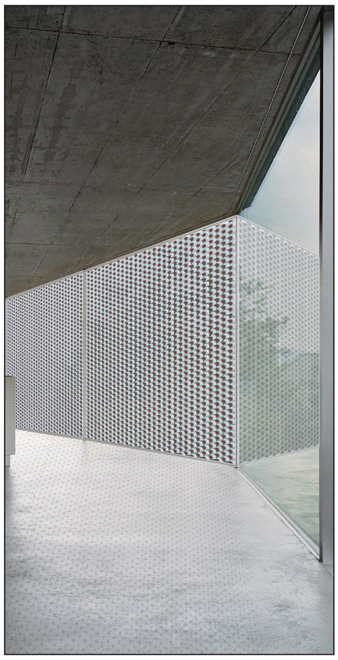


layout options





reflection diagramm



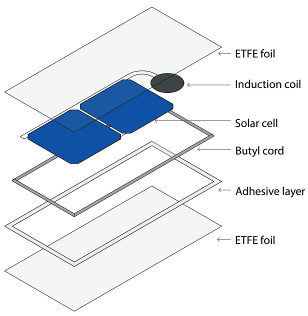
interior view

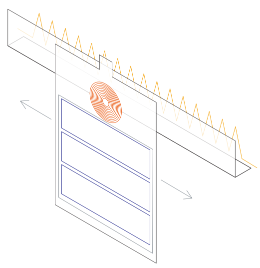
Team 8 | Lisa Stricker & Nikola Endres

$$E = G \cdot F_F \cdot A \cdot \eta_{PV} \cdot PR$$

E	Electricity production [kWh]	**5809**
G	Global horizontal radiation [kWh/m²]	**1200**
F_F	orientation factor [-]	**0.65**
A	total PV area [m²]	**56.5**
η_{PV}	efficiency of PV module [-]	**0.17**
PR	Performance Ratio [-]	**0.8**

E/A = **Area Specific Yield (KWh / m^2) = 102**





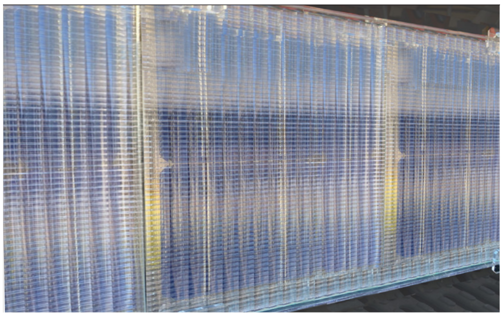
PV active curtains

Team 4 | Leandro Barroso & Ralf Zwahlen

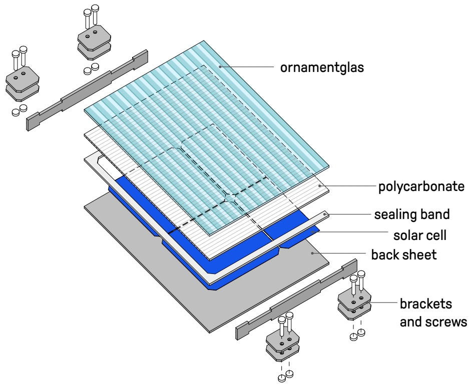
$E = G \cdot F_F \cdot A \cdot \eta_{PV} \cdot PR$

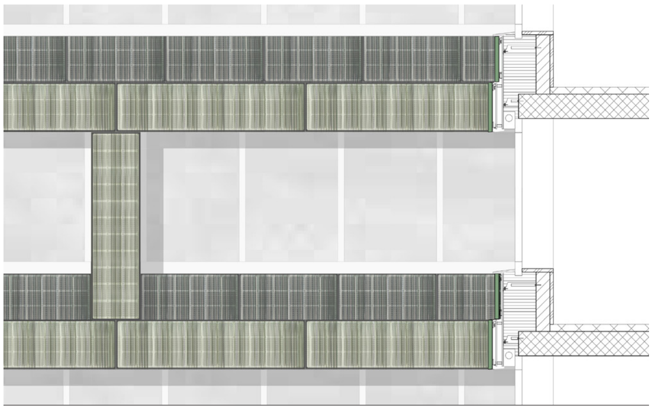
E	Electricity production [kWh]	**86'301**
G	Global horizontal radiation [kWh/m²]	**1200**
F_F	orientation factor [-]	**79%**
A	total PV area [m²]	**700**
η_{PV}	efficiency of PV module [-]	**15.3%**
PR	Performance Ratio [-]	**85%**

E/A = **Area Specific Yield (KWh / m^2) =** **123**

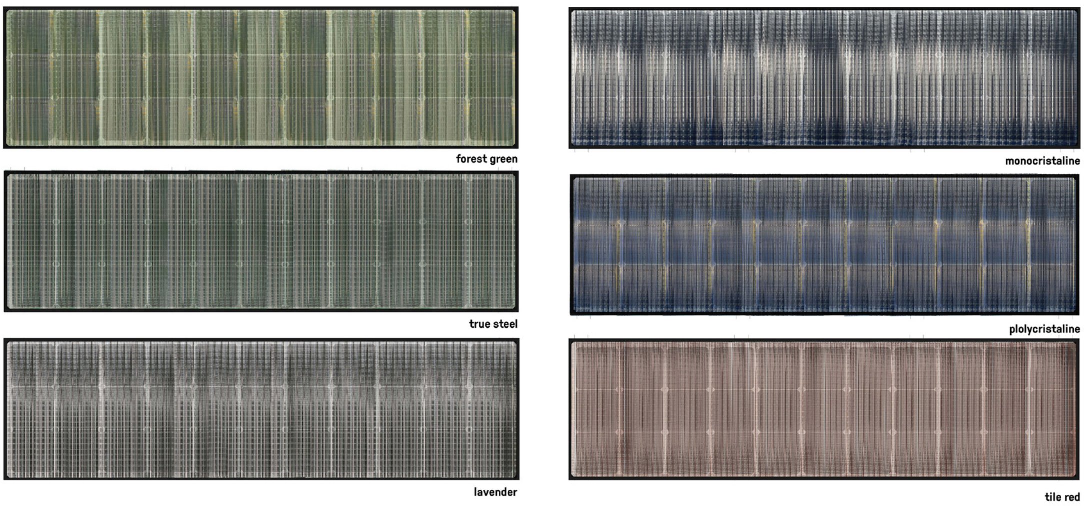


texture of module prototype





section and elevation



colour variations

Sources

01 | Detail Praxis : Photovoltaik

02 | Review of technological design options for building integrated photovoltaics (BIPV)
Tilmann E. Kuhn, Christof Erban, Martin Heinrich, Johannes Eisenlohr, Frank Ensslen, Dirk Holger Neuhaus

03 | www.solar-constructions.com/wordpress/transparente-solarmodule/

04 | Schittich , Detail Solar Architecture

05 | Viridén + Partner, Romanshorn

06 | www.indiamart.com/proddetail/low-iron-glass-21726794491

07 | Rider Glass , https://riderglass-qd.en.made-in-china.com

08 | AWM München, Ackermann und Partner Architekten BDA

09 | Liége-Guillemins, Belgien

10 | EPFL, www.actu.epfl.ch
Alain Herzog/Pilippe Vollichard/Andreas Schüler/Prof jean-Louis Scartezzini/Kromatix

Energy- and climate Systems 1 - 3, Architecture and Building Systems, ETH

Workshop on Building Integrated Photovoltaics (BIPV); Chair of Architecture and Building Systems, ETH Zurich

Economic analysis of BIPV systems as a building envelope material for building skins in Europe Hassan Gholami, Harald Nils Røstvik

www.sonnendach.ch

www.solarchitecture.ch

Module efficiencys | https://www.nrel.gov/pv/module-efficiency.html

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