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goPV

Jun. 21st 2022

Solar PV Modules

Market Trends, Materials & Manufacturing Processes

Olatz Arriaga Arruti - EPFL

co-organized with Università di Catania

(11:30-12:30)

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

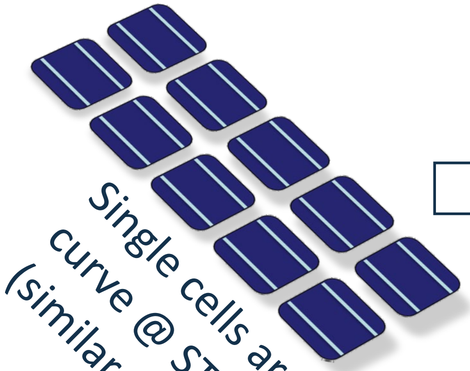
PV Modules: Market Trends, Materials & Manufacturing Processes

Session Contents

1. PV Module Fabrication Steps
2. PV Technology Market and Costs
3. Crystalline Silicon Solar Cells
4. Solar Cell Interconnections
5. Lamination Process & PV Module Materials
6. Some Degradation Mechanisms
7. Manufacturing of Reliable Silicon Heterojunction Glass/Glass Modules

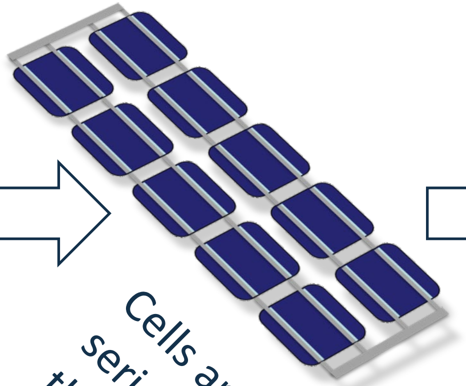
1. PV Module Fabrication Steps

1. Single cells



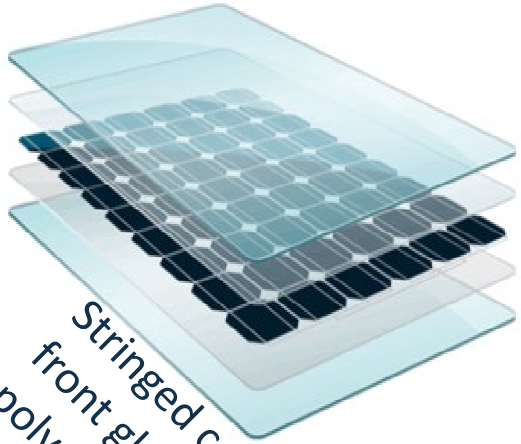
Single cells are tested (I-V curve @ STC*) and sorted (similar current/power).

2. Stringing



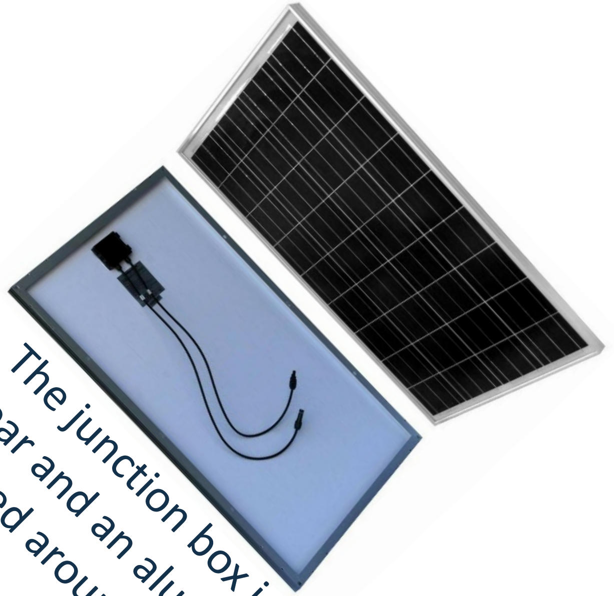
Cells are connected (in series or parallel) to match the module power output.

3. Lamination



Stringed cells are protected with a front glass and a rear cover. Two polymeric foils (encapsulant) provide the adhesion between components.

4. Junction box



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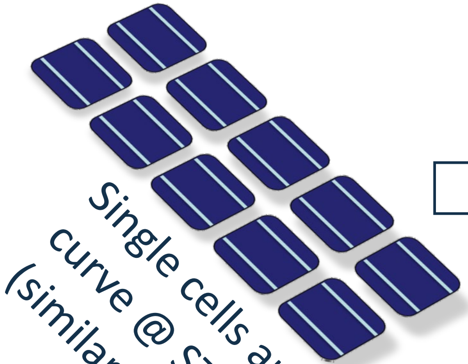

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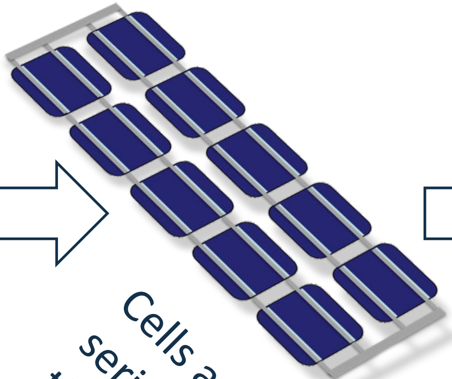

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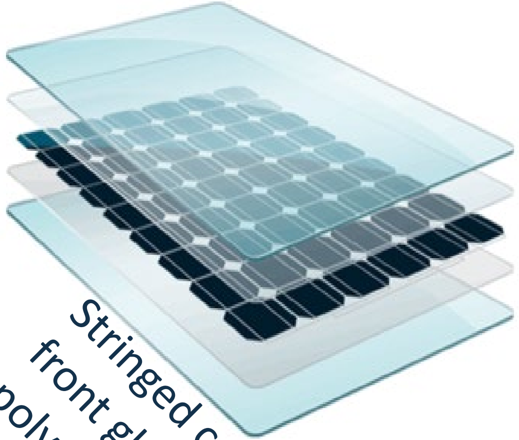

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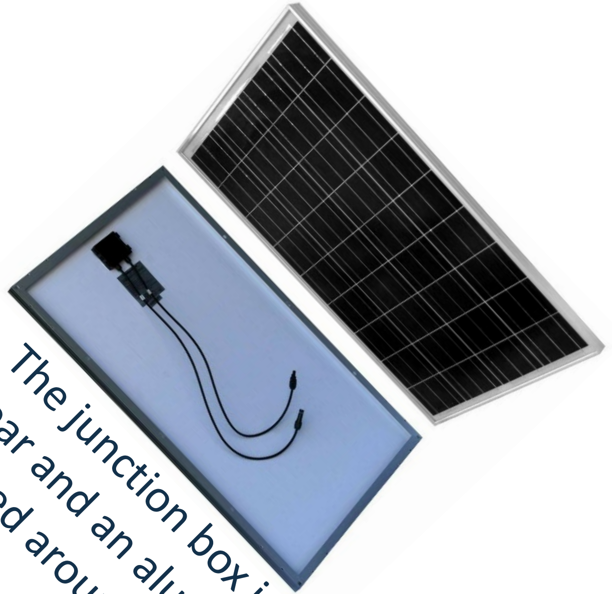

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2. PV Technology Market and Costs

PV Technology Trends

Market

Crystalline Silicon
95% market share

Thin Films
3-5 % market share

III-V solar cells
Space application

R&D stages

Concentrator PV
Failed market entrance

Perovskites (+ tandems)

Other technologies
Organic, DSSC, quantum dots…

2. PV Technology Market and Costs

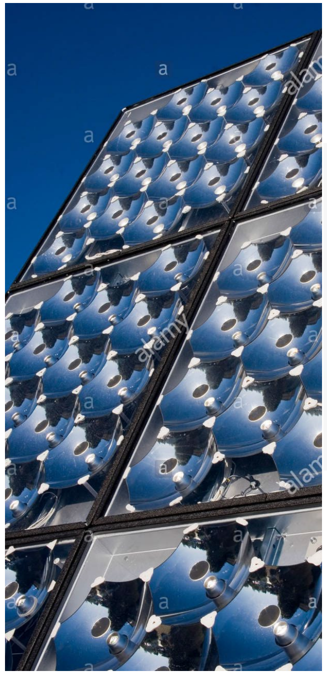
Crystalline Silicon (c-Si)

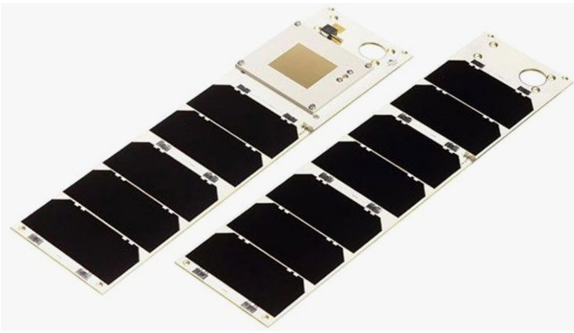
Wafer based (bulk semiconductor)
- Processing of wafers
- Series connection of individual solar cells

Thin film

- Deposition on large area substrate
- "Monolithic series integration" of the cells

III-V multi-junction

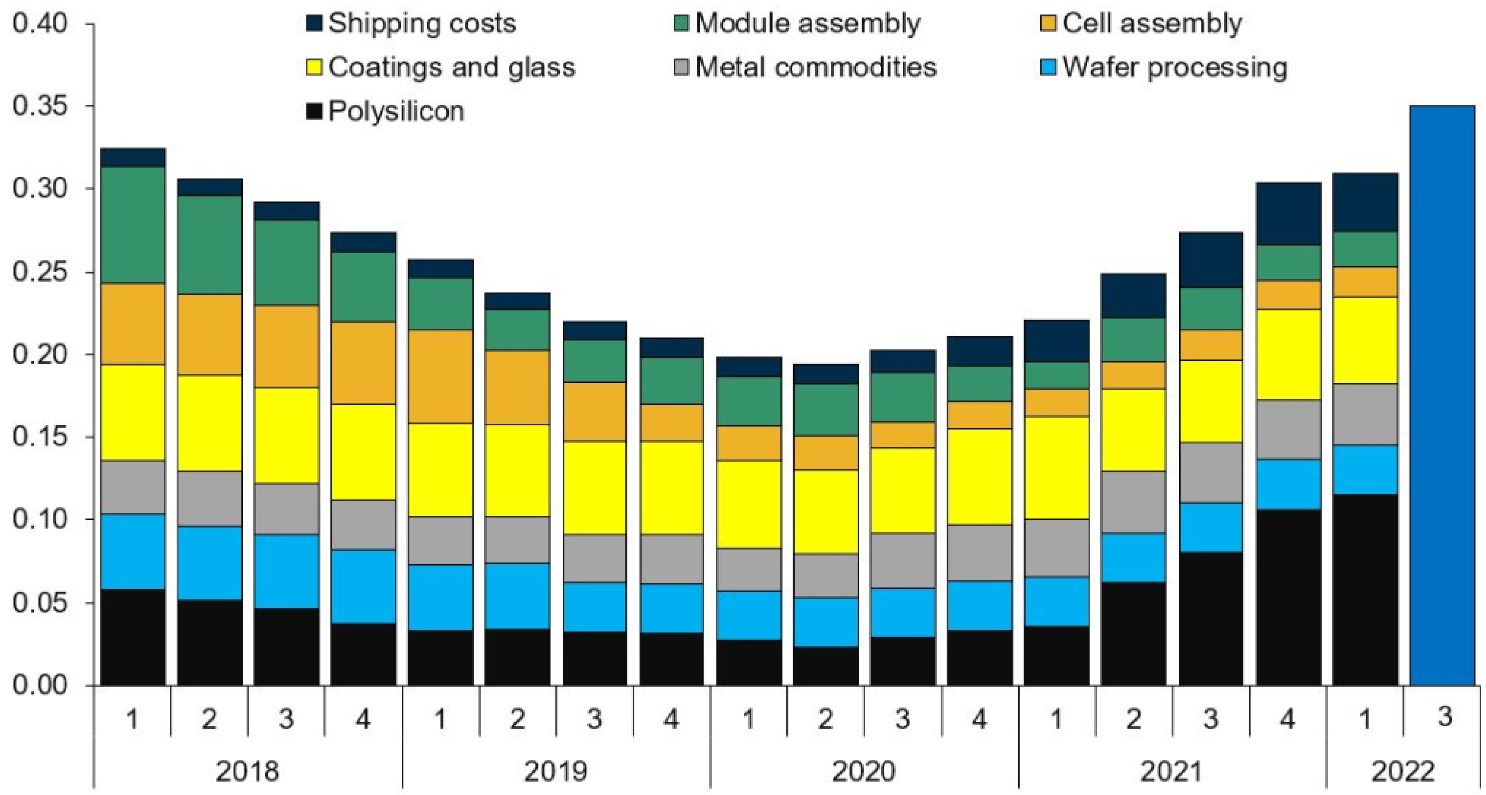




- Grown epitaxially on crystalline wafers
- Developed for space applications → very costly
- Used in concentrated PV (CPV)

2. PV Technology Market and Costs

Figure 3: Evolution in solar PV module costs by quarter, 2018-2022*
USD per watt peak (Wp)

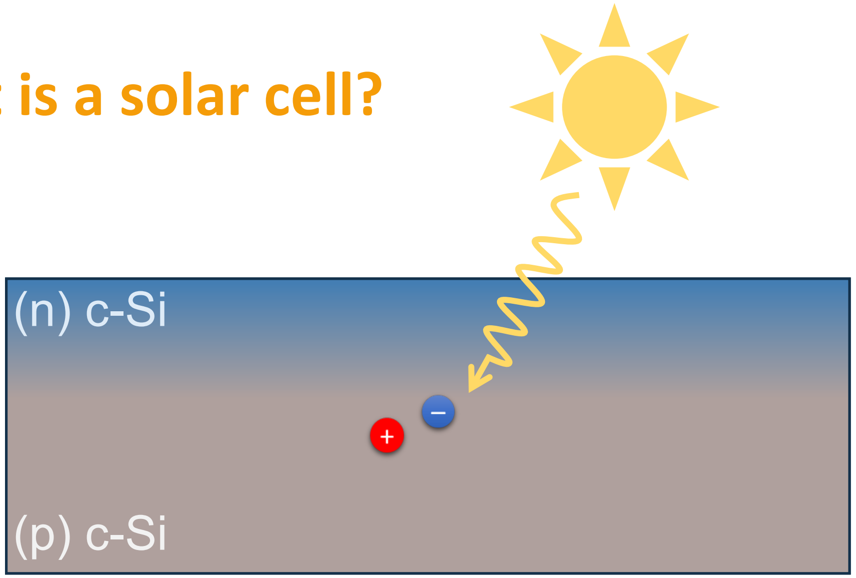


*Forecast third-quarter values shown for 2022
Source: Rystad Energy SolarSupplierCube

Production costs [cts$/Wp]		
	2017	**2020**
Total	37	20
Polysilicon	8.7	3
Wafer	5.8	3
Cells	8.6	4
Module	13.8	10

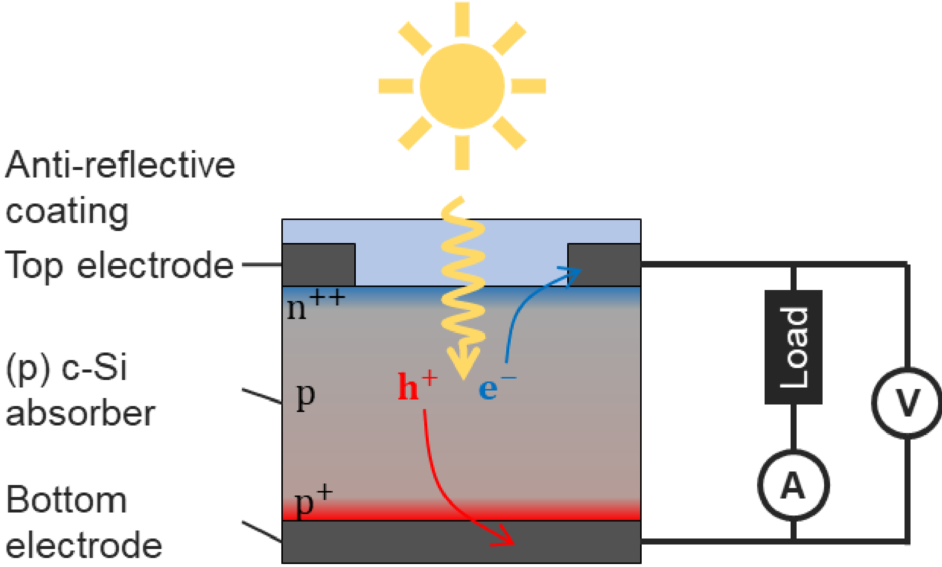
3. Crystalline Silicon Solar Cells

What is a solar cell?



p-n junction

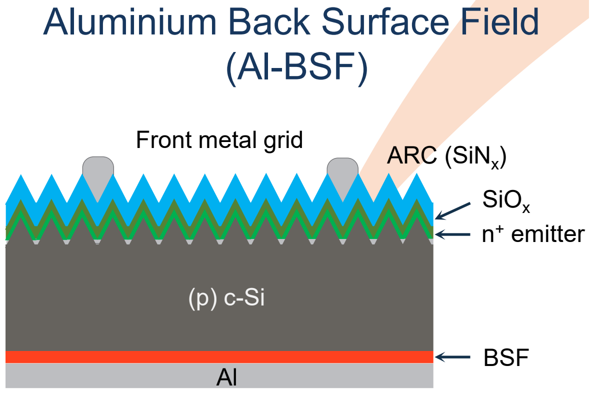
- Intrinsic (pure) **semiconductor** material (e.g. Si).
- Doped with impurities to become conductor → $+(\mathrm{p})$ or – (n) charges transporting the current.
- **Under light** → absorption of **photons** if $h\nu > E_g$ (E_g: semiconductor bandgap).
- Photogenerated carriers move towards the junction and cross it.

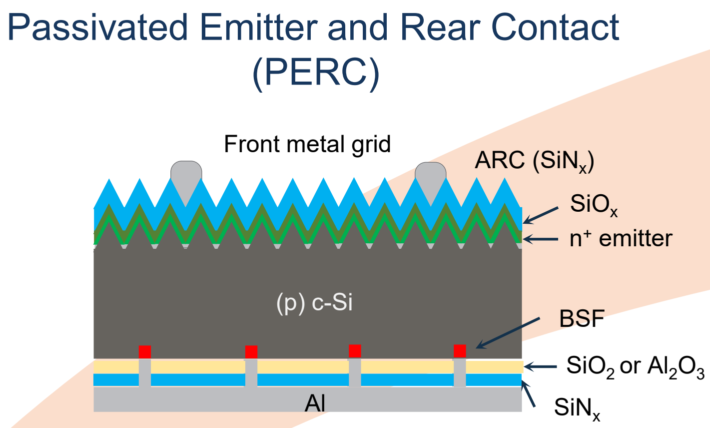


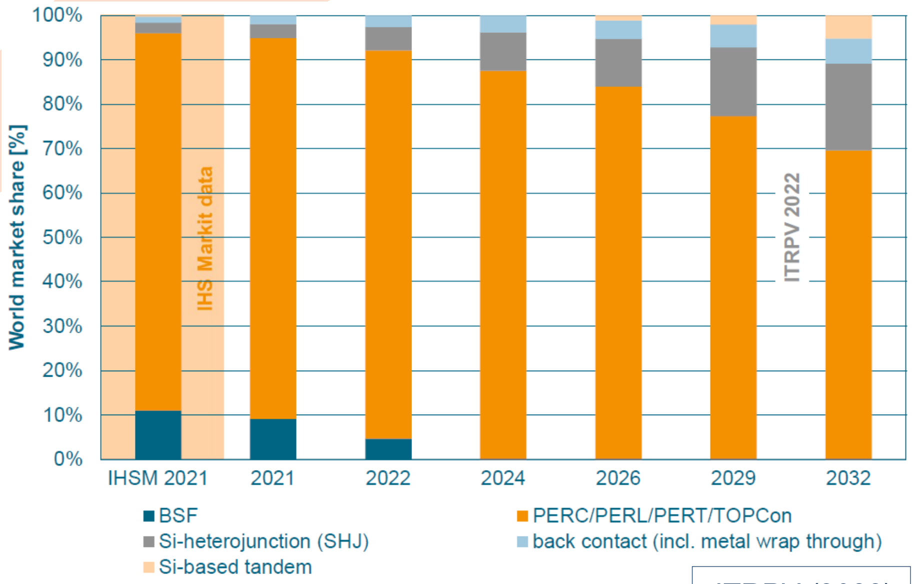
J. Hurni (2022)

Metallic contacts extract the current

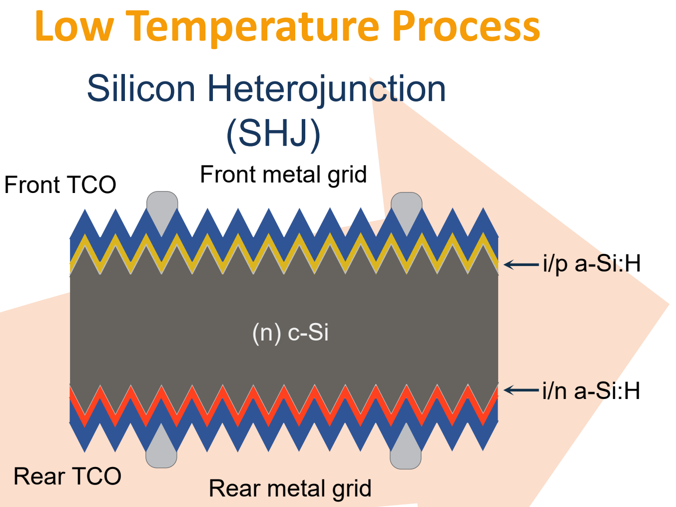
3. Crystalline Silicon Solar Cells

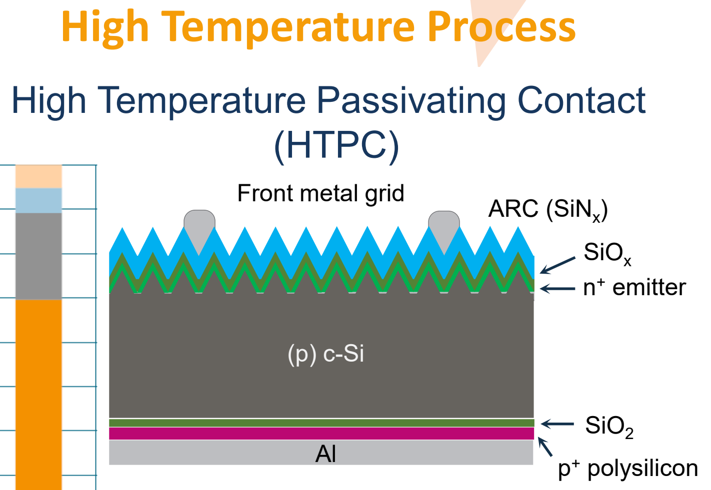






ITRPV (2022)

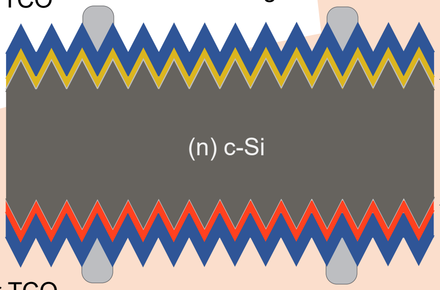




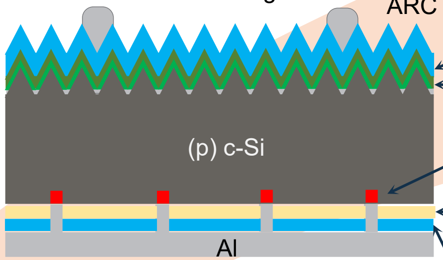
3. Crystalline Silicon Solar Cells

Low Temperature Process

Silicon Heterojunction (SHJ)



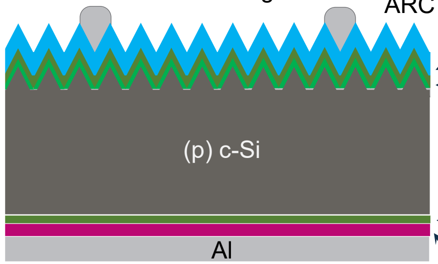
Passivated Emitter and Rear Contact (PERC)



- Better passivation (rear surface)
- ↓ Optical losses
- Similar manufacturing
- High temperature processing

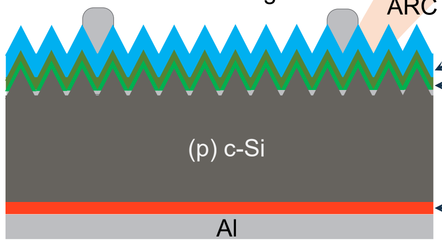
High Temperature Process

High Temperature Passivating Contact (HTPC)



- Better passivation
- Simple manufacturing processes → no patterning

Aluminium Back Surface Field (Al-BSF)



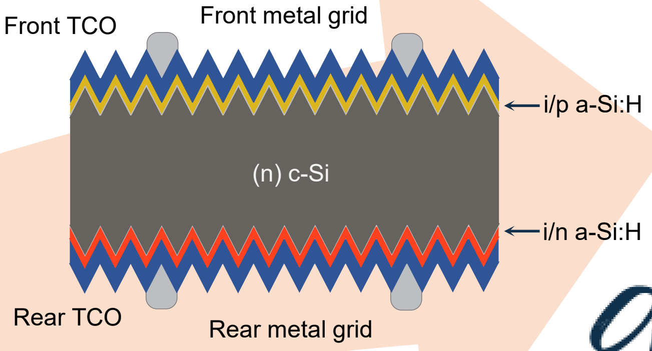
Challenges:

- **Optical losses** → reflection of photons at rear surface
- **Recombination losses** → at metallic contact
- **Ohmic losses** → high series resistance at interfaces

3. Crystalline Silicon Solar Cells

Low Temperature Process

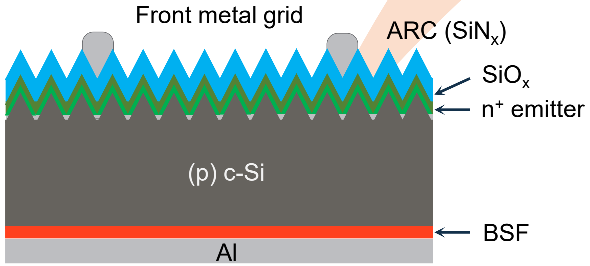
Silicon Heterojunction (SHJ)



Advantages:
- Better passivation
- ↓ Processing temperature
- ↓ Thickness, ↓ cost
- ↑ Open-circuit voltage (V_{OC})
- ↓ Temperature coefficient

Challenges:
- Need of ECA for soldering
- ↓ adhesion fingers/TCO

Aluminium Back Surface Field (Al-BSF)



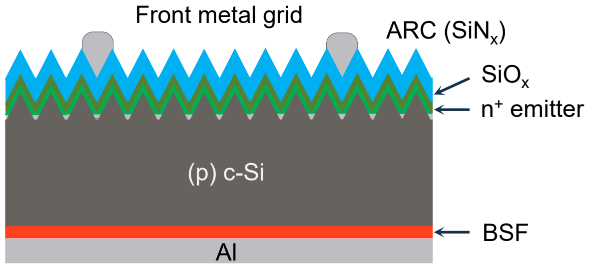
Challenges:
- **Optical losses** → reflection of photons at rear surface
- **Recombination losses** → at metallic contact
- **Ohmic losses** → high series resistance at interfaces

ECA: electrically conductive adhesive *TCO: transparent conductive oxide*

3. Crystalline Silicon Solar Cells

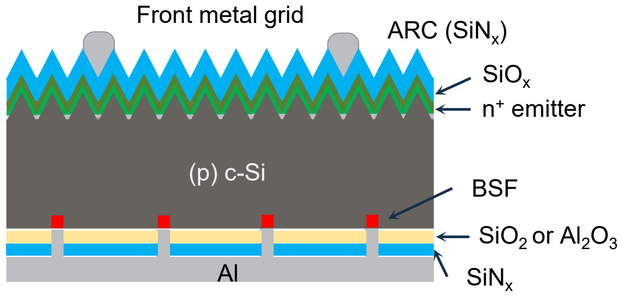
Potential for bifaciality

Aluminium Back Surface Field (Al-BSF)



Conventional Al-BSF cells do not give option for bifaciality

Passivated Emitter and Rear Contact (PERC)



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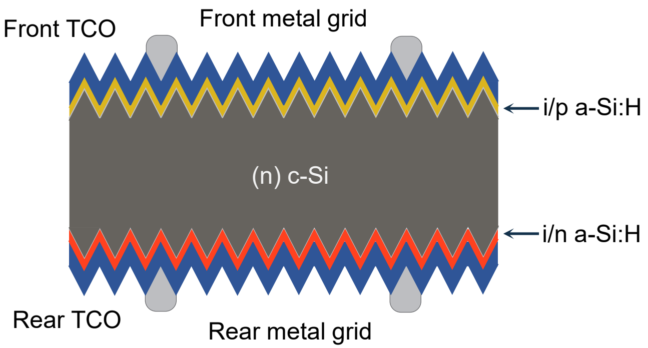
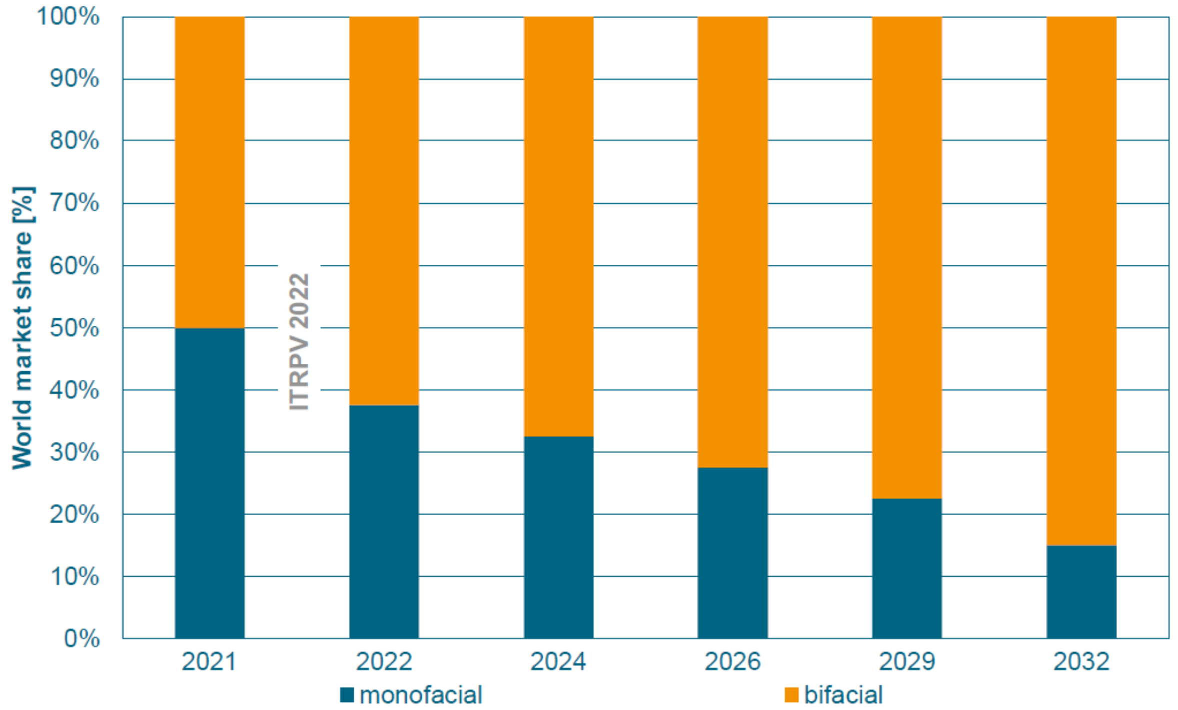


World market share of monofacial and bifacial cells



ITRPV (2022)

Novel solar cell concepts promote the development of bifacial technology

1. PV Module Fabrication Steps

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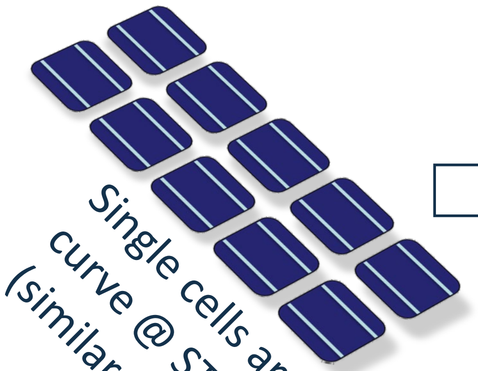

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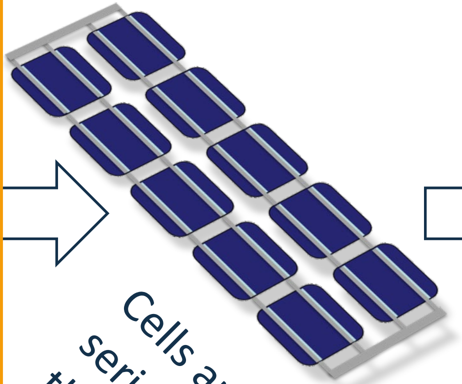

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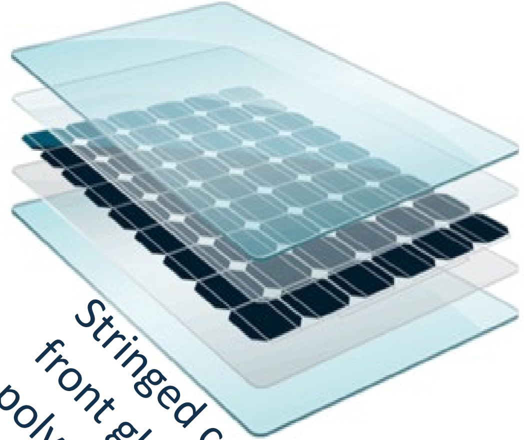
3. Lamination



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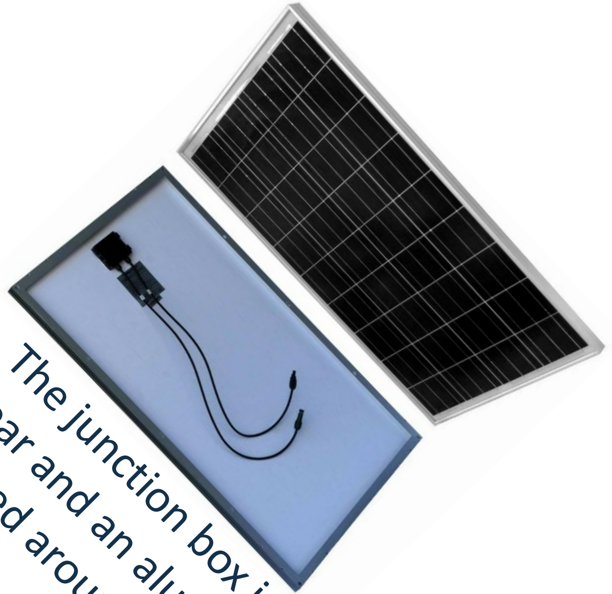

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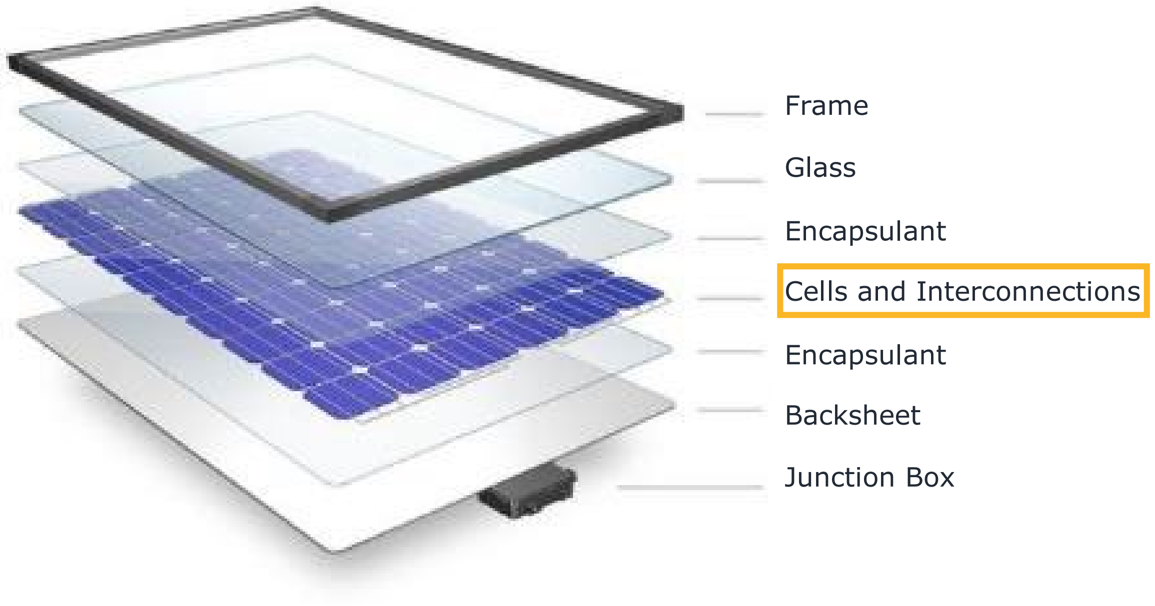
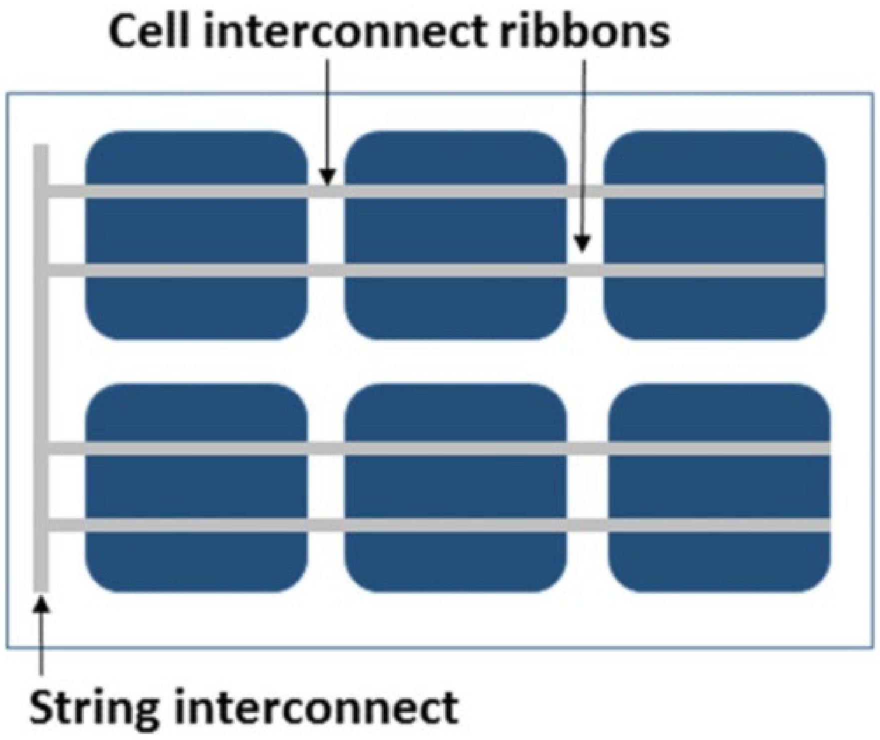
4. Solar Cell Interconnections



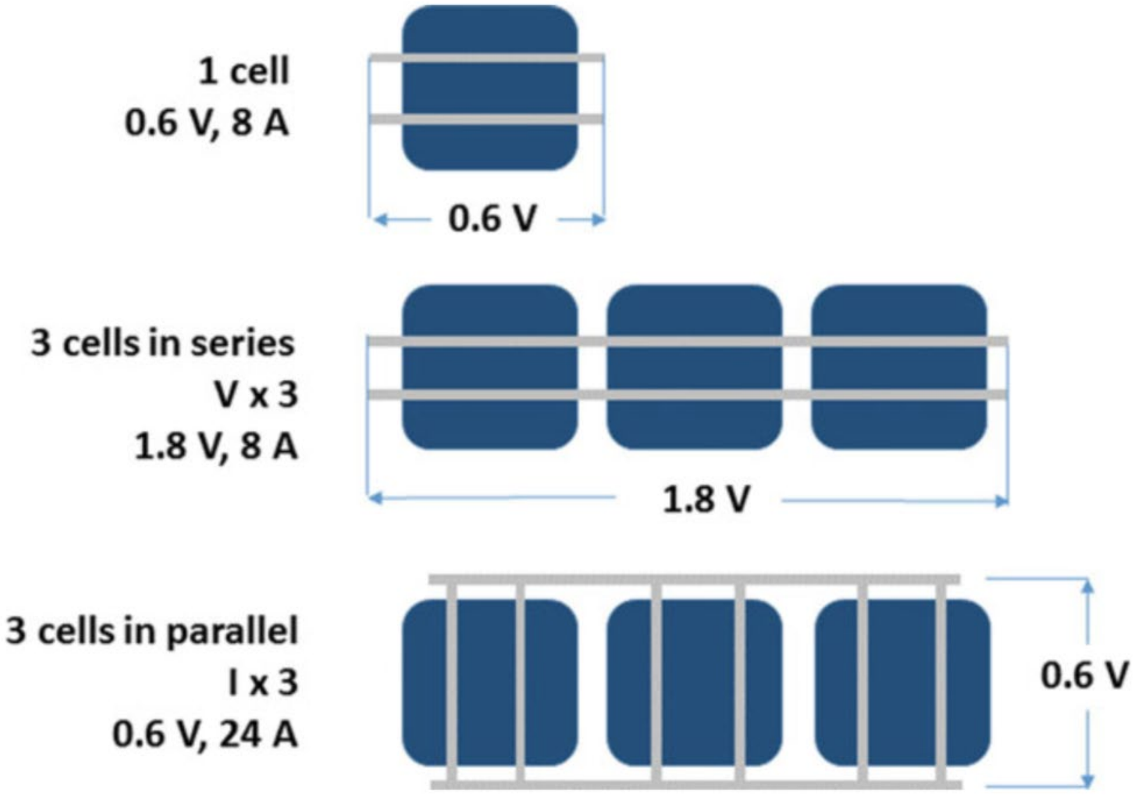


A. Shah, Solar cells and modules (2020)
Chapter 9, A. Virtuani

1. From solar cells to modules

EPFL

Cell interconnections



A. Shah, Solar cells and modules (2020)
Chapter 9, A. Virtuani

Commercial c-Si modules have 60/72 series-connected solar cells

Series connection → to get **high voltage**

- Cells must be **current-matched**

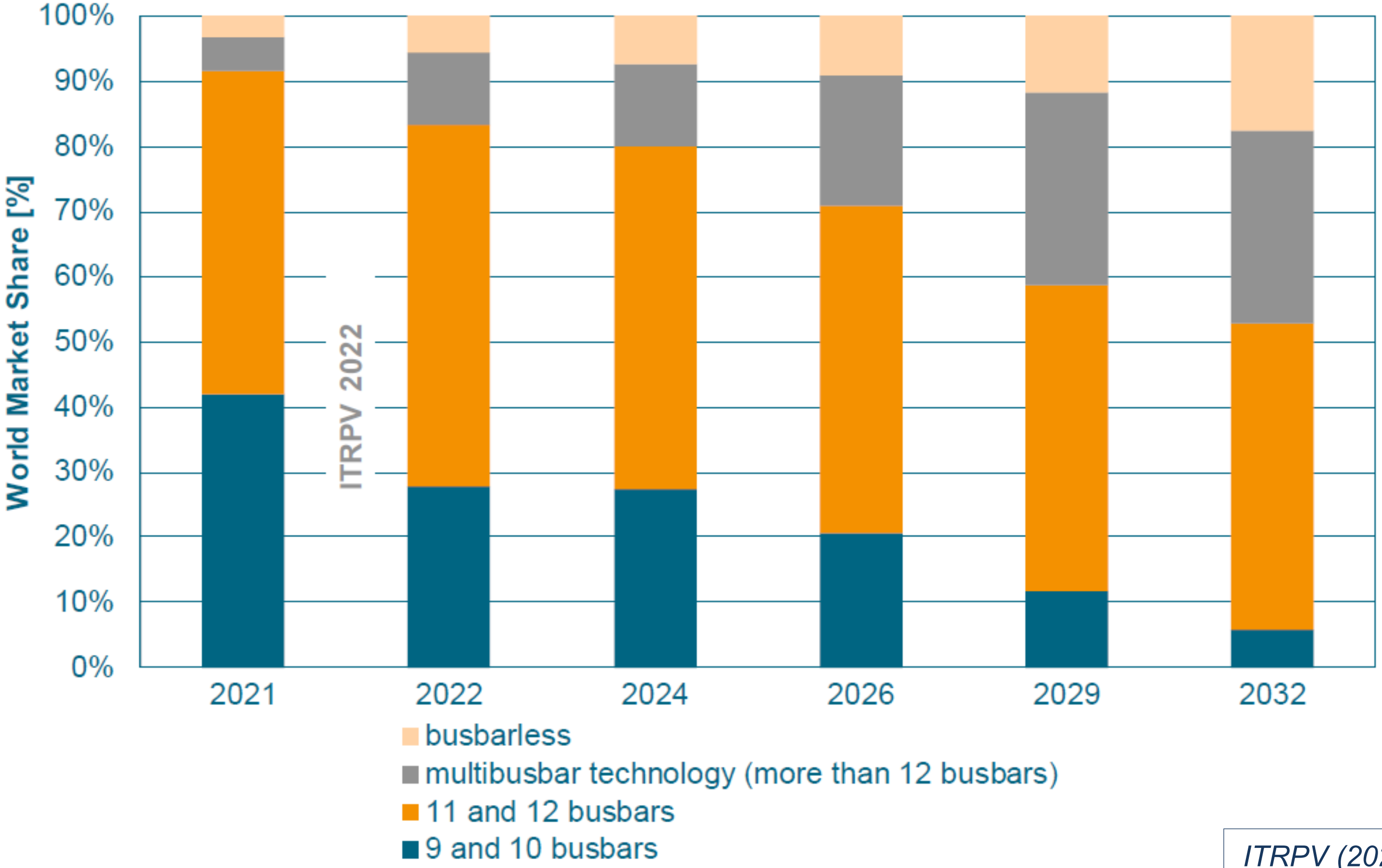
Parallel connection → currents add up

- Voltages of cells/strings need to be balanced

4. Solar Cell Interconnections

Busbar technology

A. Shah, Solar cells and modules (2020)
Chapter 9, A. Virtuani



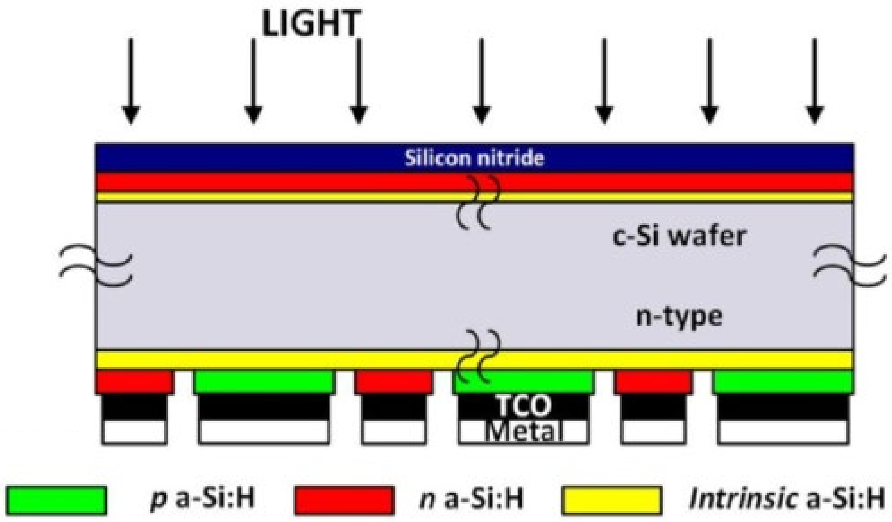
ITRPV (2022)

Clear trend for a higher amount of busbars or none at all

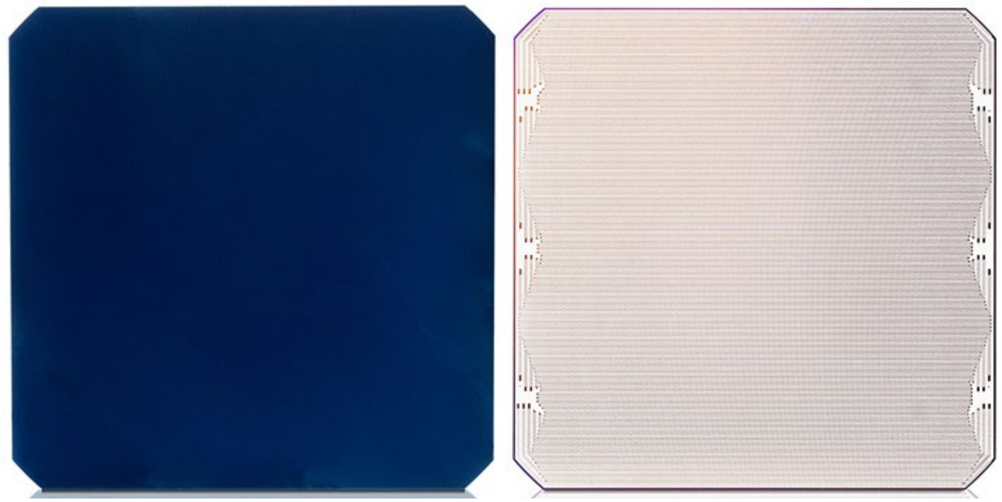
4. Solar Cell Interconnections

Interdigitated Back Contact (IBC) solar cells

No need of busbars



Y. Lee et al., Israel Journal of Chemistry (2015)



Advantages:

- More aesthetically appealing.
- Ideal candidate for Building Integrated PV (BIPV)

Challenges:

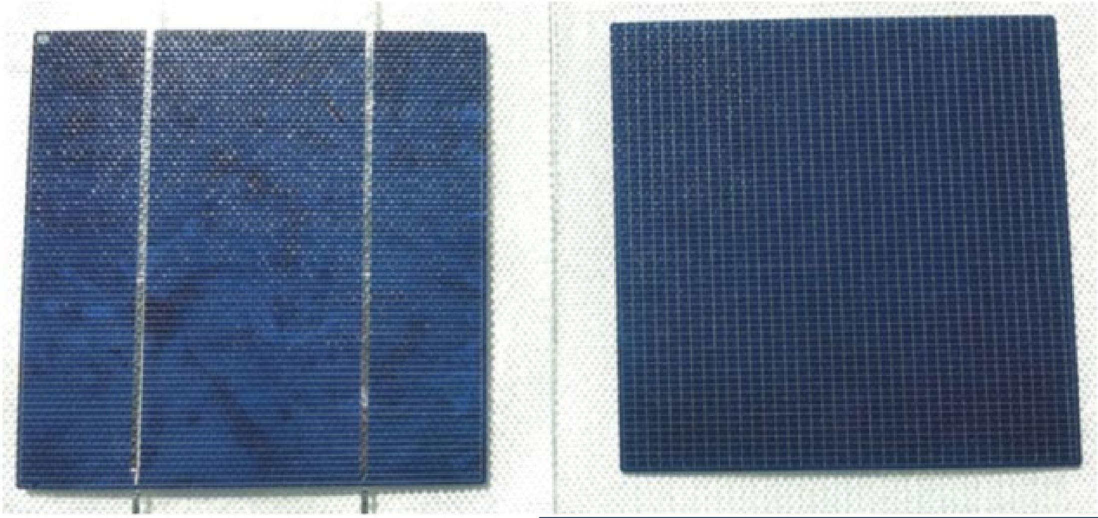
- Cost

4. Solar Cell Interconnections

Smart-wire technology (SWCT)

Multi-ribbon/multi-wire technology (MWT)

- Conventional ribbons and busbars replaced by **round wires with small diameter.**
- Ribbons (3-6) replaced by 20+ wires.
- ↑ ribbons → ↓ current distribution → wires with lower conductance
- ↓ silver consumption
- ↓ sensitivity of cell/module to cracks/breakages → ↑ durability



A. Shah, Solar cells and modules (2020) Chapter 9, A. Virtuani

4. Solar Cell Interconnections

Silicon Heterojunction solar cells

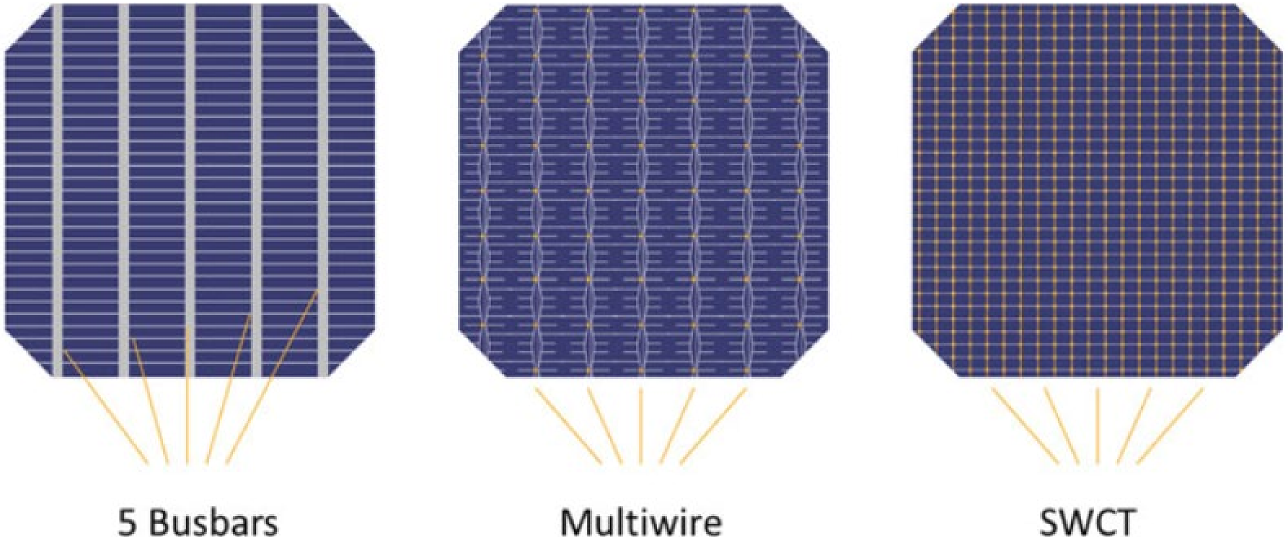
Conventional soldering processes require **high temperatures** → need to find a solution for SHJ

Low temperature process → ribbons are “soldered” by using:

- **Busbar technology** → not mainstream
- **Electrically Conductive Adhesives (ECA)**
- **MWT/SWCT.**

Challenges:

- Use of more silver.
- More expensive.
- Need to adapt stringers in commercial manufacturing processes.



A. Shah, Solar cells and modules (2020)

4. Solar Cell Interconnections

Why don't we install bare cells in the field?

PV modules are exposed to **external stressors**:

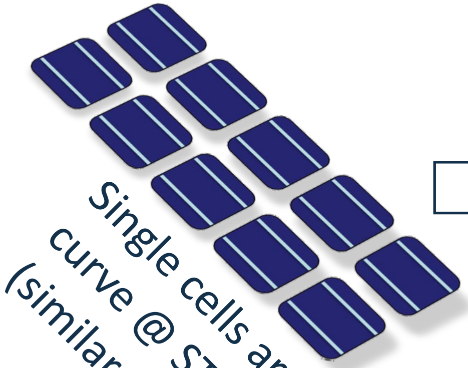
- **Temperature** variations due to performance and environment.
- **High humidity** conditions → rain, dew…
- **Mechanical stress** → wind, snow, hail..
- **Irradiance** → light, UV

Solar cells and interconnections are **encapsulated/packaged** to:

1. **Protect electrical circuit** from weathering.
2. Provide **structural stability** and protect **mechanical integrity.**
3. **Isolate electrical circuit** from environment (e.g. protect operators from electrical shocks).

1. PV Module Fabrication Steps

1. Single cells



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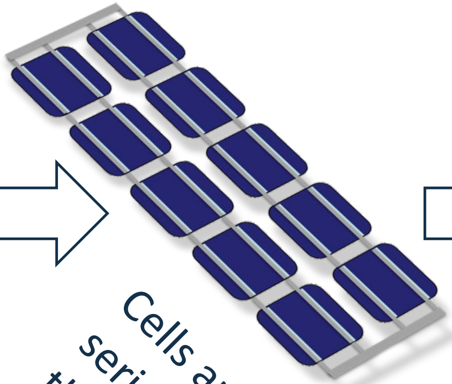

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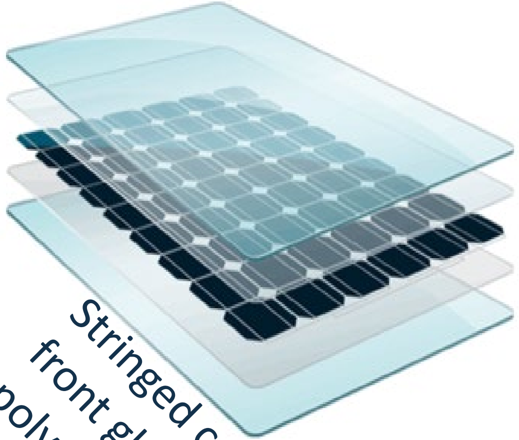

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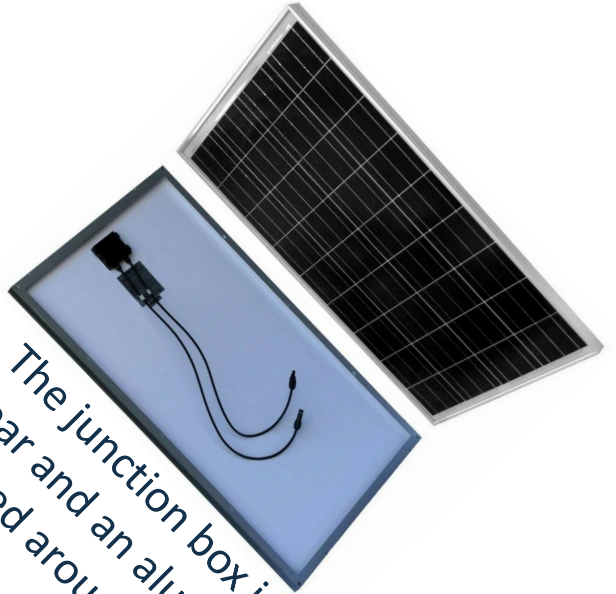


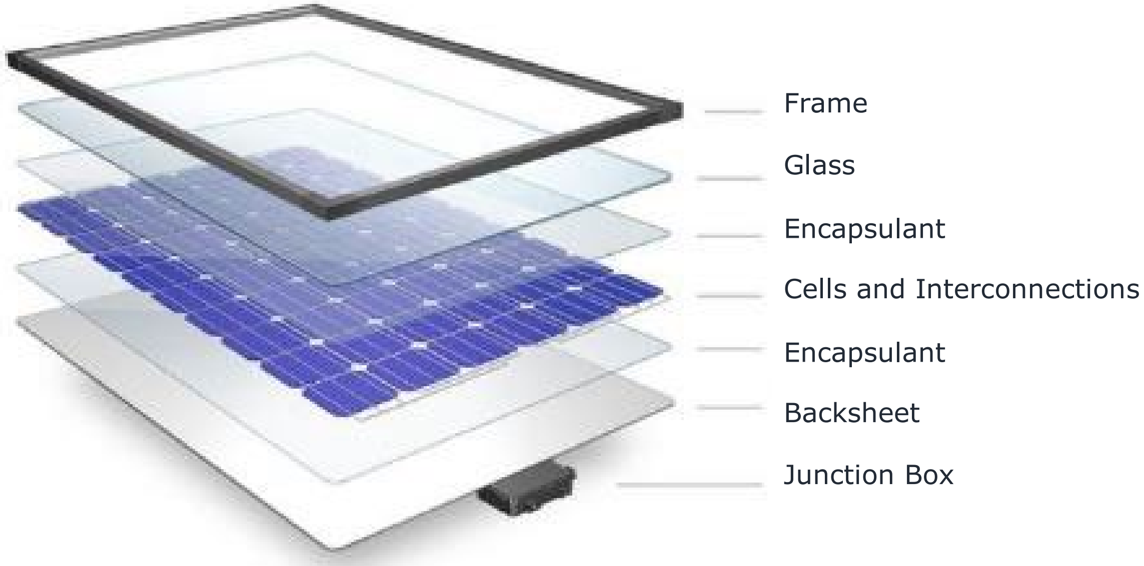
The junction box is glued at the rear and an aluminum frame is placed around the module.

*STC = Standard Test Conditions: 1000 W/m^2 @ 25°C.

5. Lamination Process & PV Module Materials

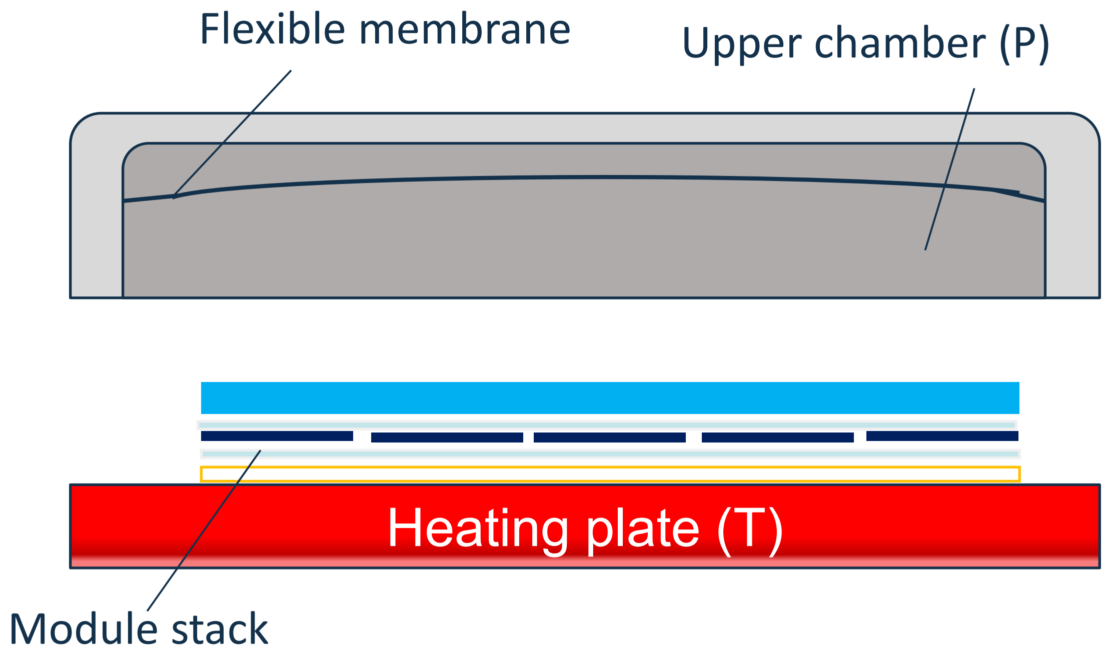
How to we bring all together?
…bringing cohesion to the full module sandwich?

The lamination process



Vacuum membrane laminator

5. Lamination Process & PV Module Materials



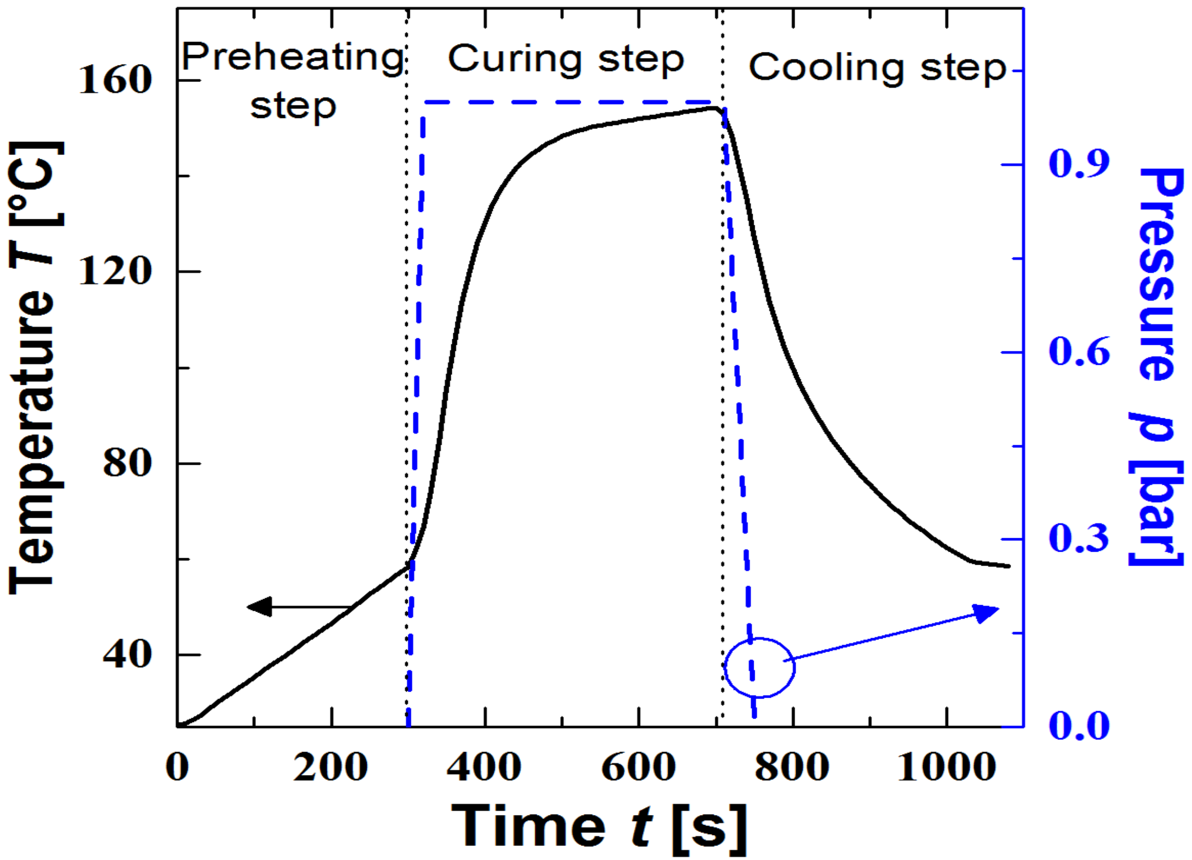
Lamination parameters:
- Temperature (T)
- Pressure (P)
- Time (t)

- **Lamination «recipe»:** combination of steps in the process.
  - Specific to a given encapsulant.
  - Critical in ensuring the modules' long-term performance.

- **Poor lamination process** → occurrence of failure modes in the field (e.g. delamination).

*In a good laminator the temperature uniformity of the heating plate is well controlled below ≤ 2°C.

5. Lamination Process & PV Module Materials



An encapsulation cycle can take **10-20 min**.

1. **Pre-heating step** (100s to 500s) → the upper and the lower chambers are evacuated.
   - **Removal of the air** (de-gas) to minimize the **risk of voids formation**.

   The softening encapsulant temperature (60-70 °C) is reached.

2. **Curing step** (300s to 900s) → the module layups lie on the **heating plate directly**. A
   - Enhances the adhesion between the encapsulant and neighboring components.

   The **gel content** (crosslink degree) at the end of the process must be >80%.

3. **Cooling step** → the encapsulated PV modules cool to room temperature.

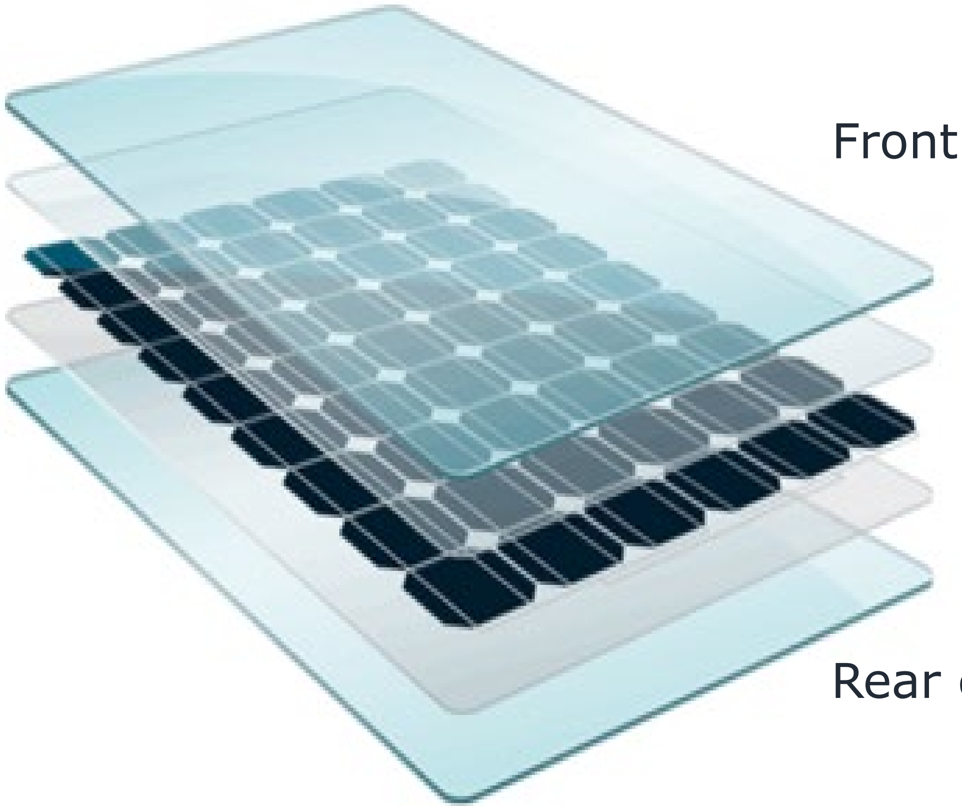
Open the Black Box: Understanding the Encapsulation Process of Photovoltaic Modules, 2013

5. Lamination Process & PV Module Materials

Module structure

«Sandwich» or module stack:

Fragile silicon solar cells need to be protected in order to operate outdoors for 25 years (at least).



Front cover → 3.2 mm-thick glass

Encapsulant, Stringed cells, Encapsulant → Provide the adhesion between components

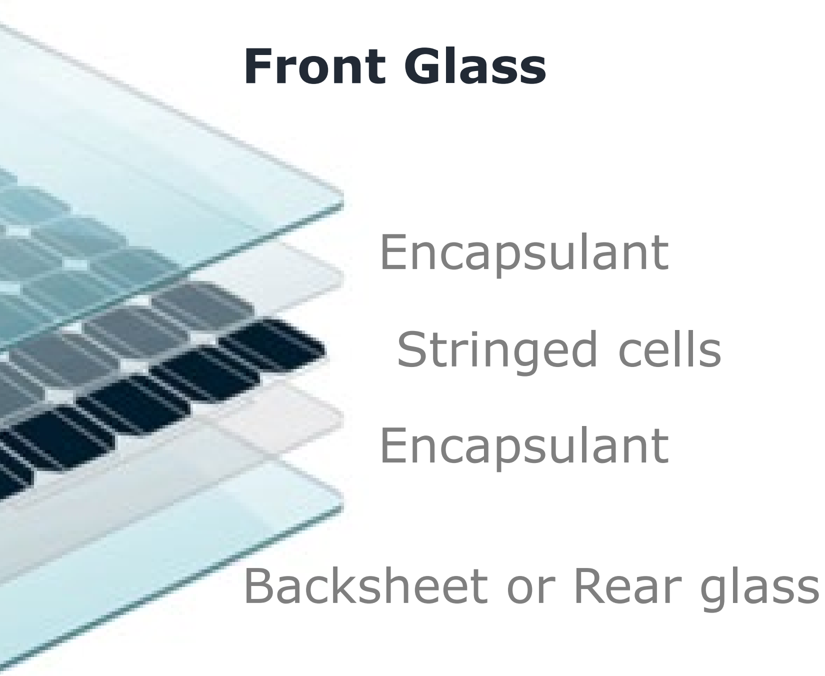
Rear cover → Backsheet (or polymeric foil) or a second glass

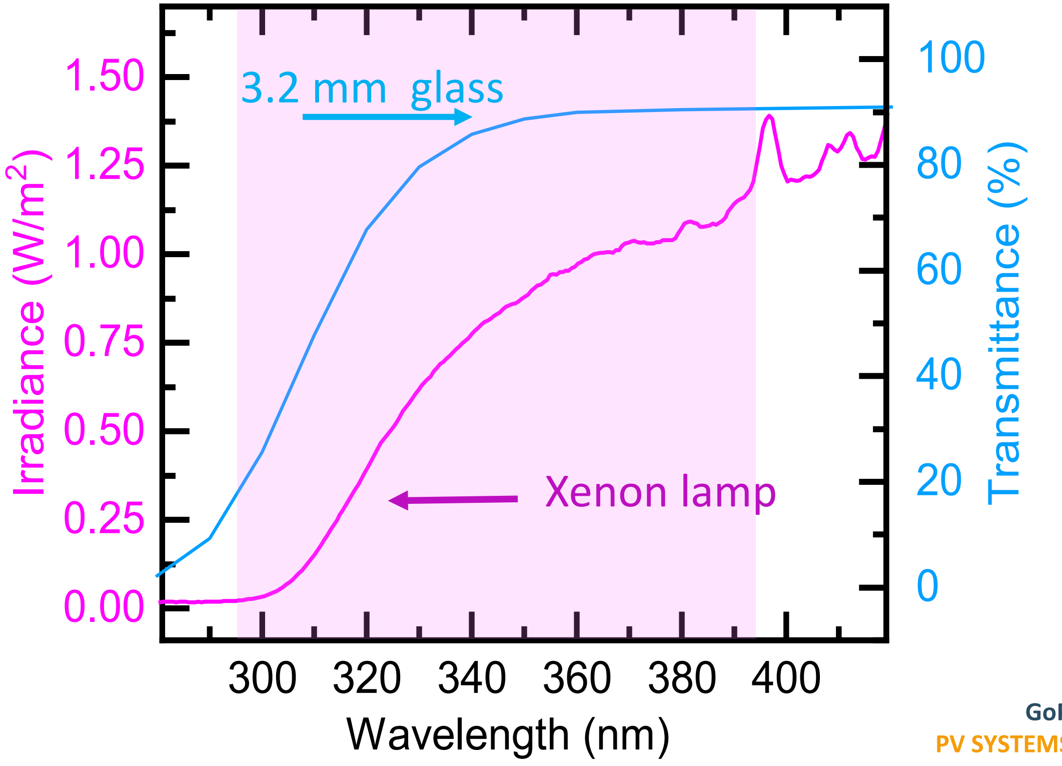
Modules generally have 60 or 72 cells (depending on applications).
Can be smaller for specific apllications: boats, telcos, etc.

Glass

Tempered glass about **3.2 mm**-thick is used as a front cover.

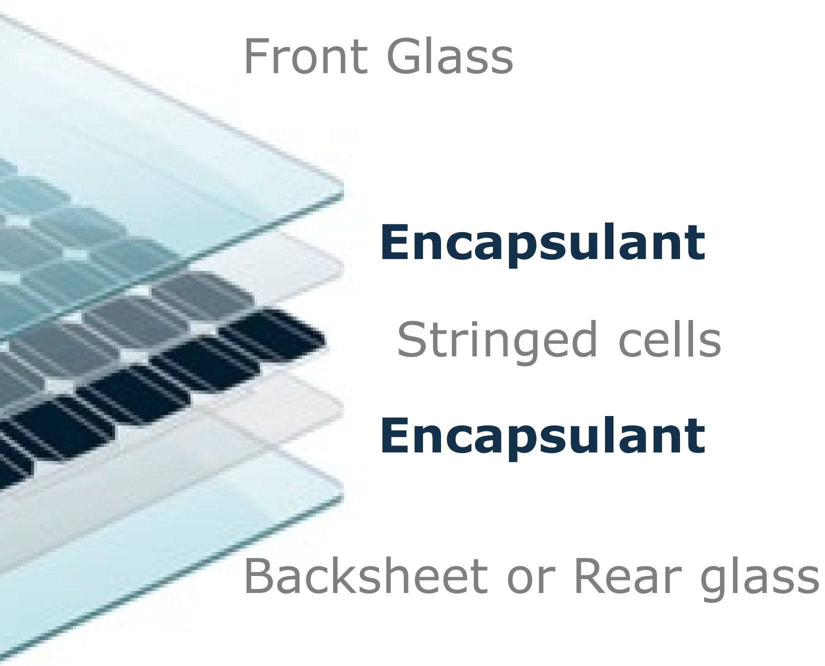
- Goal ⟶ provide **mechanical strength**.
- **Optical improvements** ⟶ texturized and/or with an antireflection coating.





5. Lamination Process & PV Module Materials

Encapsulant



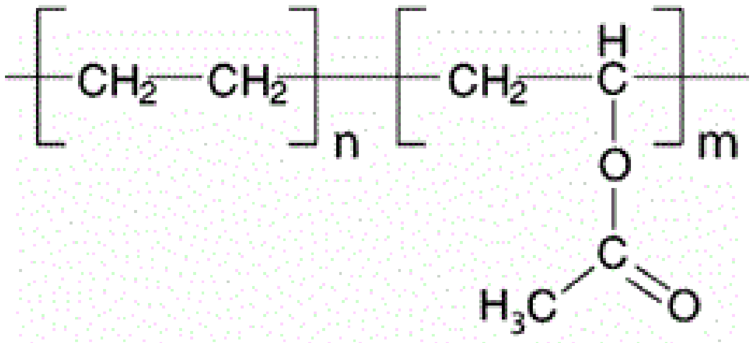
Main functions:

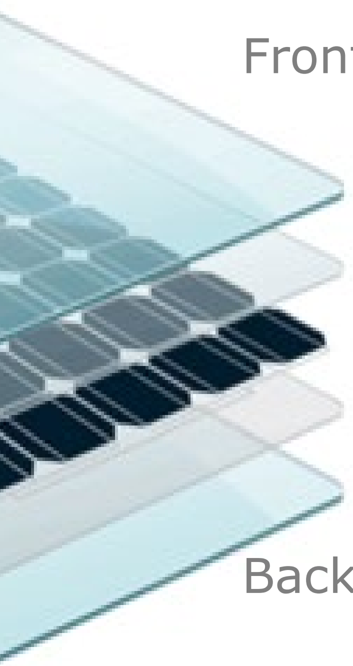
- Provide **adhesion between components** (cells-front glass, cells-backsheet, front glass-backsheet).
- **Physical insulation** – protect from weather (UV, rain, humidity, etc.);
- **Electrical insulation** – keep high voltage away from people and keep current from flowing out of the array circuit to ground;
- **Good optical properties** – couple as much incoming light as possible into the cells;

5. Lamination Process & PV Module Materials

Encapsulant

Ethylene Vinyl Acetate copolymer (EVA) has the best properties – cost ratio.





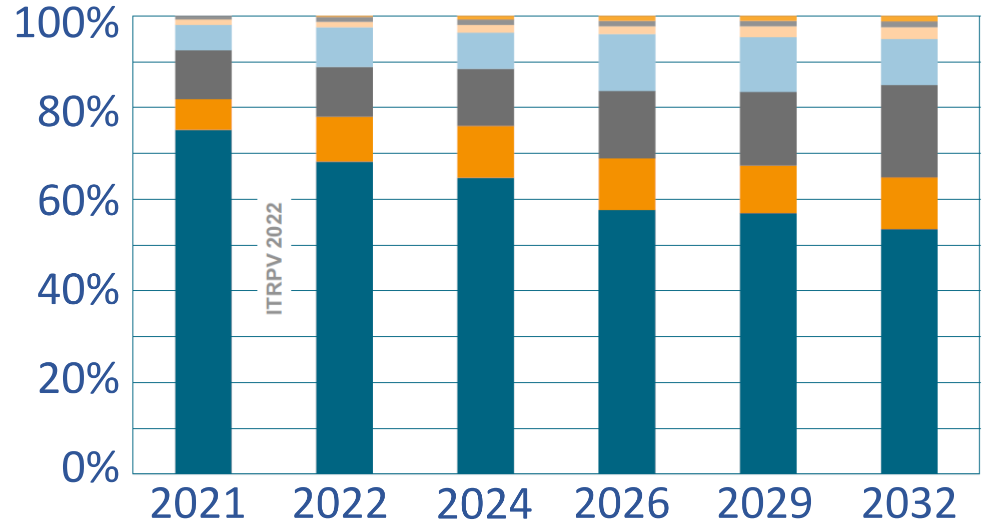
Multiple additives are present in the commercial EVA rolls:

- **Curing agent** → cross-linking reaction during lamination.
- **UV absorbers**.
- **UV stabilizers/anti-oxidants** → decompose curing agent residues;
- **Adhesion promoters** → increase adhesion between EVA and glass.

5. Lamination Process & PV Module Materials

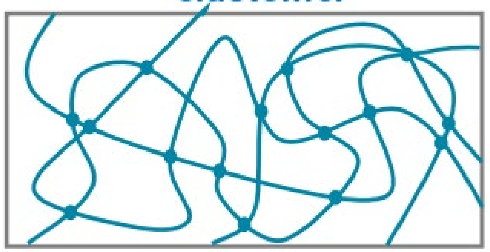
Encapsulant alternatives to EVA

Encapsulants share market



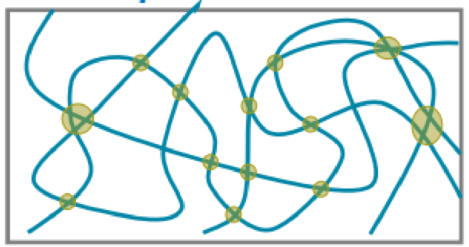
ITRPV (2022)

Chemically cross-linked elastomer



Irreversible covalent bondings

Physically cross-linked thermoplastic elastomer



(Thermo)-reversible bondings (Ion and hydrogen bonds, crystallites)

Cross-linked Polyolefines (POE)

- *Replacement of vinyl acetate group*
- *No formation of acetic acid*
- *Cross-linking necessary*

Examples: STR POE Encapsulant, 3M Solar Encapsulant Film PO8100N, Mitsui ASCE,

Thermoplastic Polyolefines (TPO)

- *Replacement of vinyl acetate group*
- *No formation of acetic acid*
- *No cross-linking*

Examples: Borealis Quentys, DOW Engage, DNP Solar encapsulants, DuPont Ionomers etc.

PCCL Polymer Competence Center Leoben

- Development of alternative **polyolefines.**
- **EVA** will still remain the **dominant encapsulant** (…for a while).

International Technology Roadmap for Photovoltaic – ITRPV 2018 *and* G. Oreski, "Encapsulant Innovations for replacement of EVA", EUPVSEC 2019.

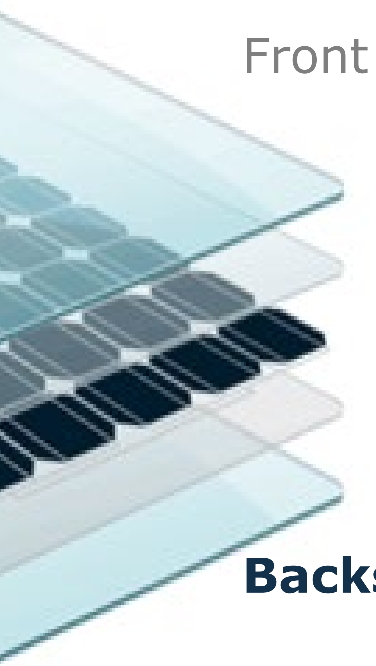
5. Lamination Process & PV Module Materials

Polymeric Backsheet

Most PV modules → **composite polymer sheet as backsheet**.

- Multi-stack structure of **three layers** with an overall thickness of 280-400 μm.

T-P-T backsheet



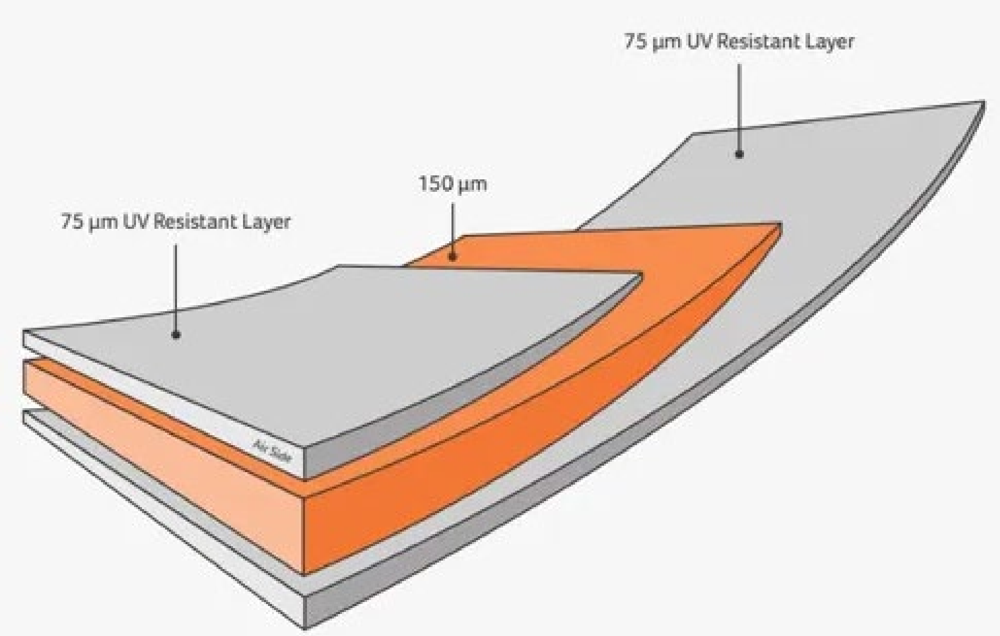
Front Glass

Encapsulant

Stringed cells

Encapsulant

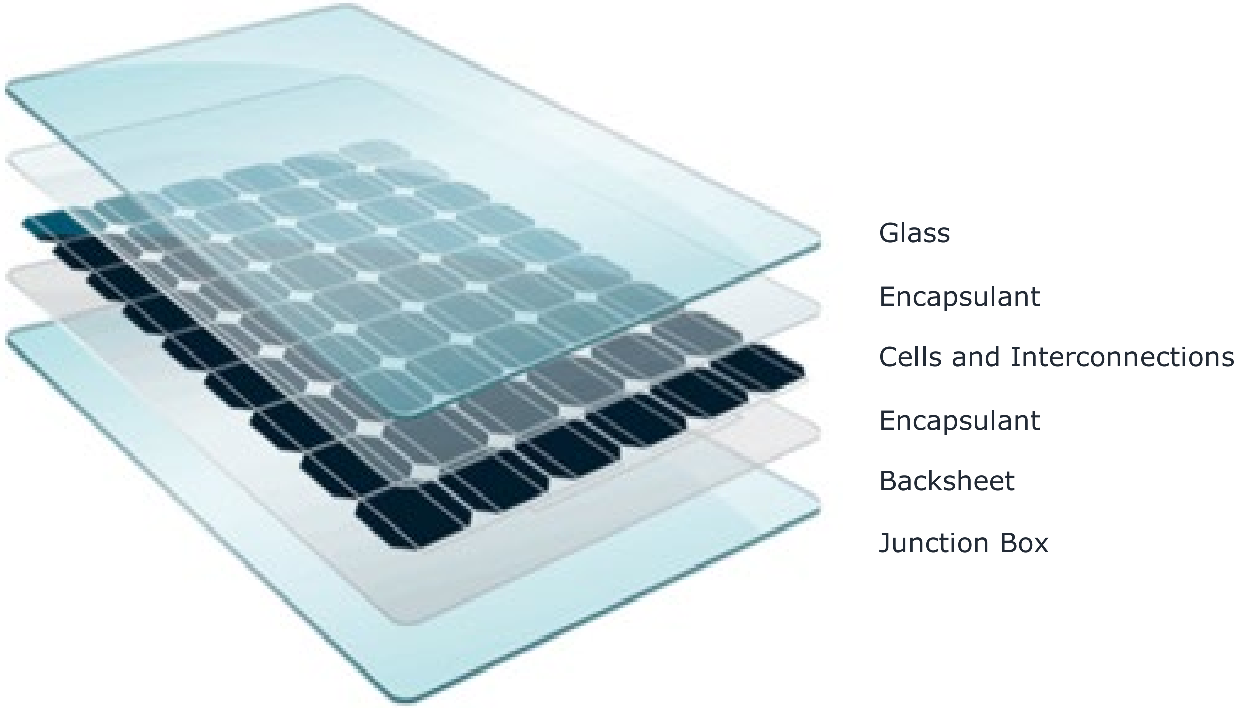
Backsheet or Rear glass



PVF (polyvinyl-fluoride) - **Tedlar**®
→ **protects** the internal circuit (and PET layer) from weathering agents

PET (Polyethylene terephthalate)
→ **isolates** the module electrically and provides **mechanical stability**.

Modules – Innovative concepts



Innovative module concepts target:

1. Increased module performance by reducing Cell-to-Module losses.
2. Increased energy-yield.
3. Increased reliability.

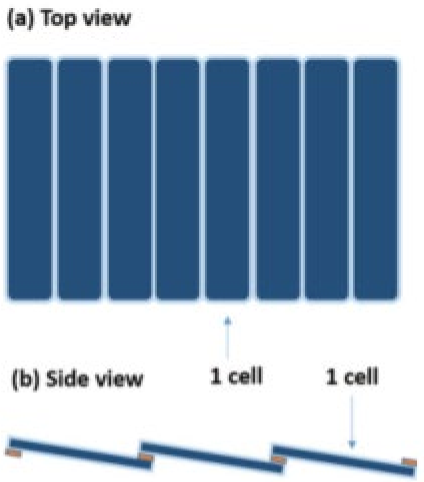
Modules – Innovative concepts

1. **Increased module performance**
2. Increased energy-yield
3. Increased reliability

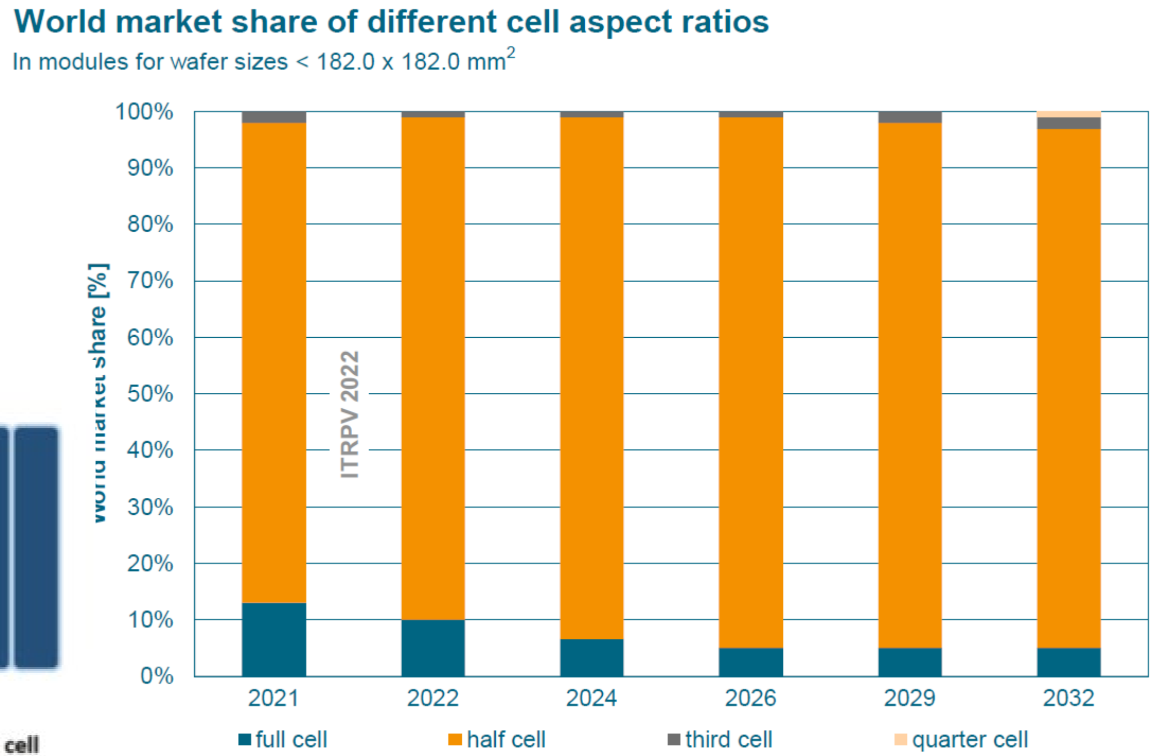
Half-cell modules → ↓ cell interconnection losses

Shingled solar cells → ↓ inactive space

Light capturing ribbons → ↓ shadding losses



A. Shah, Solar cells and modules (2020) Chapter 9, A. Virtuani



ITRPV (2022)

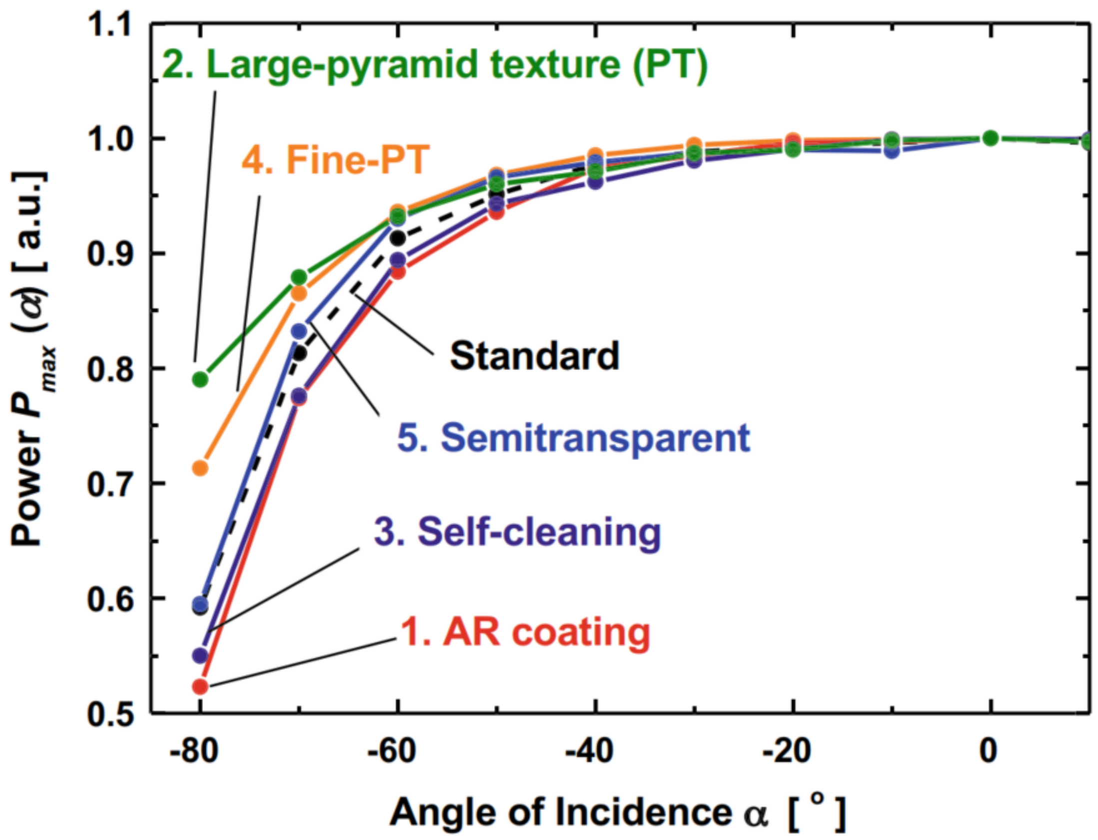
5. Lamination Process & PV Module Materials

Modules – Innovative concepts

1. Increased module performance
2. **Increased energy-yield**
3. Increased reliability

Anti-reflection coatings (ARC) on front surface of front glass → ↓ reflection at front glass/air interface

Textured glass → ↑ collection of light at low angles



A. Shah, Solar cells and modules (2020)
Chapter 9, A. Virtuani

5. Lamination Process & PV Module Materials

Modules – Innovative concepts

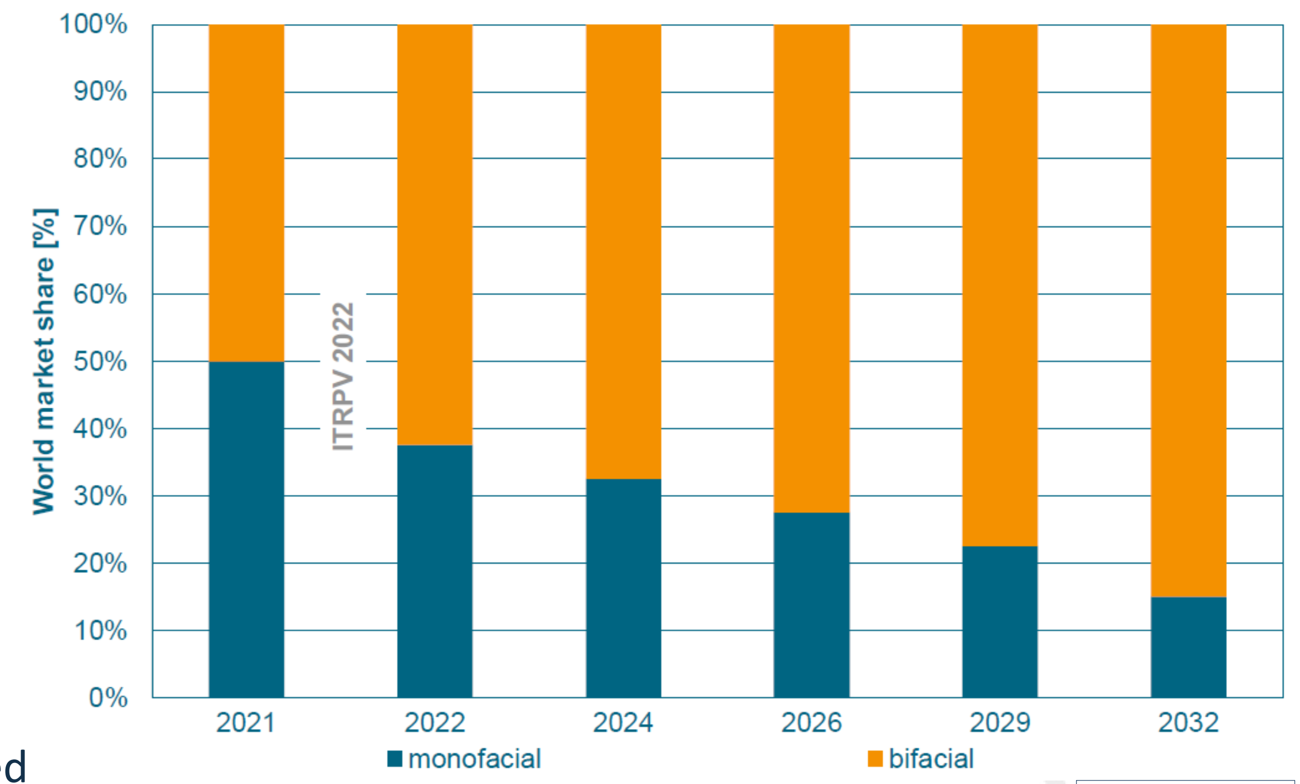
1. Increased module performance
2. **Increased energy-yield**
3. Increased reliability

Anti-reflection coatings (ARC) on front surface of front glass → ↓ reflection at front glass/air interface

Textured glass → ↑ collection of light at low angles

Bifacial cells/modules → collection of sunlight reflected by ground

World market share of monofacial and bifacial cells



ITRPV (2022)

5. Lamination Process & PV Module Materials

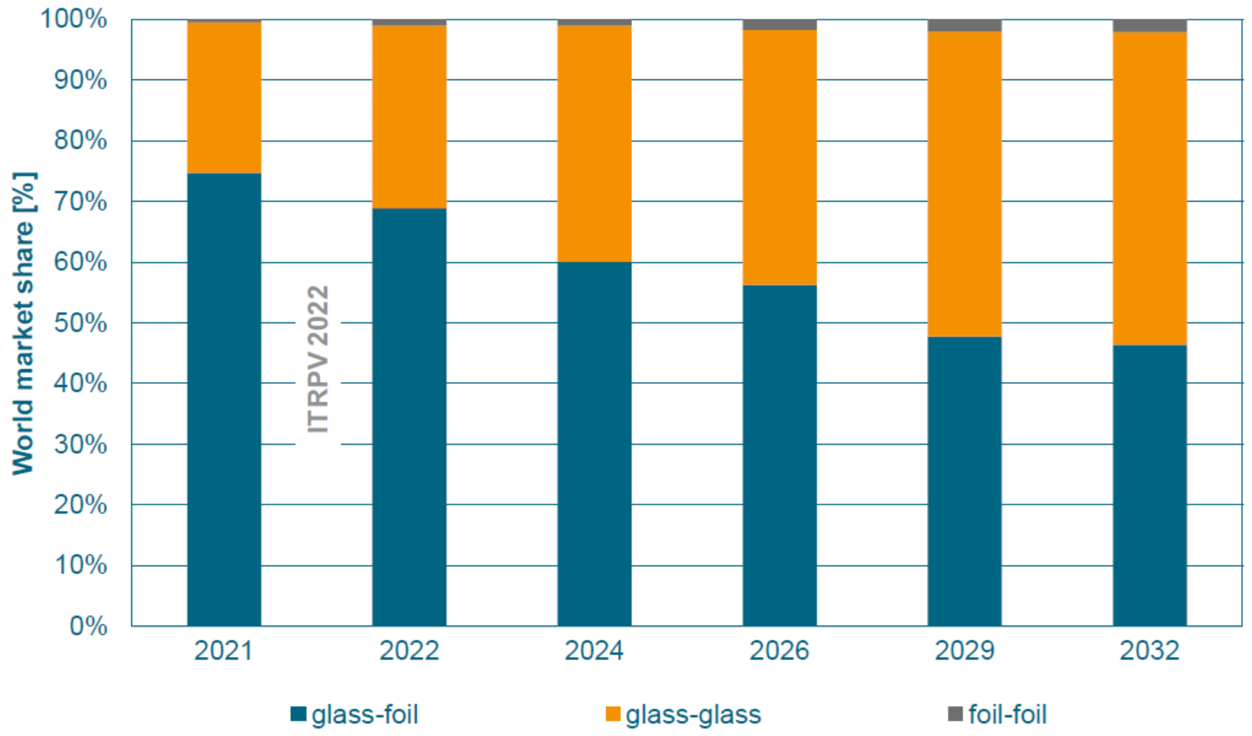
Modules – Innovative concepts

1. Increased module performance
2. Increased energy-yield
3. **Increased reliability**

Glass/glass modules → additional protection in harsh environments (snow, hail or wind loads).

SWCT and MWT → minimize the impact of cracks on the performance.

World market share of different front and back cover materials



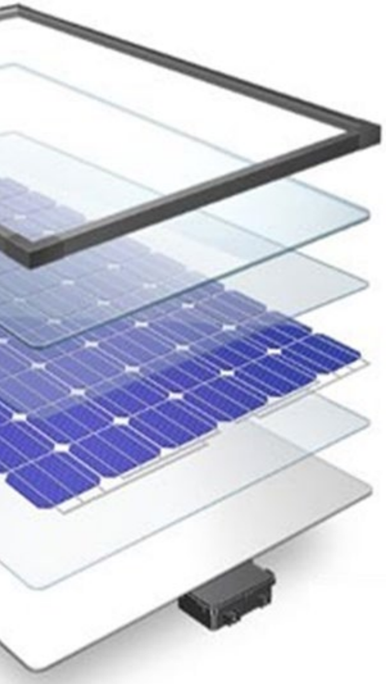
ITRPV (2022)

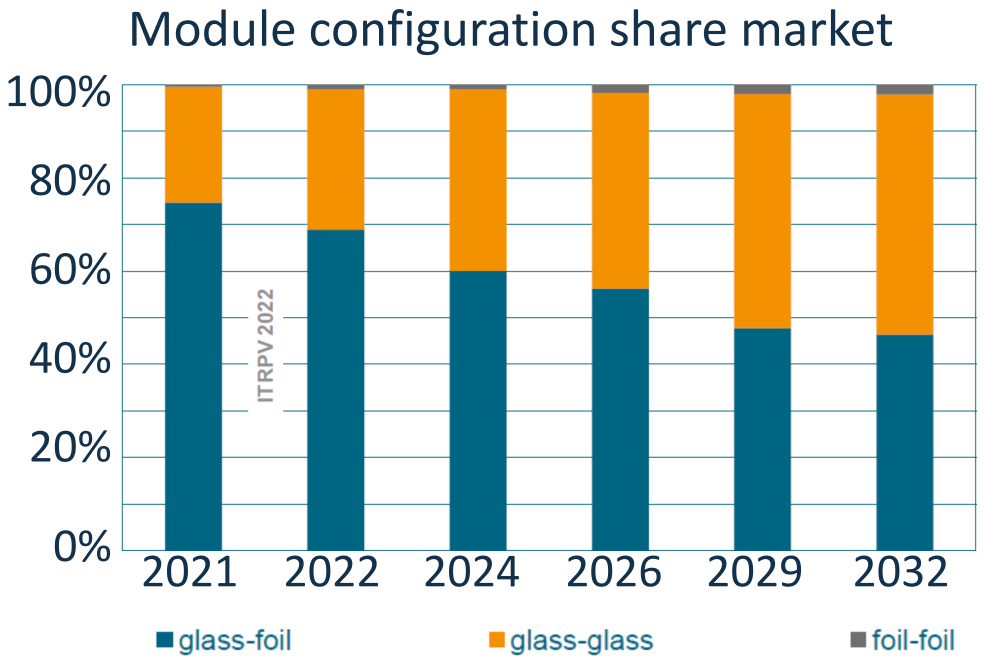
5. Lamination Process & PV Module Materials

Backsheet vs. Rear-glass

G-BS advantages:

- Cheaper.
- Lighter.
- Possibility to modify the «breathability» of the BS.

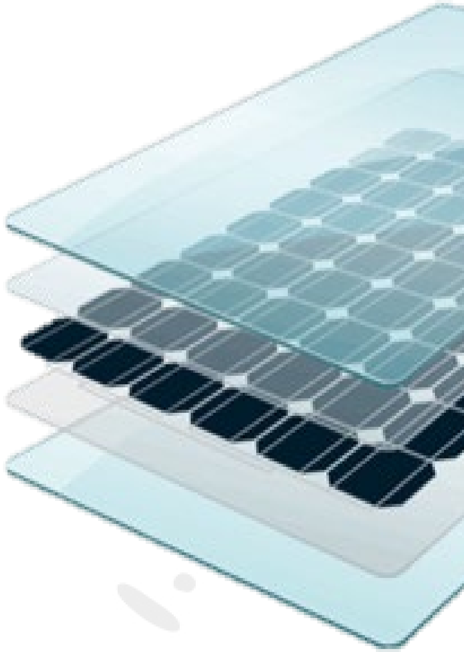




ITRPV (2022)

G-G advantages:

- Possibility to use bifacial cells.
- More rigidity (frameless).
- High insulation.
- 30 years performance warranty.



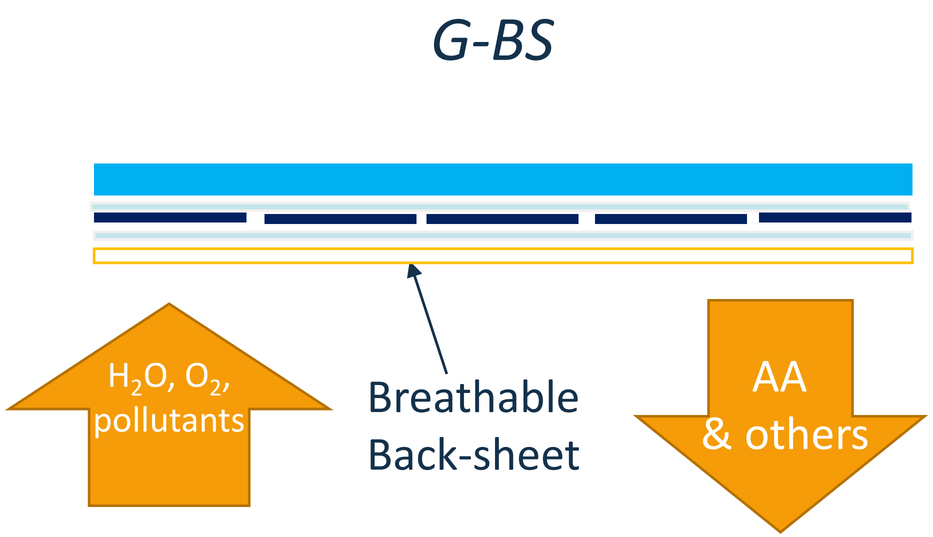
Bifacial modules (increase PV system's energy-yield) – are starting to enter the market.

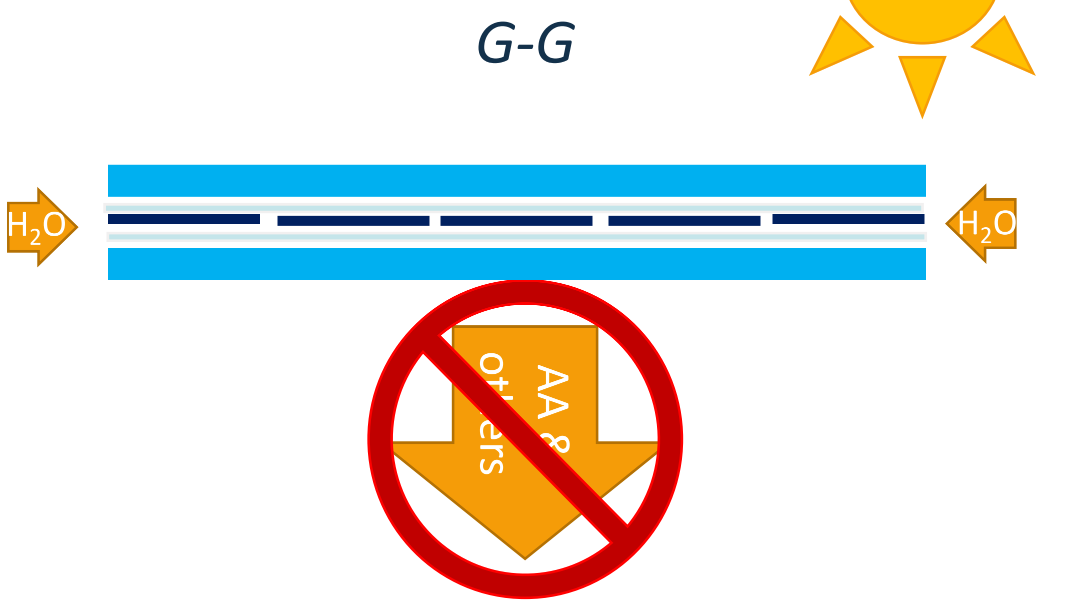
This is the main boost for the adoption of glass/glass structures.

International Technology Roadmap for Photovoltaic – ITRPV 2018.

5. Lamination Process & PV Module Materials

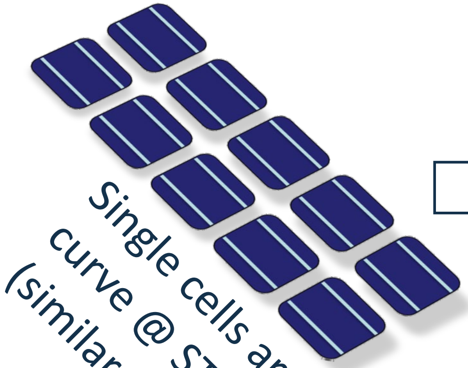
Backsheet vs. Rear-glass





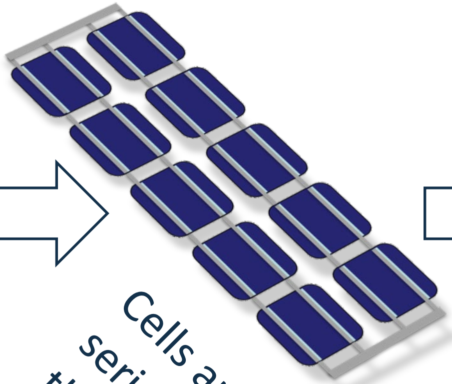
1. PV Module Fabrication Steps

1. Single cells



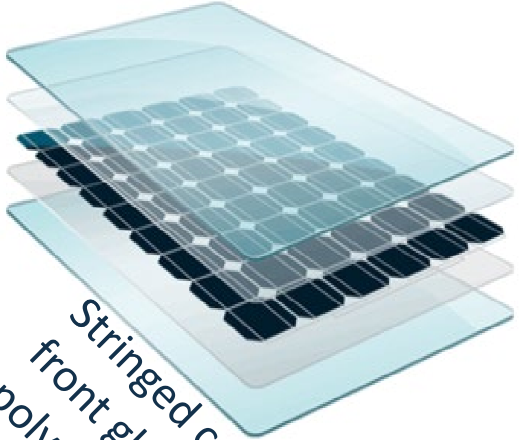
Single cells are tested (I-V curve @ STC*) and sorted (similar current/power).

2. Stringing



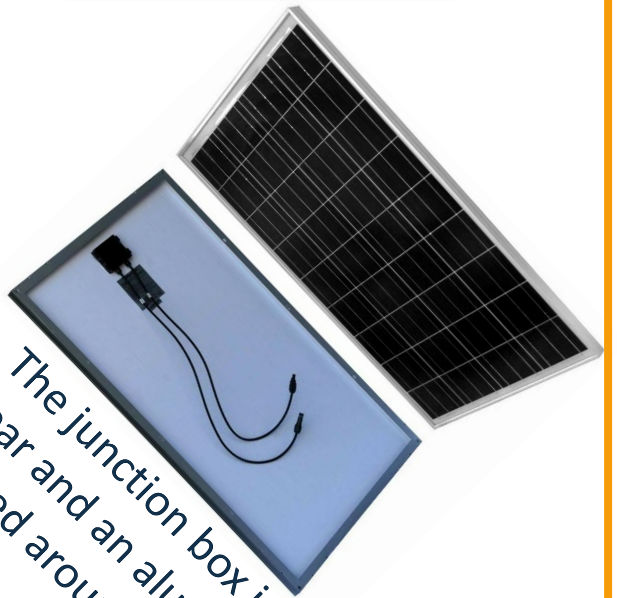
Cells are connected (in series or parallel) to match the module power output.

3. Lamination



Stringed cells are protected with a front glass and a rear cover. Two polymeric foils (encapsulant) provide the adhesion between components.

4. Junction box

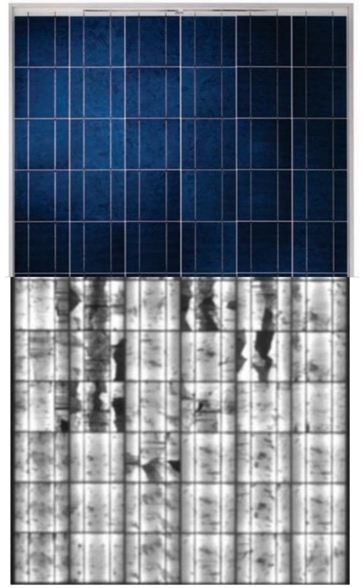


The junction box is glued at the rear and an aluminum frame is placed around the module.

*STC = Standard Test Conditions: 1000 W/m^2 @ 25°C.

1. PV Module Fabrication Steps – Post Production

5. Module check



Module power output:
- I-V curve @ STC.

Major defects:
- Visual inspection.
- Electroluminescent images.

6. Product certification**

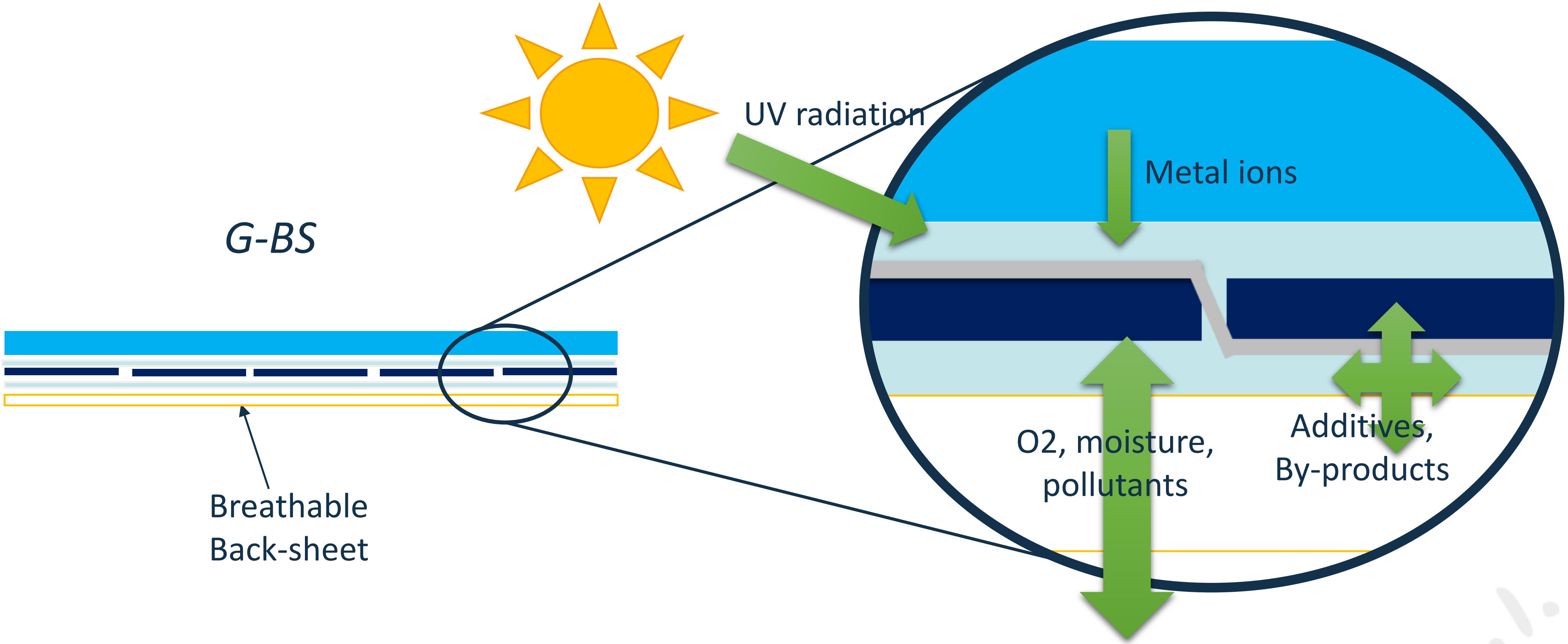
Pass a series of qualification tests** (i.e. IEC61215).

** It is a liability of the manufacturer.

7. Marketing & Installation

6. Some Degradation Mechanisms

Materials interactions under operating conditions

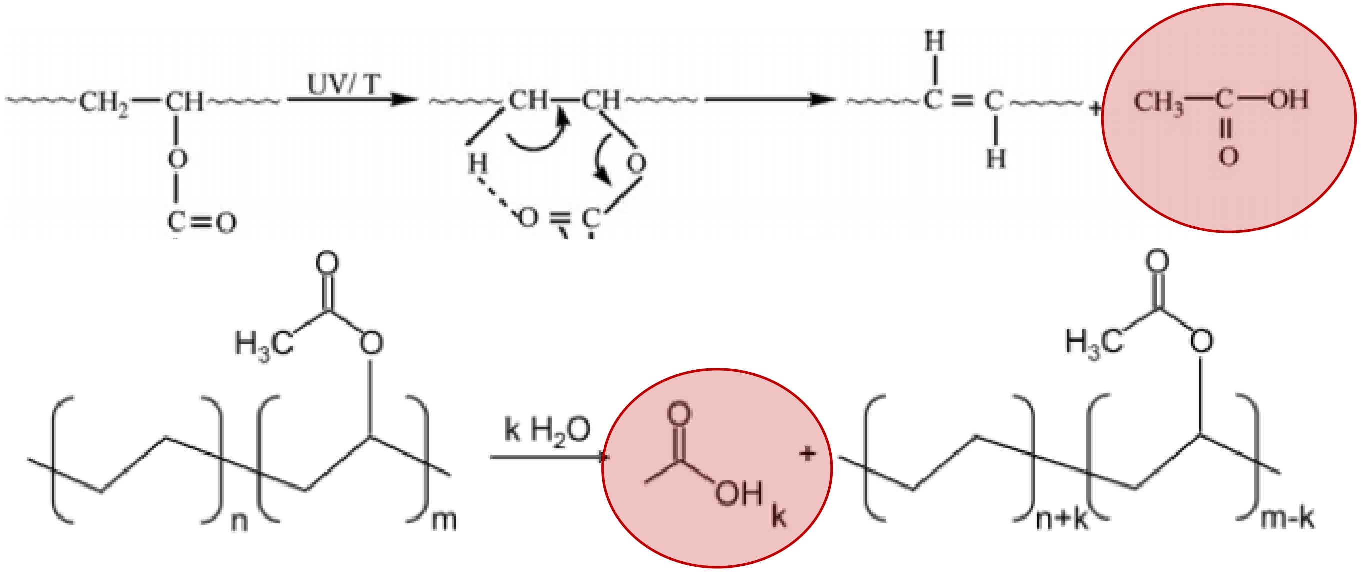


Multiple interactions between different components and outdoor stresses may lead to unwanted degradation reactions.

6. Some Degradation Mechanisms

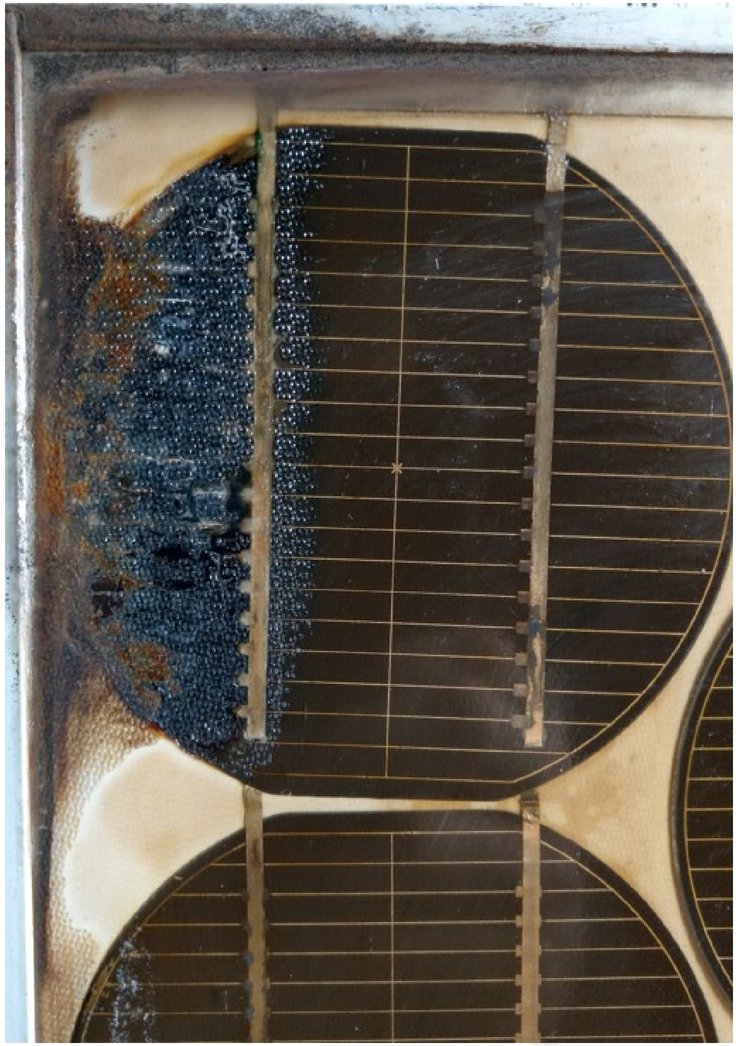
EVA degradation mechanism

- Temperature, UV radiation and humidity ⇒ **acetic acid** generation.



It reduces locally the pH inside the module → metallic corrosion.

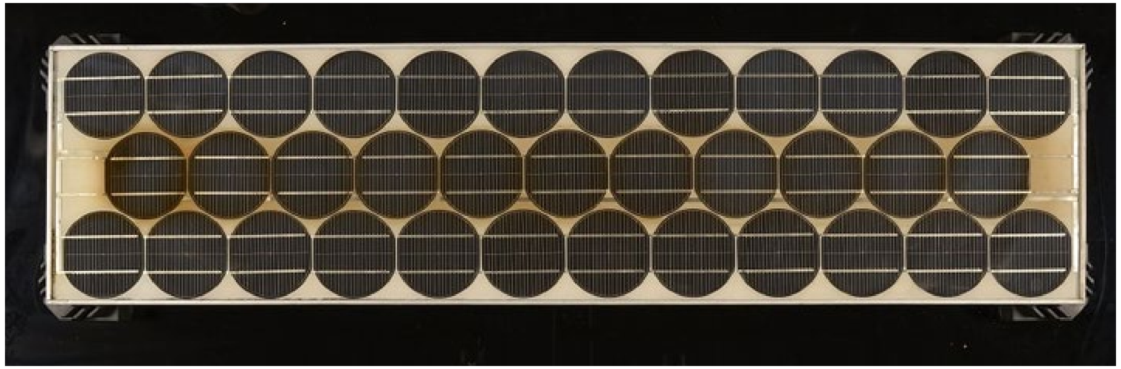
The main consequeces on the module performance are:
- Incresase of the electrical resistance ↑ **Rs**;
- Reduction of the fill factor ↓ **FF**.



De Oliveira, M.C.C., et al. in *Renewable and Sustainable Energy Reviews*, 2017.

6. Some Degradation Mechanisms

EVA degradation mechanism



- A non optimised lamination parameters
  → residue of cross-linking precursor
  → formation of **chromophores**.

- Additives degradation during exposure (i.e. UV absorbers)

EVA YELLOWING

- Humidity ingress in the module causes a loss of adhesion → **DELAMINATION**

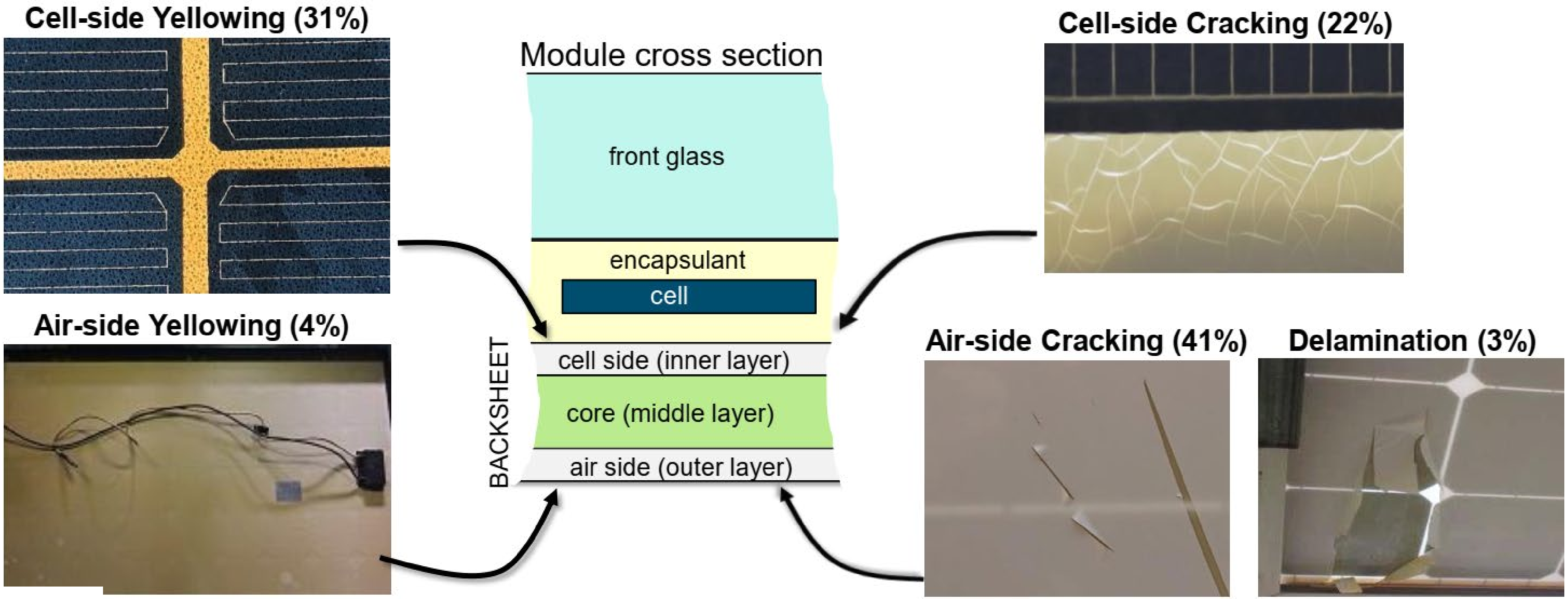
The main consequeces on the module performance:

- Reduction of transmittance → ↓ **Isc**

De Oliveira, M.C.C., et al. in *Renewable and Sustainable Energy Reviews*, 2017.

6. Some Degradation Mechanisms

Backsheet degradation mechanism



DUPONT

Cracking and delamination can compromise electrical insulation of the module

Yellowing can be a precursor to mechanical degradation and embrittlement of many backsheet polymers

J. Tracy, Durability of Packaging Material in Globally Fielded PV Modules, 2019 .

7. Manufacturing of Reliable Silicon Heterojunction Glass/Glass Modules

Lessons learnt

Increased reliability when encapsulated in a good bill of materials (BOM).

Sensitivity to	Prevention
Water ingress & diffusion	Impermeable module structure → **edge sealant (ES)**
High voltages – Potential Induced Degradation (**PID**)	High-volume resistivity encapsulants → **POEs, ionomer**
UV exposure	**Non UV-transparent** encapsulants or with cut-off > 353 nm

GLOBAL OPTIMIZATION OF INTEGRATED PHOTOVOLTAIC SYSTEM FOR LOW ELECTRICITY COST

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792059

Thank you for your attention!

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