PV modules, design and fabrication

34553: Applied Photovoltaics

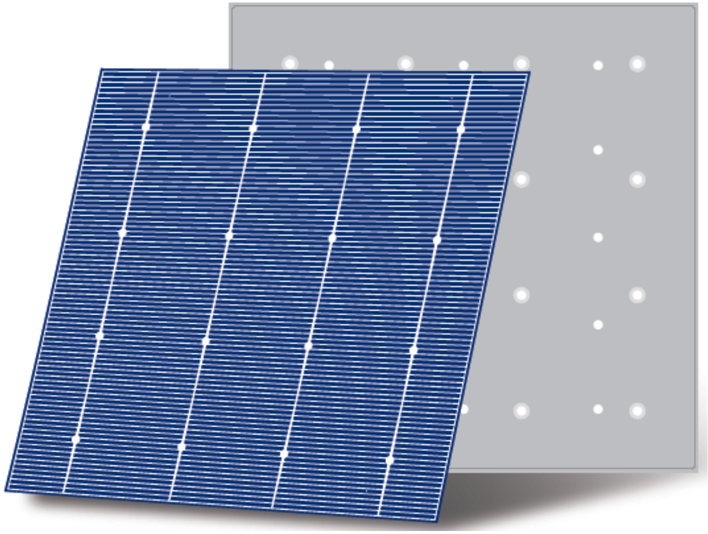
Cell interconnection and modules

Content

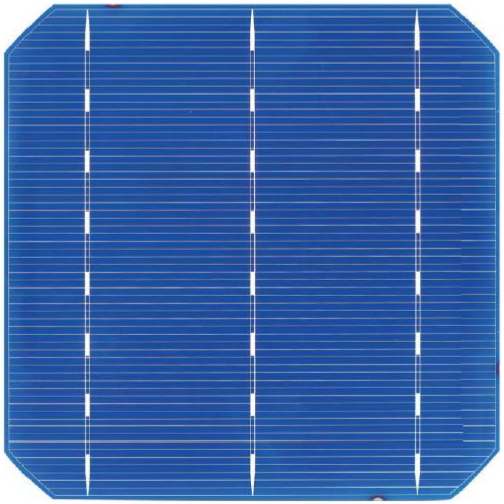
1. **PV module construction**
2. **Module materials**
3. **PV module fabrication**

Building blocks - Solar Cells

- **<u>Crystalline Cells facts:</u>**
- Electrical
  - P-type
    - Frontside minus terminal
    - Backside plus terminal
  - H-Pattern – (2-10 busbars and fingers)
  - Efficiency 17.5 – 22%
  - (~0.55 V and 8-9 amps (6”))
  - Mono typical 0.5-1% abs higher
- Cell Prices 2020 (gate factory):
  - ~0.13 USD/WP
- Mechanical
  - Fragile
  - Sizes: 5 ”, 6 “ and new larger sizes



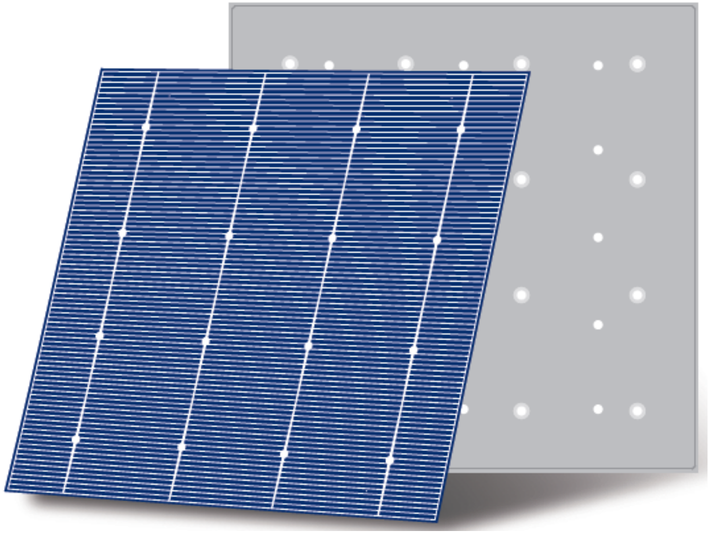
MWT Cell



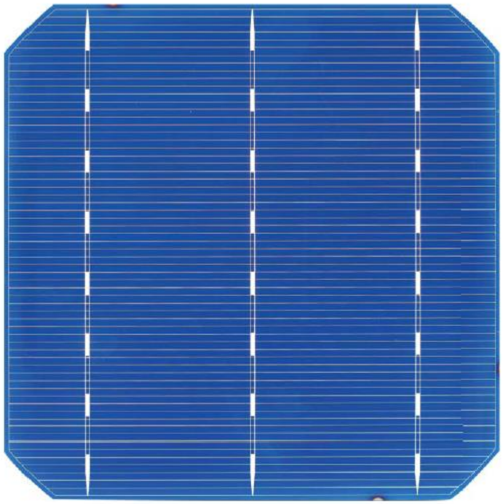
3 BB Cell

Building blocks - Solar Cells

- **<u>Crystalline Cells facts:</u>**
- Electrical
  - (~0.5 V and 8-9 amps (6”))
- Mechanical
  - Fragile
- Challenges
  - 0.5 V not very useful
  - Fragility
  - Open conductors
  - Not very useful for outdoor operations
- Encapsulation needed.

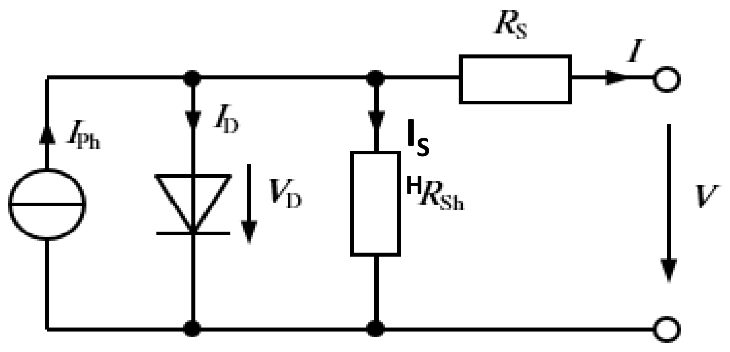


MWT Cell



3 BB Cell

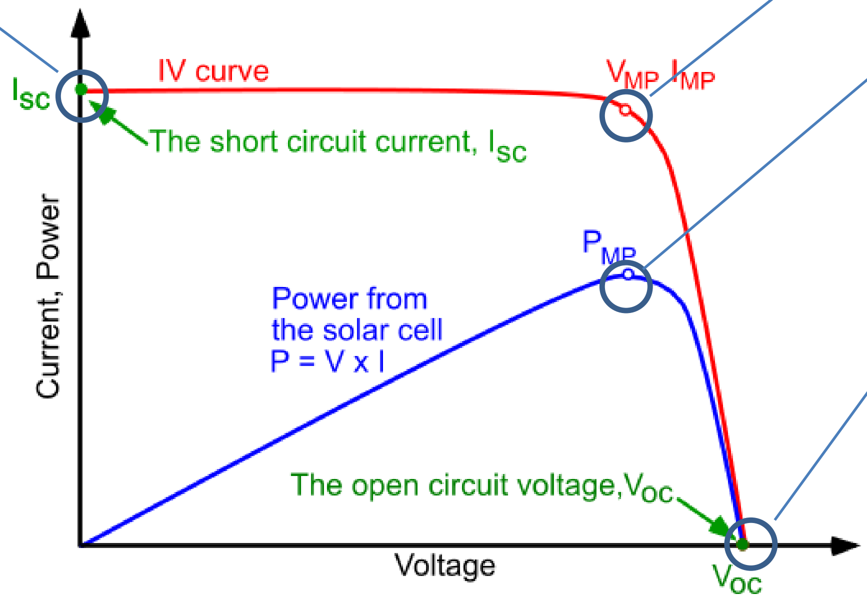
Important Electrical parameters



Short circuit Current
Isc

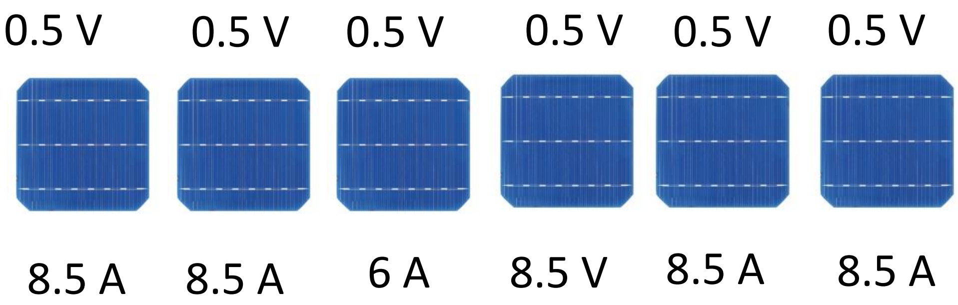
Maximum powerpoint
Vmp, Imp,Pmp

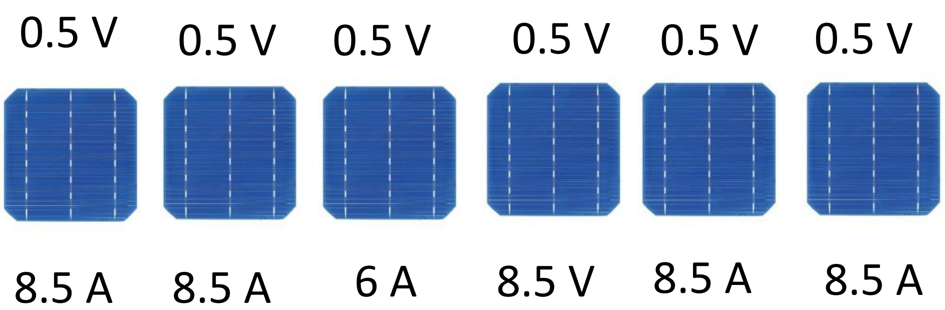
Open circuit Voltage
Voc



Serial /parallel

What is the MPP output of below strings, and which is serial?

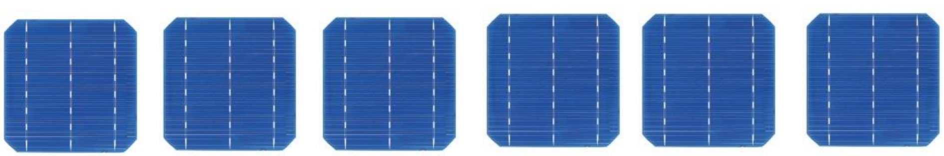




Serial /parallel

What is the MPP output of below strings, and which is serial?

Serial:
Voltages Adds
This cell is limiting:
So (5*0.55+0.5V)*6 A= 19.5 W



Parallel:
Currents add:
So 0.5V*(6+5*8.5)A=0.5V*50A=
24.25 W

Cells to Module Objectives

Efficient Power production for at least 25 years:

- Good light coupling to the cell
- Low resistive interconnection
- Safe operation
- Withstand weathering
- Cheap commodity

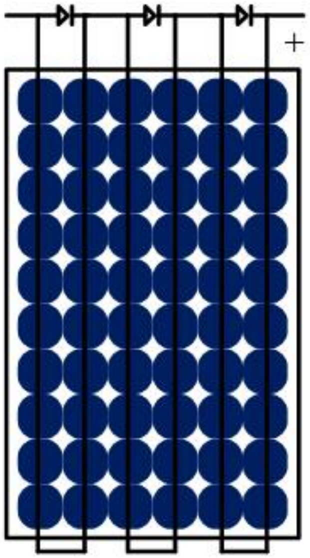
IEC 61215

"Terrestrial photovoltaic (PV) Modules - Design qualification and type approval" developed to qualify modules

Typical PV module Layout

- **<u>Module</u>**
- 48, 54, **60**, 72 Cells Connected in series - typical
- Divided into **3 strings**
- 1 Bypass diode paralleled in each string.
- 2 outlets from the junction box
- Sorting in Bins

- 60 Cell module
- Weight ~ 17-19 kg
- Dimensions 1.7m *1m*40 mm
- Electrical:
- 300 W, VMP ~32 V ISC ~9.5 A



PV module Construction

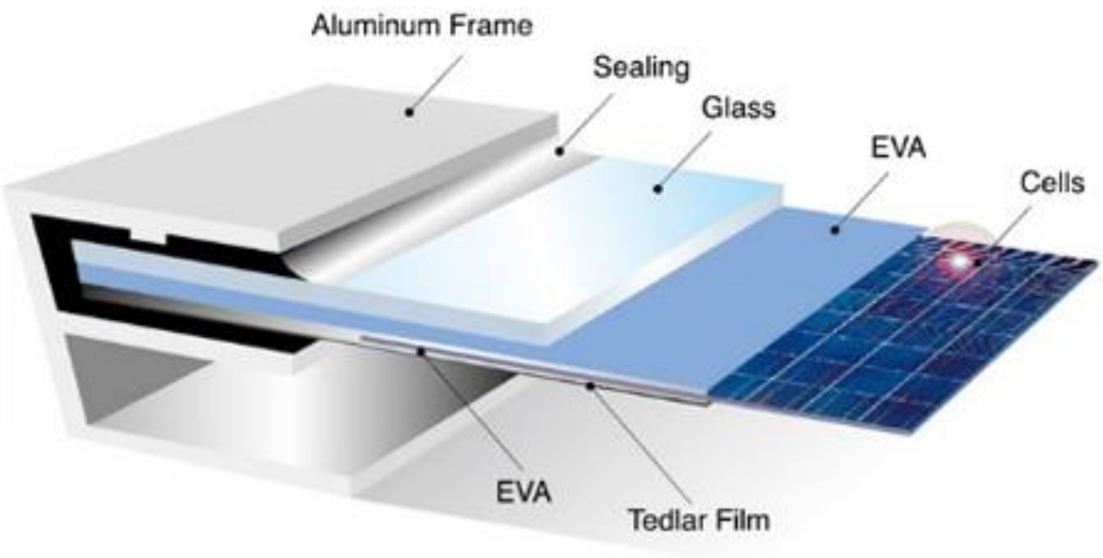
- <u>Bill of Materials - Typical</u>

Sunny side

1. **Superstrate**
   - 3.2 mm Low Iron Tempered glass
2. **Encapsulant**
   - 450 µm EVA
3. **Cell strings**
4. **Encapsulant**
5. **Back sheet**
   - Polyester/PVF sheet
   - Trade name Tedlar

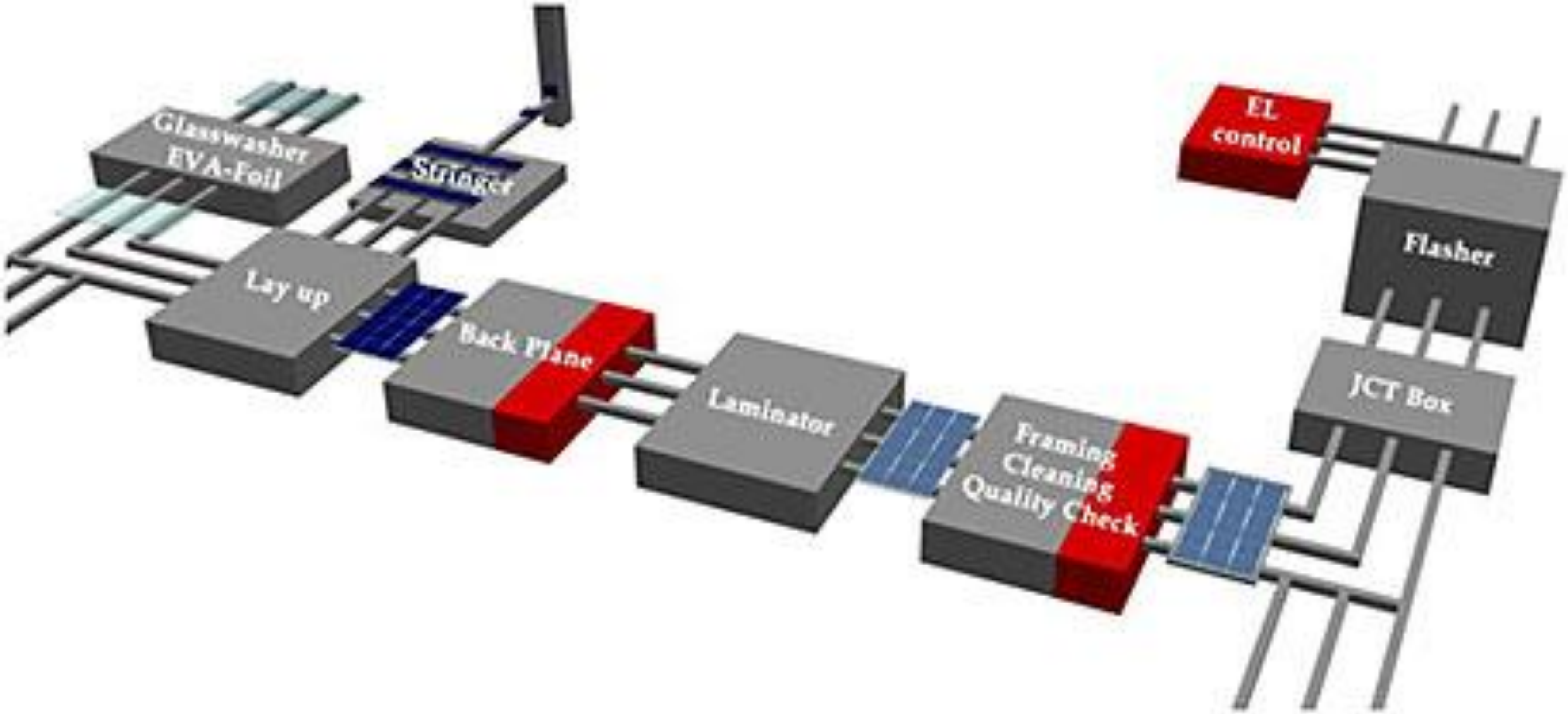
- Non Laminate

1. **Junction box**
   - Incl. Diodes and connectors
2. **Frame Seal**
3. **Frame**



Module Fabrication Wafer based

https://www.youtube.com/watch?v=BKrOZ6OogmQ



Front glass

Mechanical stability

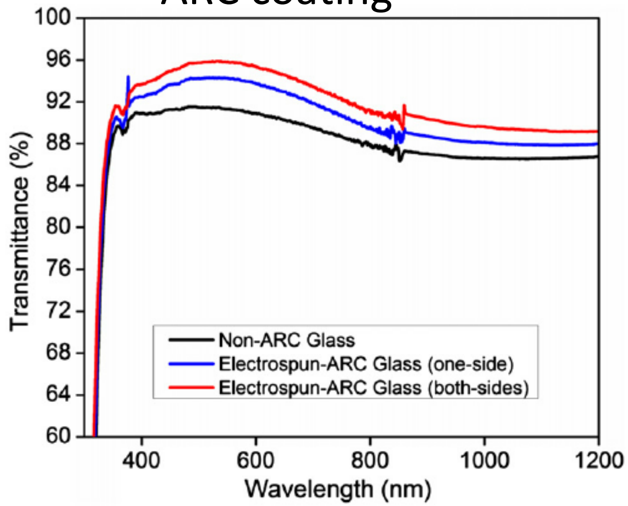
Optical light coupling

- Good light coupling to the cells
    - all angles
    - relevant wavelengths
- Aesthetic appearance (BIPV/BAPV applications)

$$R = \left| \frac{n_1 - n_2}{n_1 + n_2} \right|^2$$

Indexmatching

ARC coating



Methods

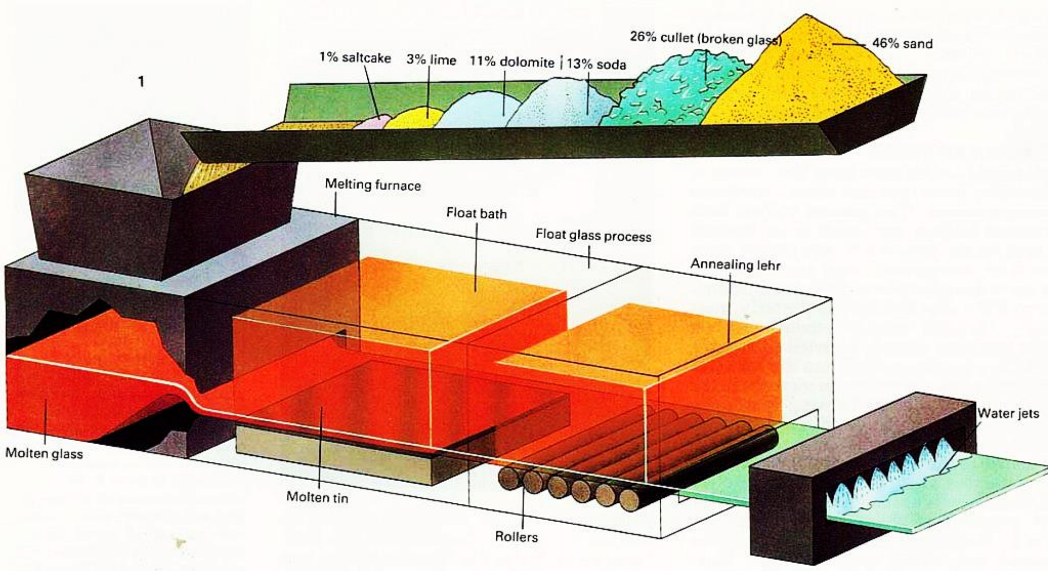
- Index Matched materials
- Antireflective glasses
- Deep structured glasses

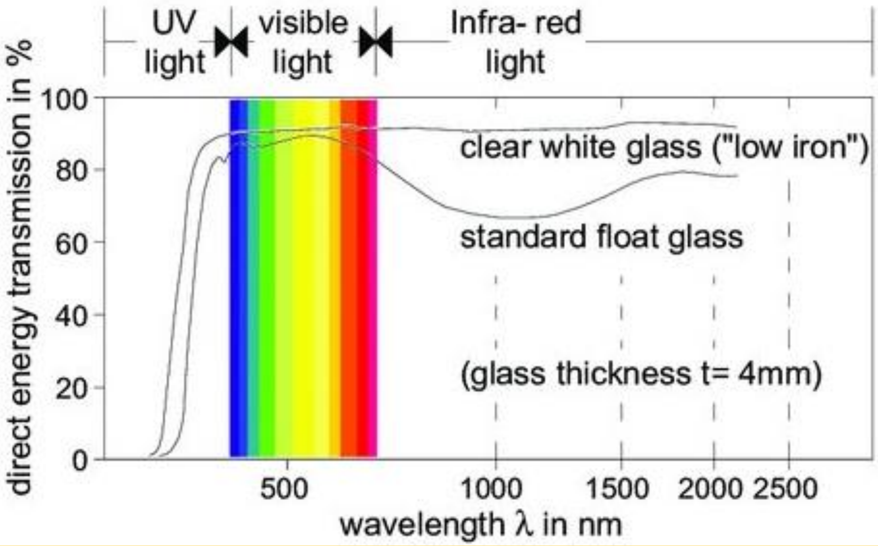
Deep structured

Glass

Fabrication of Solar glass

- Base material
  - Soda lime float glass
  - 3.2 mm mostly
  - Contents:
    - 73% SiO2
    - 13%Na2O
    - 9 %CaO
    - 4 %MgF
    - Al oxides
    - Little to no content of Fe Oxides
- Low Iron (Fe)

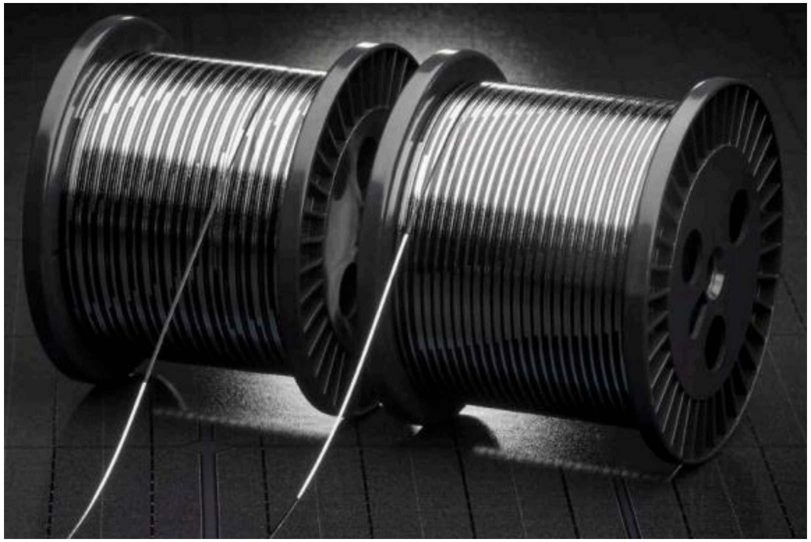




Interconnection

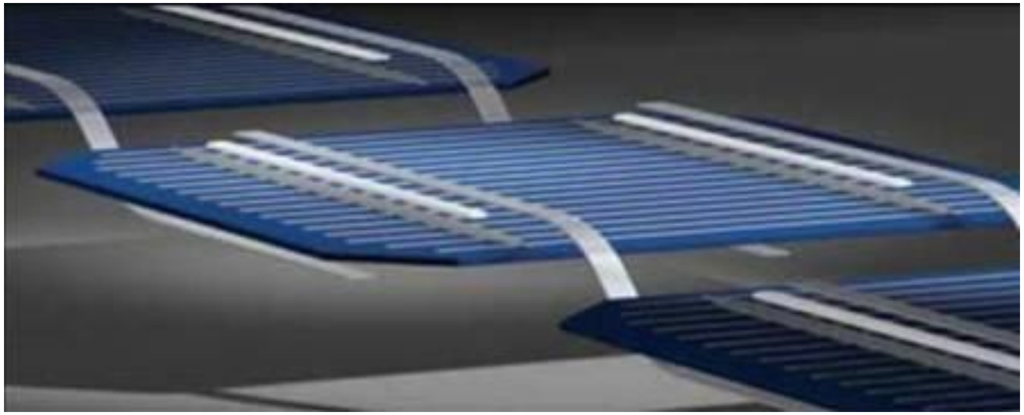
Material:

- Ribbons
- Tin coated copper ribbons
- To be soldered on the silver paste of the cells



Process:

- Ribbons starting from front cell surface to rear surface of the next. (Serial connection)
- Soldering



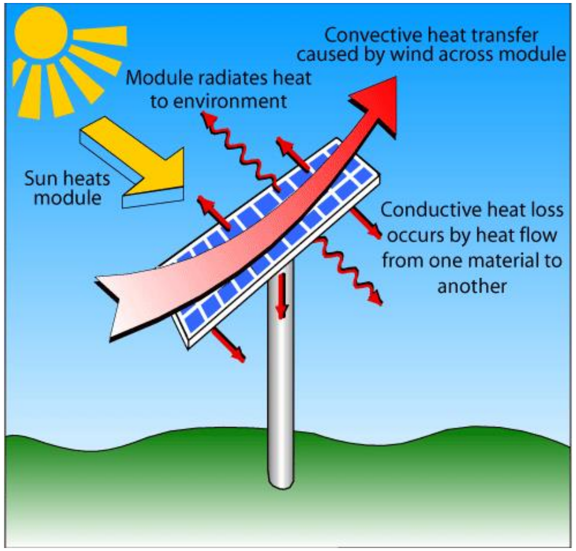
Climatic Module design

Objectives

1. Protect for UV light
2. Protect for rain and humidity
3. Temperature variations (operating temperatures -20-70 deg C)
4. Mechanical Stability
5. Electrical Safety

Methods

1. Glass, encapsulant
2. Glass, frame, backsheet
3. Thermal design: Cooling and thermal expansion
4. Glass, frame
5. Encapsulant, glass, backsheet, lamination

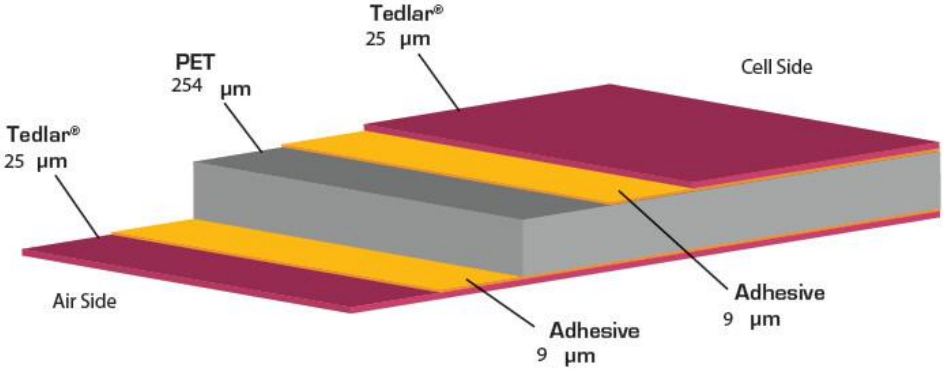


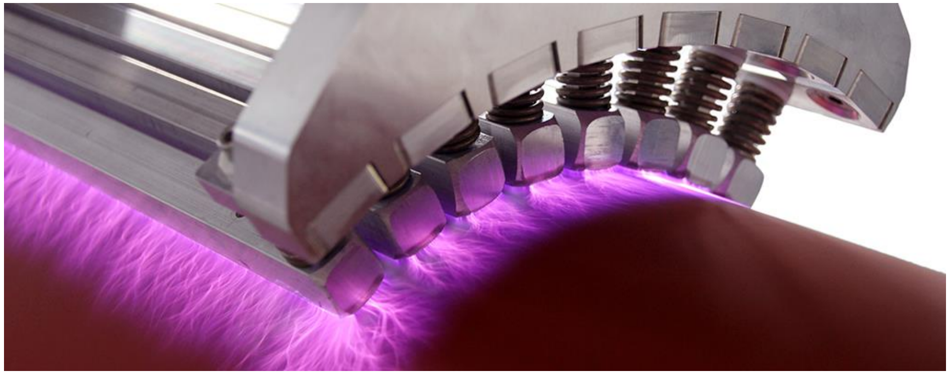
Backsheets

Polymeric backsheet

- Traditionally TPT
  - Tedlar (Tradename of Poly Vinyl fluoride PVF)
  - Polyester (PET)
  - Tedlar
  - Additives (UV stabilizers etc)
- Good durability and water transmission
- Cheaper alternatives exists with other polymers
- Many colors available
- White give gains of 1-2 % pa
  - Reflection -> cooler module

Adhering anything to PET requires pretreatment (Corona discharge or primers)





Backsheets

Polymeric backsheets

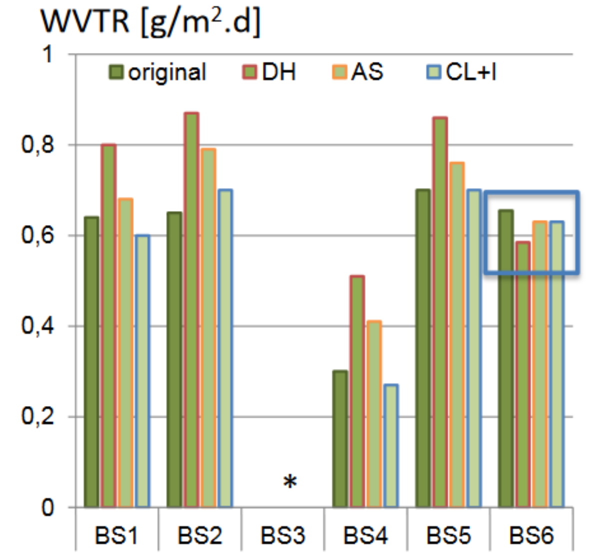
Materials:

PET: Polyethylene terephthalate (Polyester)
PVF: Poly Vinyl flouride PVF
PVDF: polyvinylidene difluoride
EVA: Ethylene Vinyl Acetate
PA: PolyAmide (Nylon)
AL: Aluminum

Polymers can be modified widely by adjusting chain lengths and using additives.

Environmental Conditions:

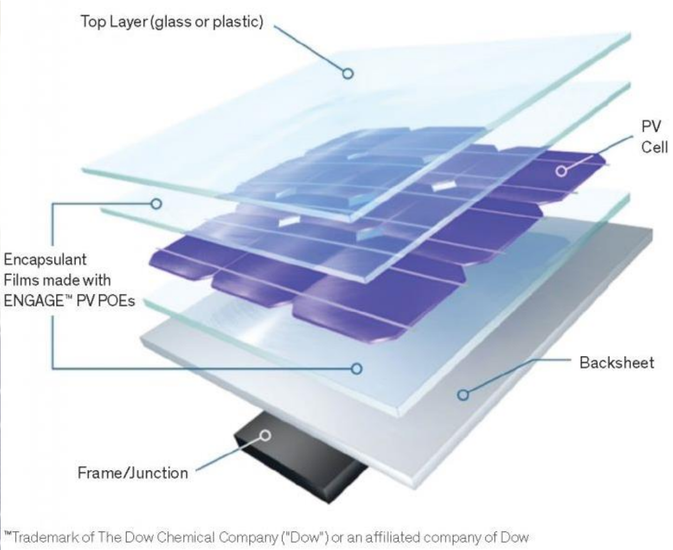
DH: Damp heat
AS: Ammonia Storage
CL+I: Climate + irradiation
WVTR: Water Vapor transmission rate



PET – core layers **PA-core**

name	composition	thickness [μm]
BS1	PVF / PET / PVF	340
BS2	PVDF / PET / PVDF	327
BS3	PET / Al / PET / EVA	388
BS4	PET / PET / EVA	377
BS5	PA / PET / PA	350
BS6	PA / PA / PA	369

Encapsulants

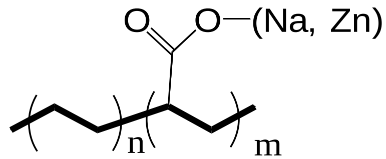


Encapsulants

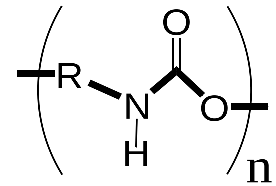
- Glue that glues the layers together
- Comes as extruded in sheet form
- **Ethylene Vinyl Acetate (EVA)** is the standard
  - EVA is cross-linking
- Cheap and sufficient

Desired properties

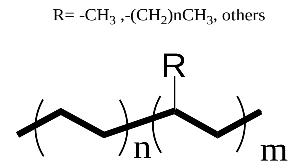
- Good adhesion
- Good transmission
- Good UV stability
- Good moisture ingress resistance
- Electrical insulation



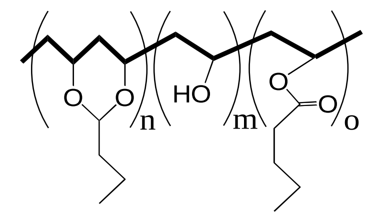
Ionomer



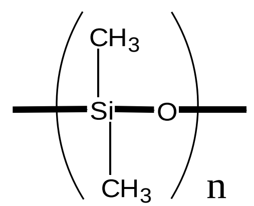
Thermoplastic Polyurethane (TPU)



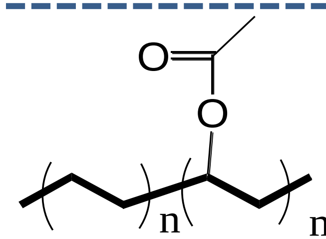
Thermoplastic Polyolefin (TPO)



Polyvinyl Butyral (PVB)



Polydimethyl Silicone (PDMS)



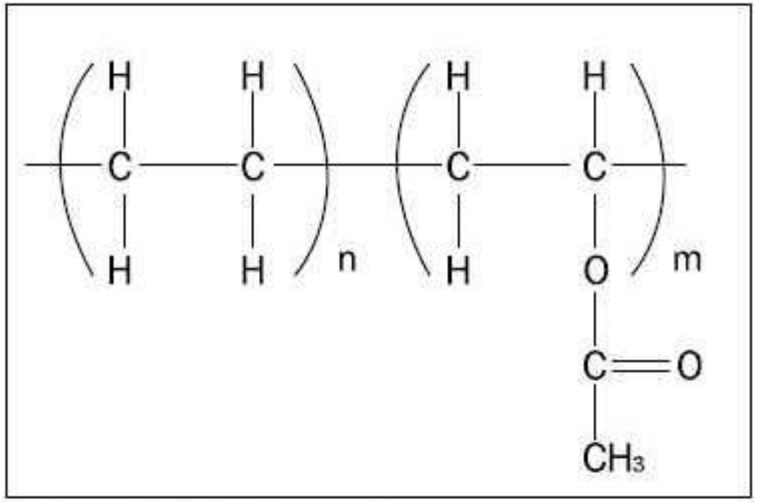
Ethylene Vinyl Acetate (EVA)

Encapsulants

EVA

Ethylene

Vinyl with an Acetate Radical



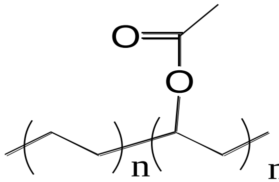
Acetate

Figure 3. EVA (Source: Madico)

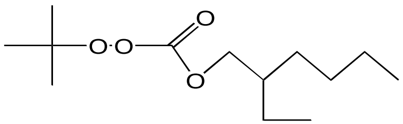
Encapsulants

EVA formulation

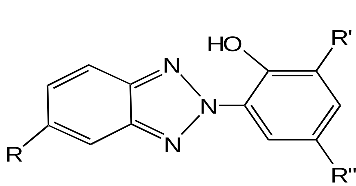
- Is not only EVA
- Additives added
  - Crosslinking
  - UV absorption
  - Adhesion promotors
  - Radical scavenger



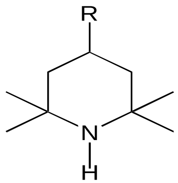
Ethylene Vinyl Acetate
(EVA, 96% to 98%)



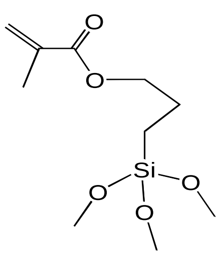
Peroxide
(1% to 2%)
Cross-Linker



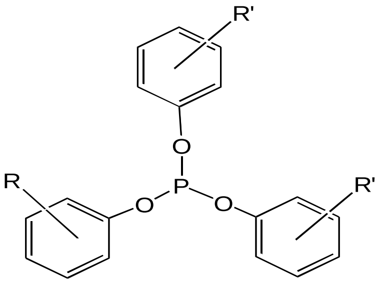
Benzoltriazole
(0.2% to 0.35%)
UV Absorber



Hinder Amine Light Stabilizer
(HALS, 0.1% to 0.2%)
Decomposes Peroxide Radicals



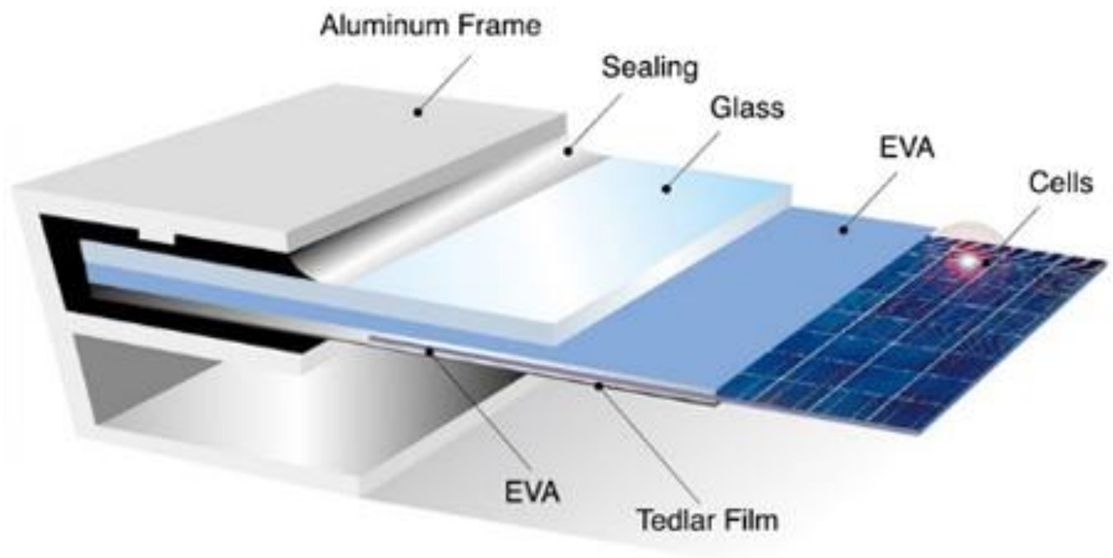
Trialkoxy Silane
(0.2% to 1%)
Adhesion Promoter



Phenolic Phosphonite
(0% to 0.2%)
Peroxide Decomposer/
Radical Scavenger

PV module Fabrication

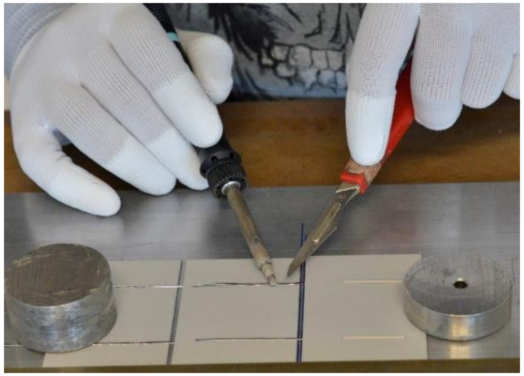
- Stringing
- Layup
- Lamination
- Testing
- Framing
- Junction Box
- Palleting

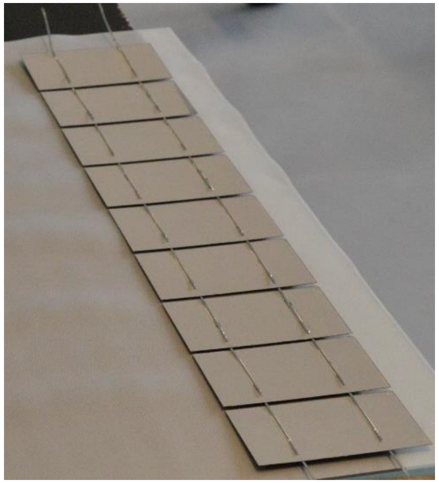


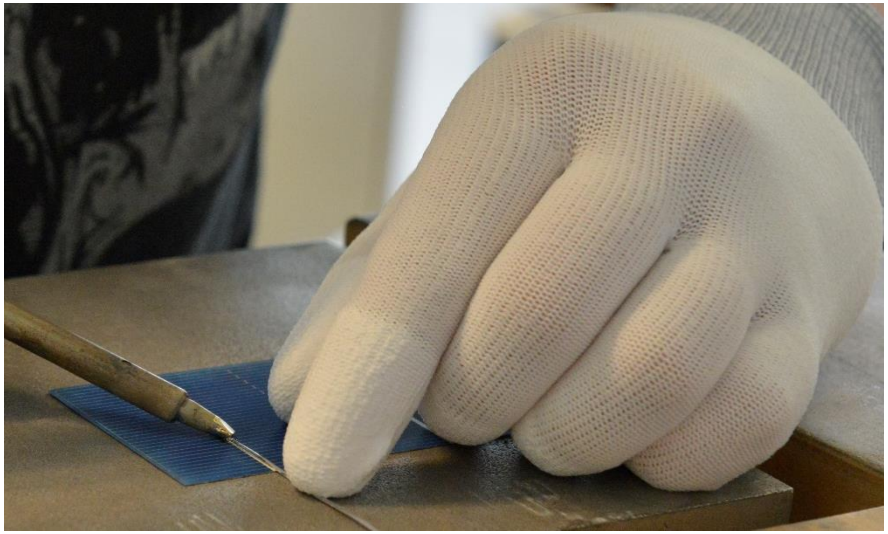
PV module Fabrication

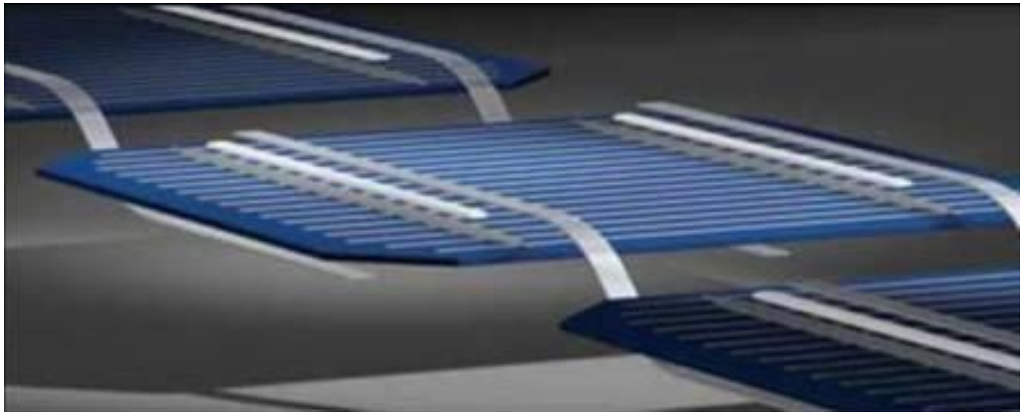
Tabbing and stringing:

- Series connect cells into strings









PV module Fabrication

Layup:

- Sunny side down
- Layup glass, EVA and Cell strings
- Interconnect Cell strings
  - Maybe cover strings with interlayer
- Layup EVA and Backsheet
- Module outlets
  - (Interconnection ribbons)
  - Cut slits in EVA and Backsheet
  - Wrap the ribbons through the sheets
  - Special tape to protect outlets

Lamination

Objective:

- Adhere the module using heat and vacuum

Pressure in upper chamber

Laminator schematics

Vacuum in lower chamber

Lamination

Lamination cycle:

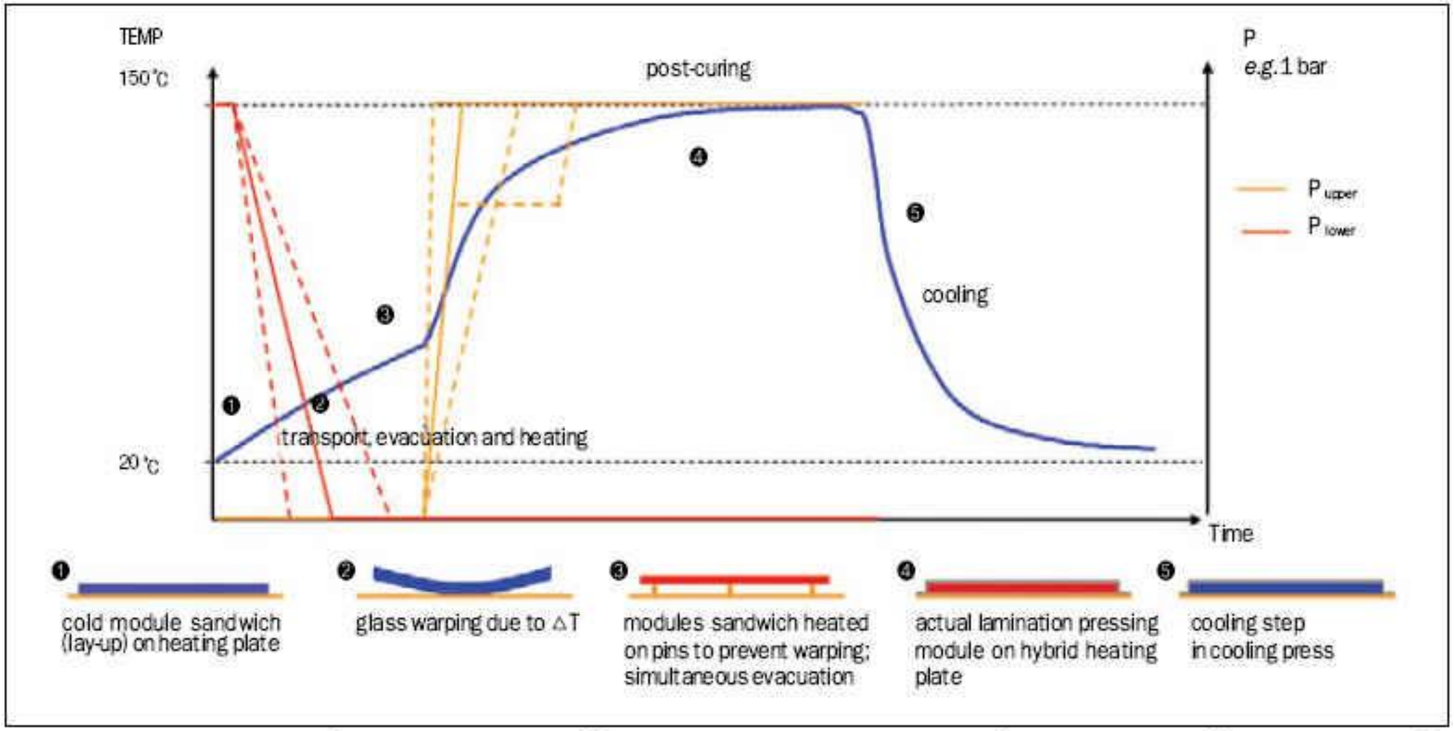
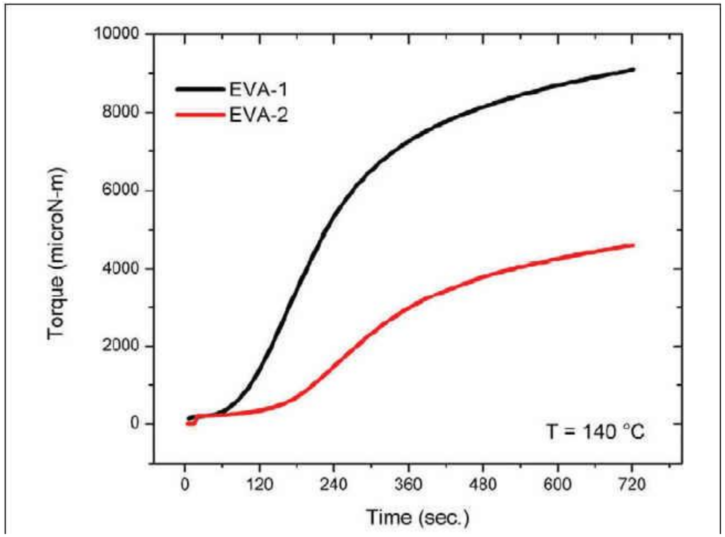


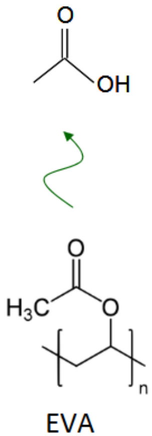
Figure 1. Variation of the temperature and pressure in function of time during a typical lamination cycle of a PV module (schematic presentation) as well as a schematic representation of the module during the lamination process. (Source: 3S Swiss Solar Systems)

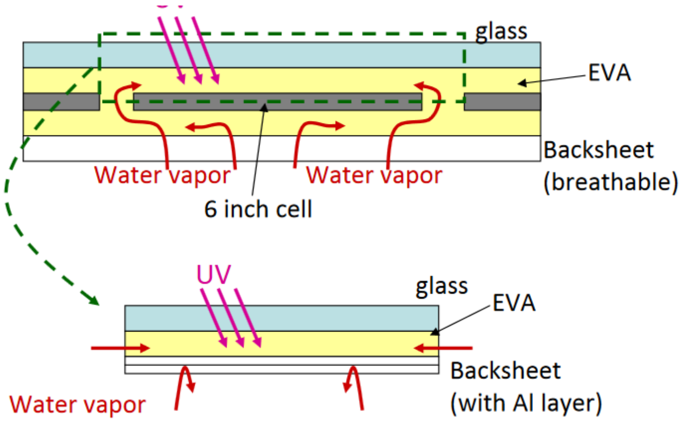
Curing of EVA

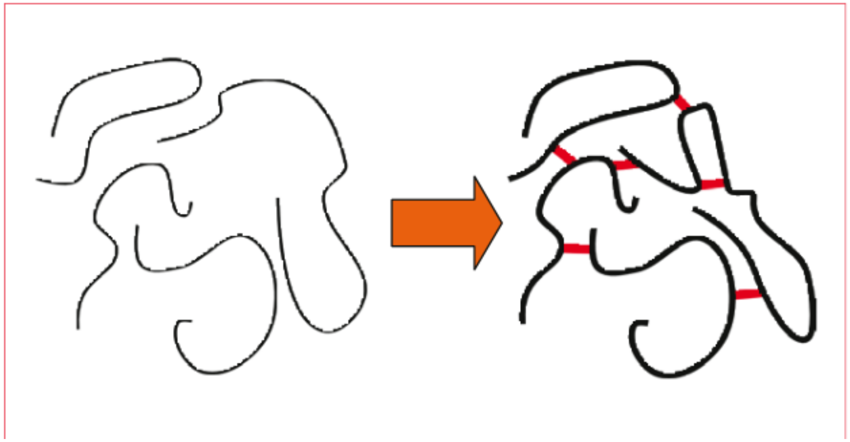
EVA

- Melts, floats and crosslinks during lamination
- Uncured EVA unstable compounds:
  - Peroxides
  - Degrades to Acetic Acid





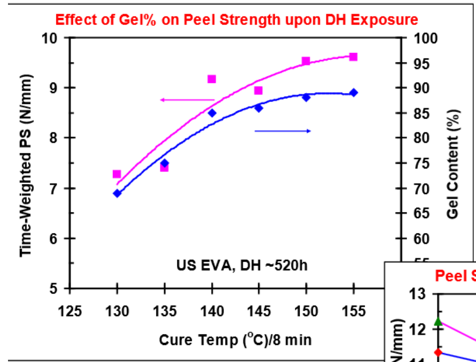




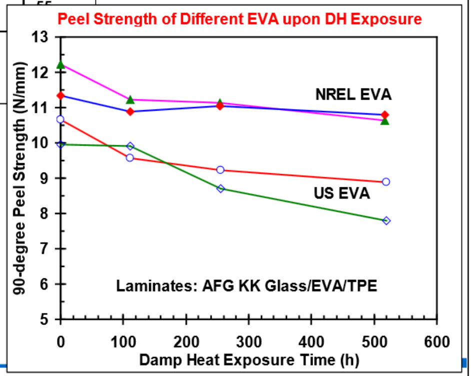
Properties of cured EVA

Cured EVA

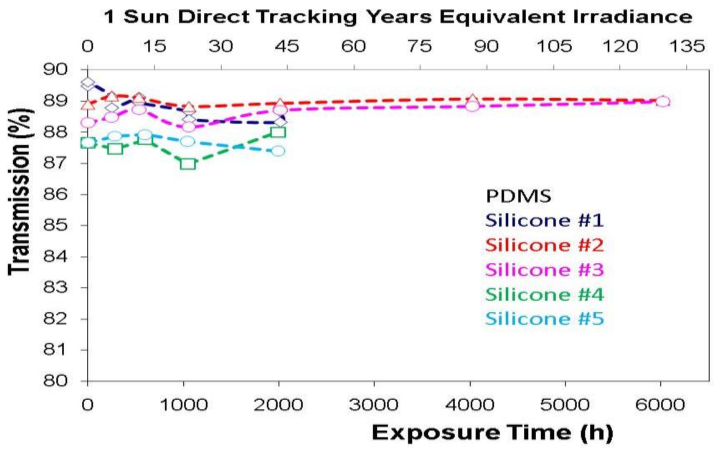
- Fraction of cross-linked polymers is expressed in **gel-content**
- Non cross-linked molecules
  - Free radicals (side reactions)
  - Susceptible to degradation
- In good modules >75 %
- **Degrades with**
  - Moisture
  - UV

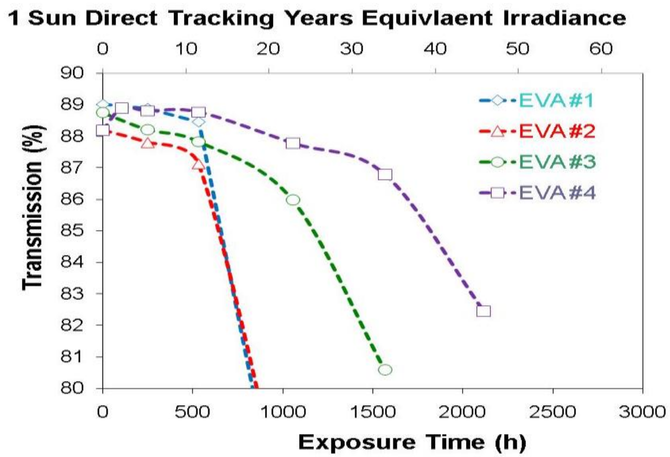


EVA Adhesion Strength affected by Processing Condition



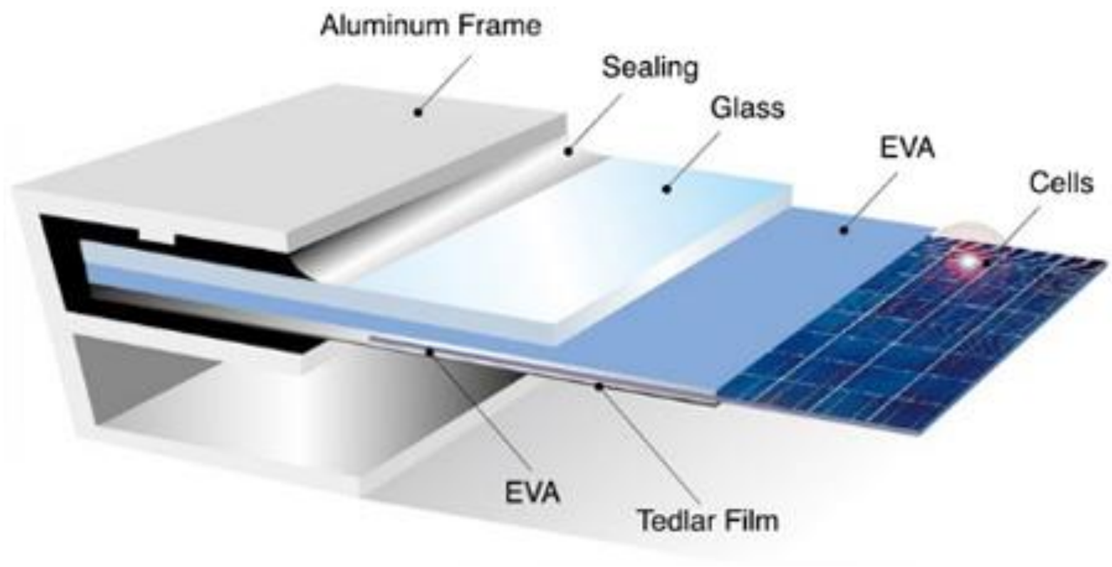
and by Damp Heat Exposure Time





PV module Fabrication

- Stringing √
- Layup √
- Lammination √
- Testing
- Framing
- Junction Box
- Palleting

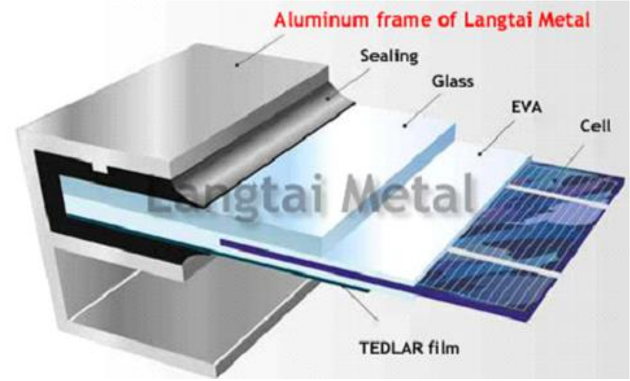


PV module Fabrication

MODEL		SV60-245	SV60-250	SV60-255	SV60-260
Peak power P_{MPP}	[W]	245	250	255	260
Peak power tolerance	[W]	-0/+4,9			
Short circuit current I_{SC}	[A]	8,76	8,79	8,88	8,95
Open circuit voltage V_{OC}	[V]	37,3	37,4	37,7	37,9
Rated current I_{MPP}	[A]	8,15	8,20	8,34	8,47

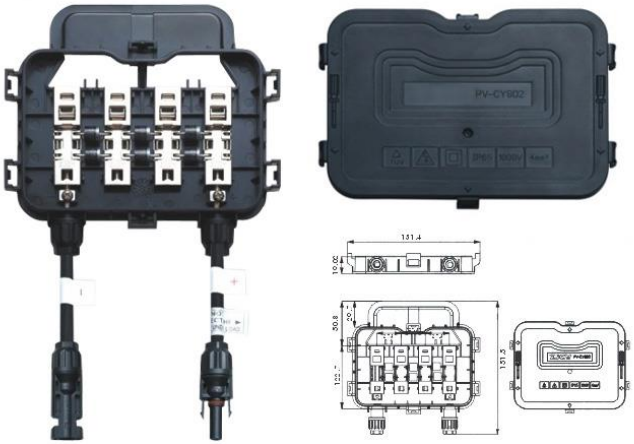
Finishing the module

- IV measurement and Binning to power class
  - Typical 0+5W binning
  - Optional Electroluminescence
- Frame mounting
  - Typical aluminum profiles
  - Edge seal (Tape or silicone)
  - Prevents moisture ingression from the side
- Junction box mounting
  - J-box pre-mounted with wires and bypass diodes



PV module Fabrication

- Junction box mounting
  - Ribbons attached in clamps
  - J-box pre-mounted with wires and bypass diodes
  - Standardized PV connectors
    - Environment protection
    - design preventing connection faults



Cut Cells

Most crystalline cells can be cut.

Purpose

- Match voltage and area (PIPV applications)
- Reduce current to reduce ohmic loss
- $P_{ohmic} = RI^2$

Methods

- Laser Scribing
- Thermal laser separation

(Details course 34552)

From 34552 (3bb cell)

$$R_{ribbon} = 8\,m\Omega$$

$$P_{loss,Full} = 6 * 3A^2 * 8m\Omega/3 = 144\,mW{\sim}3\%$$

$$P_{loss,half} = 6 * 1.5A^2 * 8m\Omega/3 = 36\,mW{\sim}0.75\%$$

PV panel

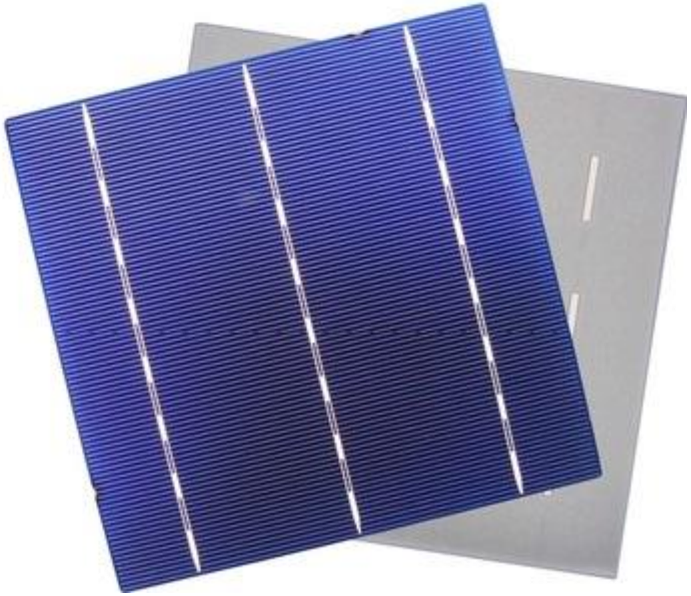
- 310*310mm^2
- Full cells 4 ~2V
- Cut cells ~10 V

Cut Cells

Question?

To gain the ohmic loss reduction using cut cells which direction to cut?

1. Parallel with busbar?
2. Perpendicular to the busbar?



Cut Cells

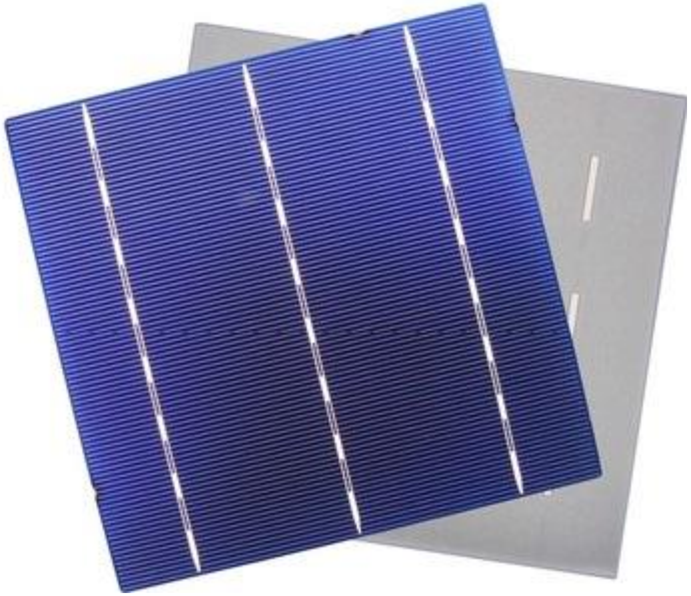
Answer:

To gain the ohmic loss reduction using cut cells which direction to cut?

2. Perpendicular to the busbar?

This reduces the current in the busbar

Cutting parallel changes nothing ohmic, but may have some layout benefits?



Cells to Module ratio

Cell to module ratio

CTM$= \frac{P_{module}}{\sum P_{cells}}$

Question?

Can the CTM be larger than 1?

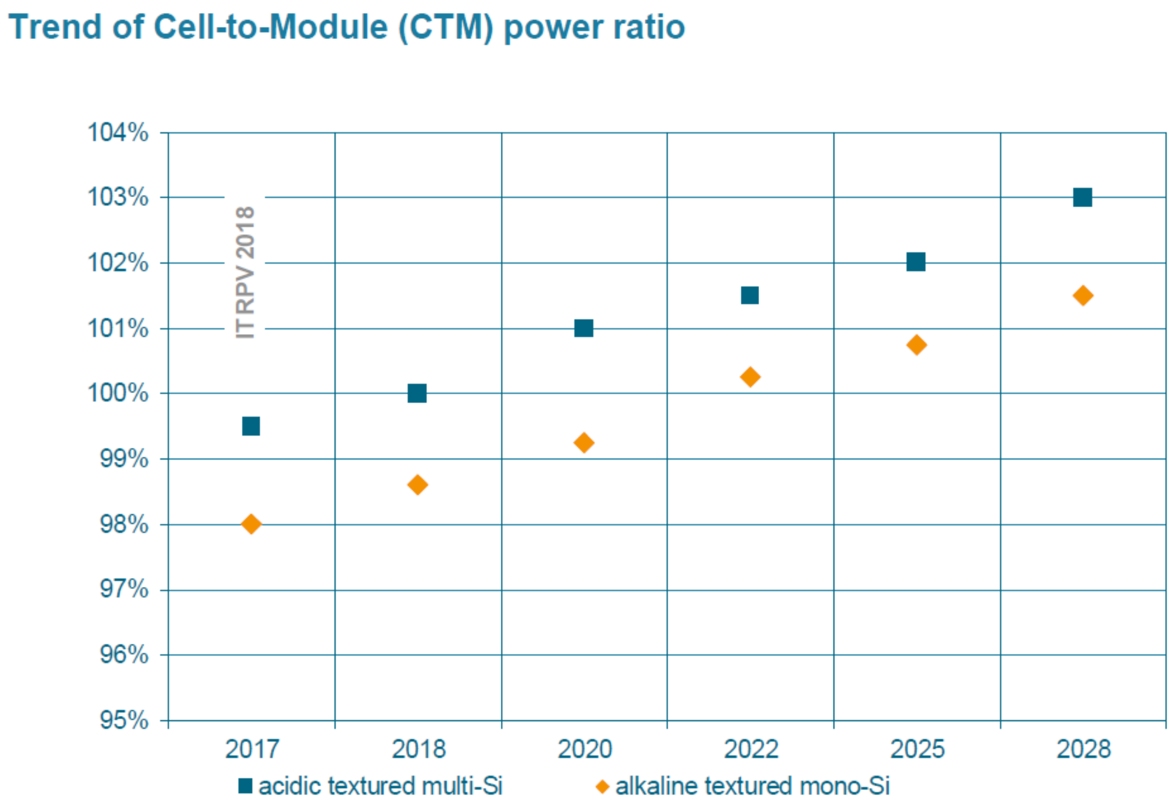
Cells to Module ratio

Cell 2 module ratio

$$\text{CTM}=\frac{P_{module}}{\sum P_{cells}}$$

Answer.

Yes, but not yet….



Module Losses and gains

Cell to module Optimization:

Optical optimization

- Reduce unwanted reflections
- Recapture reflected photons
- Reduces unwanted optical absorption
- Increase desired reflections
- Modelling by raytracing

Electrical optimization

- Increase conductivity
- Reduce current
- Reduce length of current paths
- Analytical or FEM calculations (geometric complexity)

I. Haedrich et al. / Solar Energy Materials & Solar Cells 131 (2014) 14–23

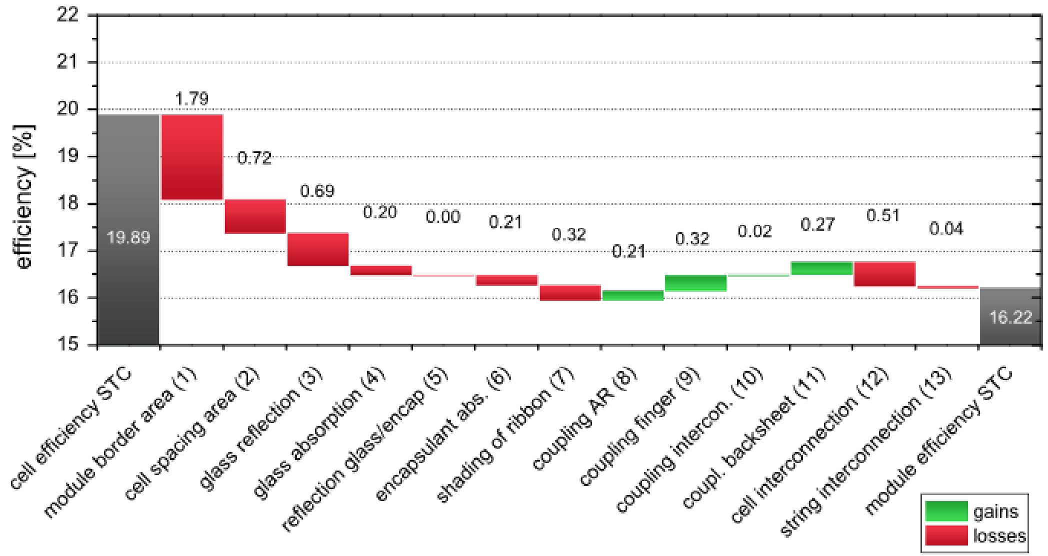


Fig. 1. Overview of absolute efficiency gains and losses calculated for the described 60 cell module configuration.

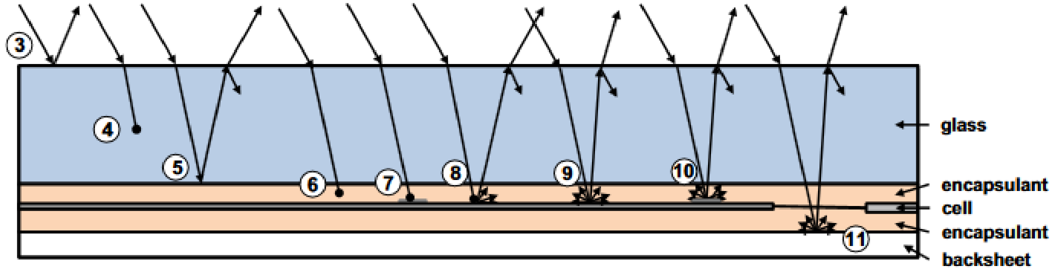


Fig. 2. Illustration of optical effects in module numbered according to Fig. 1. The sketch is modified from [12].

Module design

1. **Equal cells**
   - Same binning
   - Same type
   - Same area (for cut cells)
     - (Same contact layout)
2. **Voltage**
   - Nominal voltage a STC
   - N_{series}*Vmp_{cell} =Vmp_{module}
   - Check temperature extremes
3. **Current**
   - Current is proportional to the cell area and the number of cells in parallel
4. **Compliance with application**
   - Voltage and current within the limits at all operating temperatures

Cell data sheet:

JACP6RF-4 4BB CYPRESS3

MULTICRYSTALLINE SILICON SOLAR CELLS

JA Solar's High-efficiency Poly Cells. Manufa

320Wp (6×12) power output becomes eas

MECHANICAL DATA AND DESIGN

Format	156mm×156mm±0.5mm
Thickness	210μm±30μm
Front(-)	1.1 mm bus bars(silver), blue anti-reflecting coatinç
Back(+)	1.6 mm wide soldering pads(silver) back surface fie

TEMPERATURE COEFFICIENTS

TkVoltage	-0.35%/K
TkCurrent	+0.06%/K
TkPower	-0.42%/K

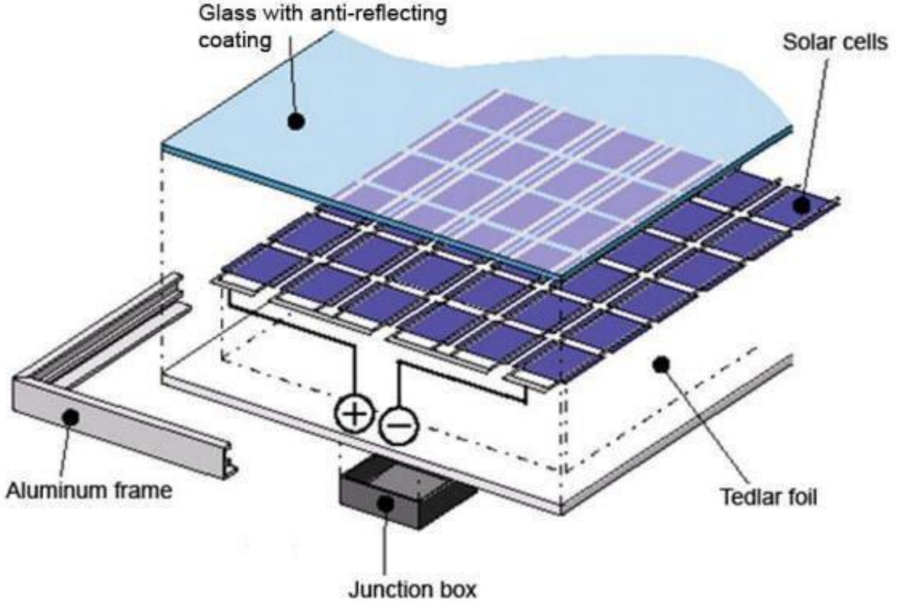
No.	Efficiency(%)	Pmpp(W)	Umpp(V)	Impp(A)	Uoc(V)	Isc(A)	FF(%)
10	18.80-20.00	4.58	0.542	8.448	0.641	8.988	79.46
09	18.70-18.80	4.55	0.541	8.424	0.640	8.964	79.40
08	18.60-18.70	4.53	0.539	8.399	0.638	8.939	79.35
07	18.50-18.60	4.50	0.538	8.375	0.637	8.914	79.30
06	18.40-18.50	4.48	0.536	8.352	0.636	8.891	79.25
05	18.30-18.40	4.46	0.535	8.330	0.634	8.871	79.17
04	18.20-18.30	4.43	0.533	8.310	0.633	8.853	79.06
03	18.10-18.20	4.41	0.531	8.291	0.632	8.836	78.95
02	18.00-18.10	4.38	0.530	8.269	0.630	8.817	78.86
01	17.90-18.00	4.36	0.528	8.248	0.629	8.804	78.66

Specifications subjects to technical changes and tests. JA Solar reserves the right of final interpretation.

Binning Classes

Module design

1. **Even number of strings**
   - Electrical Outlets at the same position
   - No long DC lines in the module
2. **Edge space to cell a few cm**
   - Shading from frame
   - Water ingress from side
3. **Cell Spacing**
   - Min 2 mm for Ribbon (Ribbon bending)



Competition

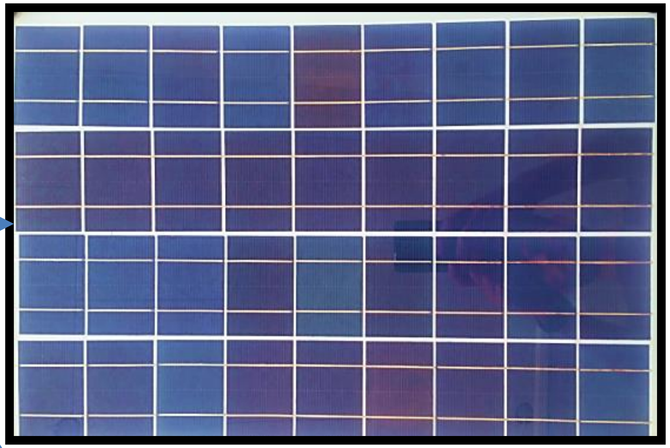
Competition:

Your group will enter a competition with the panel.

- Power output
- Aesthetics
- Quality (EL images)
- Workmanship

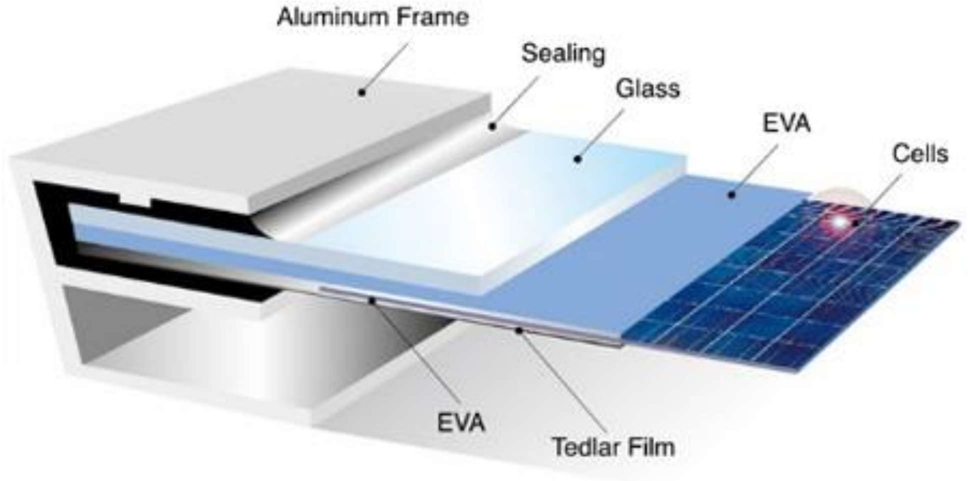
Tricks for module fabrication

1. **Be Need and organized**
   - Straight ribbons
   - Neat pile of soldered cells
   - Keep straight lines in the module
   - Place the cell strings parallel to the glass
2. **Soldering**
   - Soldering contact area to be maximized
   - Maximizing heat transfer



Sum up

1. **Module Construction**
2. **Module materials**
3. **Processing**
   1. Vacuum lamination
   2. Curing of EVA
4. **PV module fabrication**
   1. Stringing
   2. Layup
   3. Lamination
   4. Finishing
5. **Module design**
6. **Tips and tricks**



Time for Exercise 1

Design and make you own module in your group.

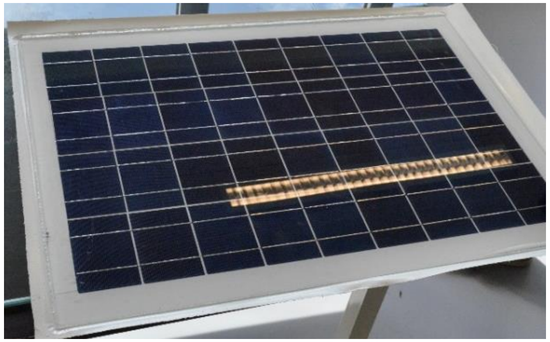
Schedule:
Too lunch:
- Module dimensioning and drawing.

Group 1 + 2
- Tabbing, Stringing Monday Afternoon
- Layup and lammination Tuesday morning

Group 3 +4
- Tabbing, Stringing Tuesday Afternoon
- Layup and lammination Wednesday morning

Finsihing
- Wednesday afternoon

Characterization
- Thursday



Help from Michael Graversen, CEO MGSolar, Former production Manager Gaia Solar.

Schedule

Monday	**17**	AM	Block 1 intro + module design			
		PM	Block 1 stringing		Preparation of presentation	
Tuesday	**18**	AM	Block 1 layup and lamination		Preparation of presentation	
		PM	Preparation of presentation		Block 1 stringing	
Wednesday	**19**	AM	Preparation of presentation		Block 1 layup and lamination	
		PM	Module finishing on shift 1 hour			
Thursday	**20**	AM	**Quiz @ 10:00**			
		PM	EL and IV for all the made modules (GARB & AASL)			
		1 pm - 2 pm	EL	Prep of pres.	Prep of pres.	IV
		2 pm - 3 pm	Prep of pres.	EL	IV	Prep of pres.
		3 pm - 4 pm	Prep of pres.	IV	EL	Prep of pres.
		4 pm - 5 pm	IV	Prep of pres.	Prep of pres.	EL
Friday	**21**	10 am - 11 am	**Oral exam**			
		11 am - 12 am		**Oral exam**		
		1 pm - 2 pm			**Oral exam**	
		2 pm - 3 pm				**Oral exam**
		3.30 pm	**Course round off**			