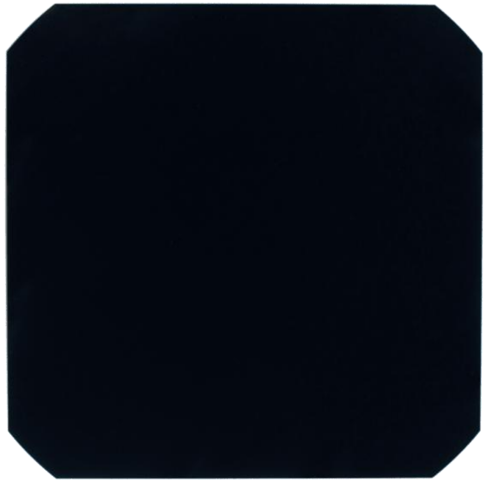
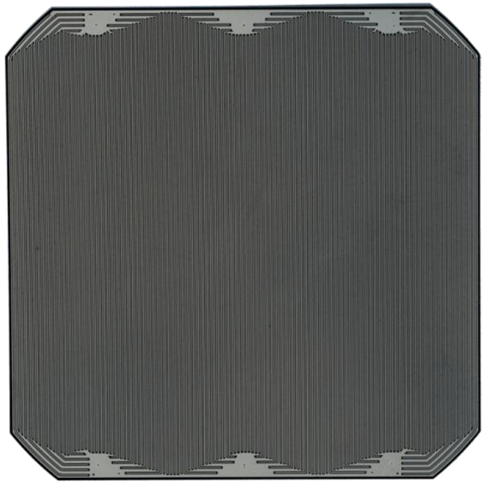
University of Applied Sciences and Arts of Southern Switzerland
Department for Environment Constructions and Design
Institute for Applied Sustainability to the Built Environment
SUPSI PVLab laboratory

SUPSI

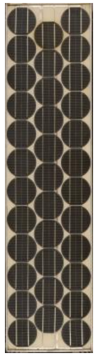
Overview of recent technological development





Mauro Caccivio
SUPSI PVLab Industry day 2026
Mendrisio, 21.05.2026

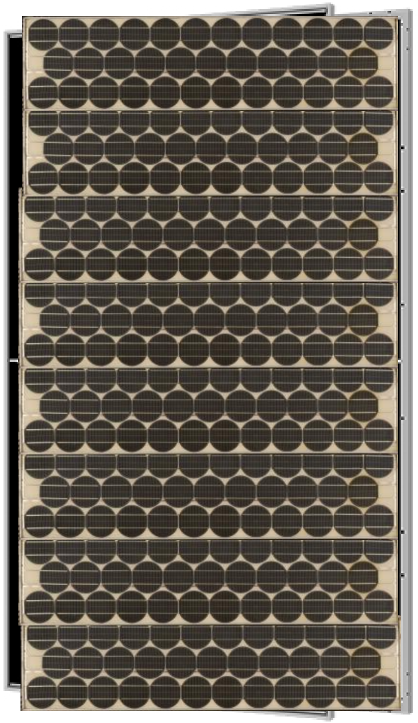
The evolution of photovoltaic modules from the 1980s to the present day



1982: 35W

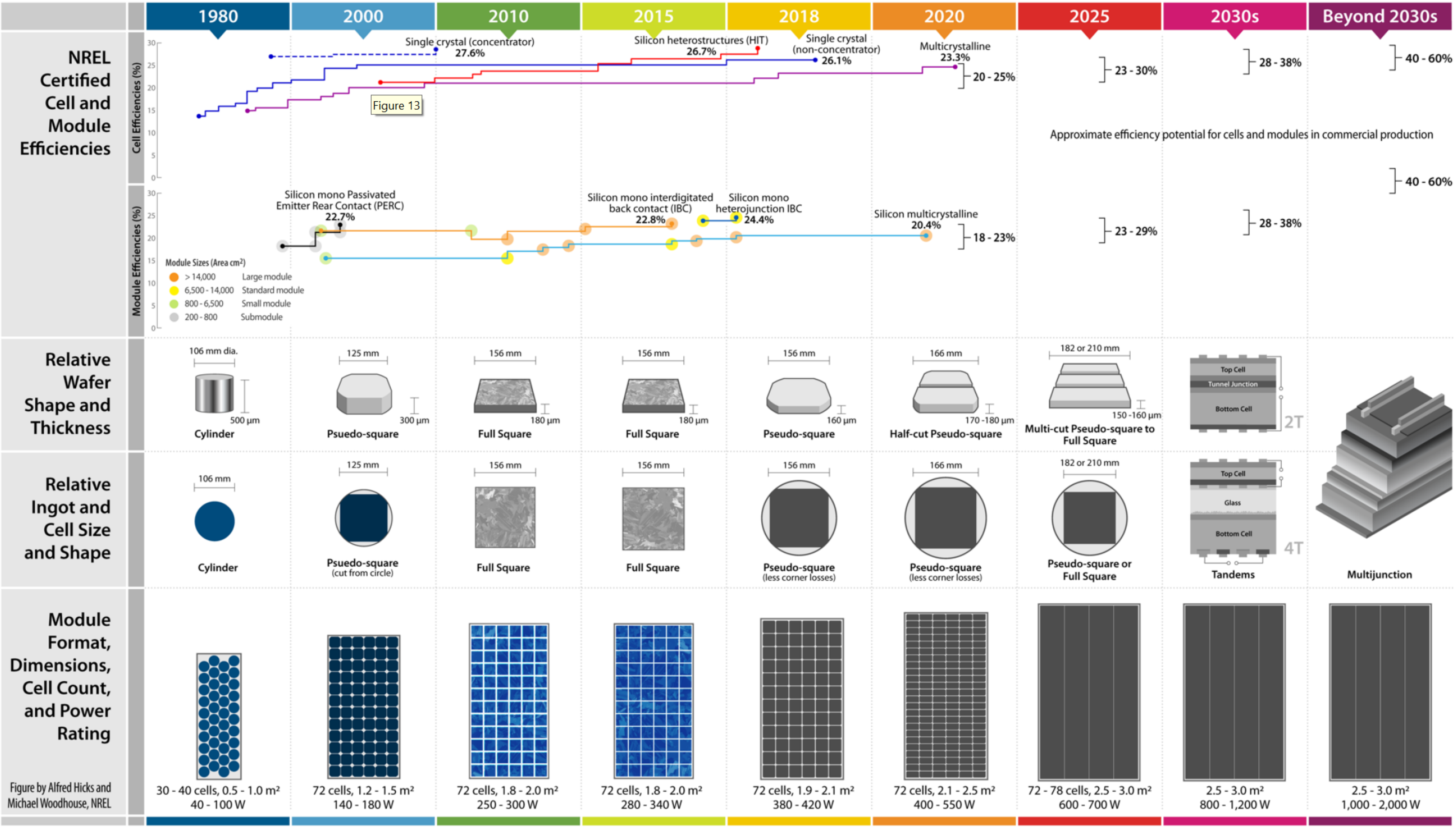
2012: 240W

2018: 320W



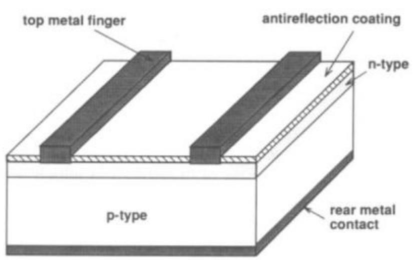
2026: 800W

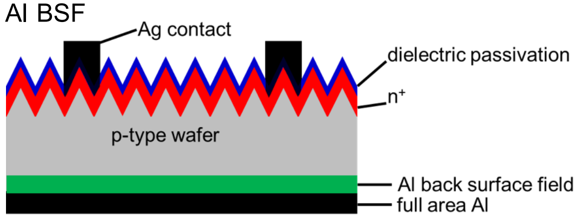
The evolution of photovoltaic modules from the 1980s to the present day

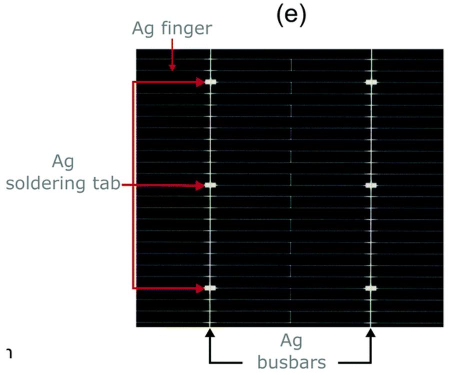


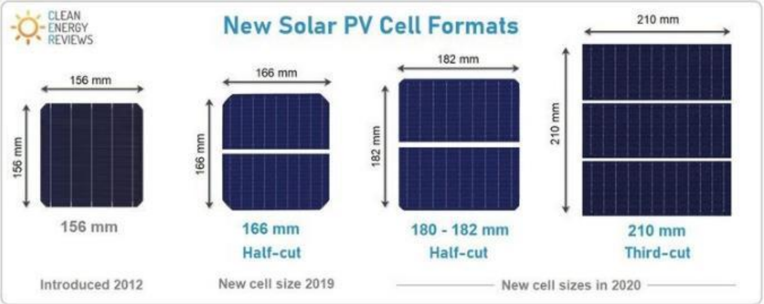
“Research and Development Priorities to Advance Solar Photovoltaic Lifecycle Costs and Performance” Michael Woodhouse, NREL, 2021

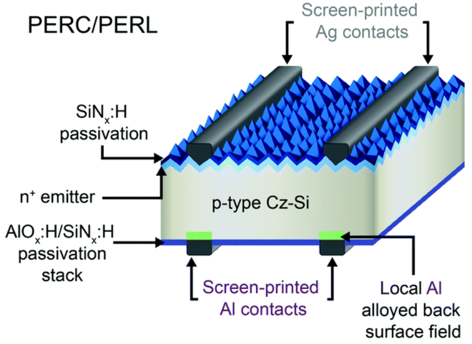
The evolution of photovoltaic cells

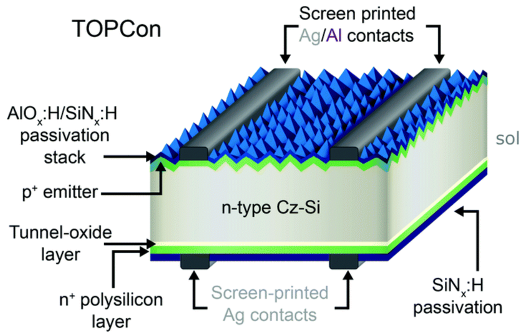


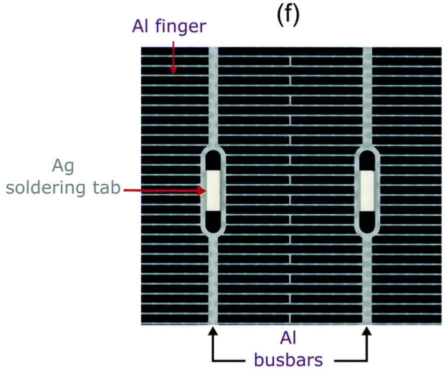




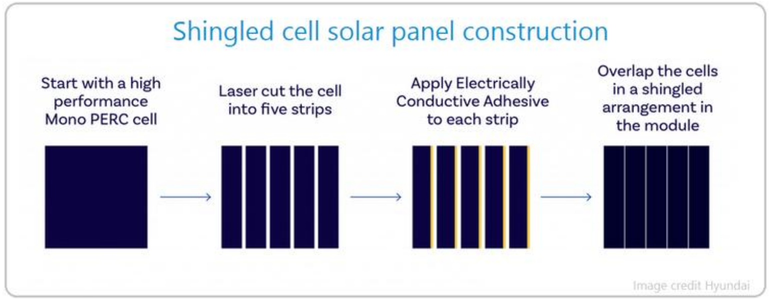


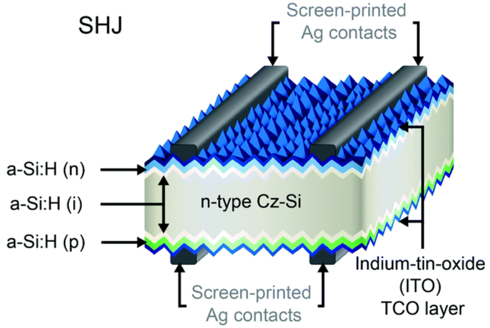


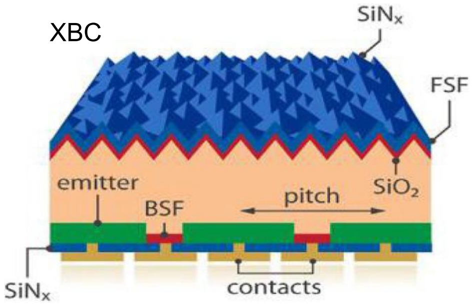


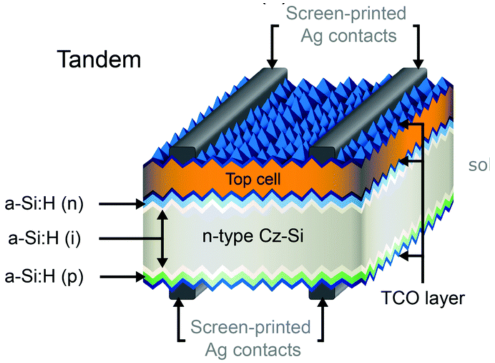


Larger cells divided into several sections; various solutions for electrical contacts

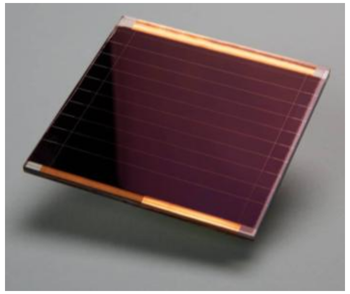






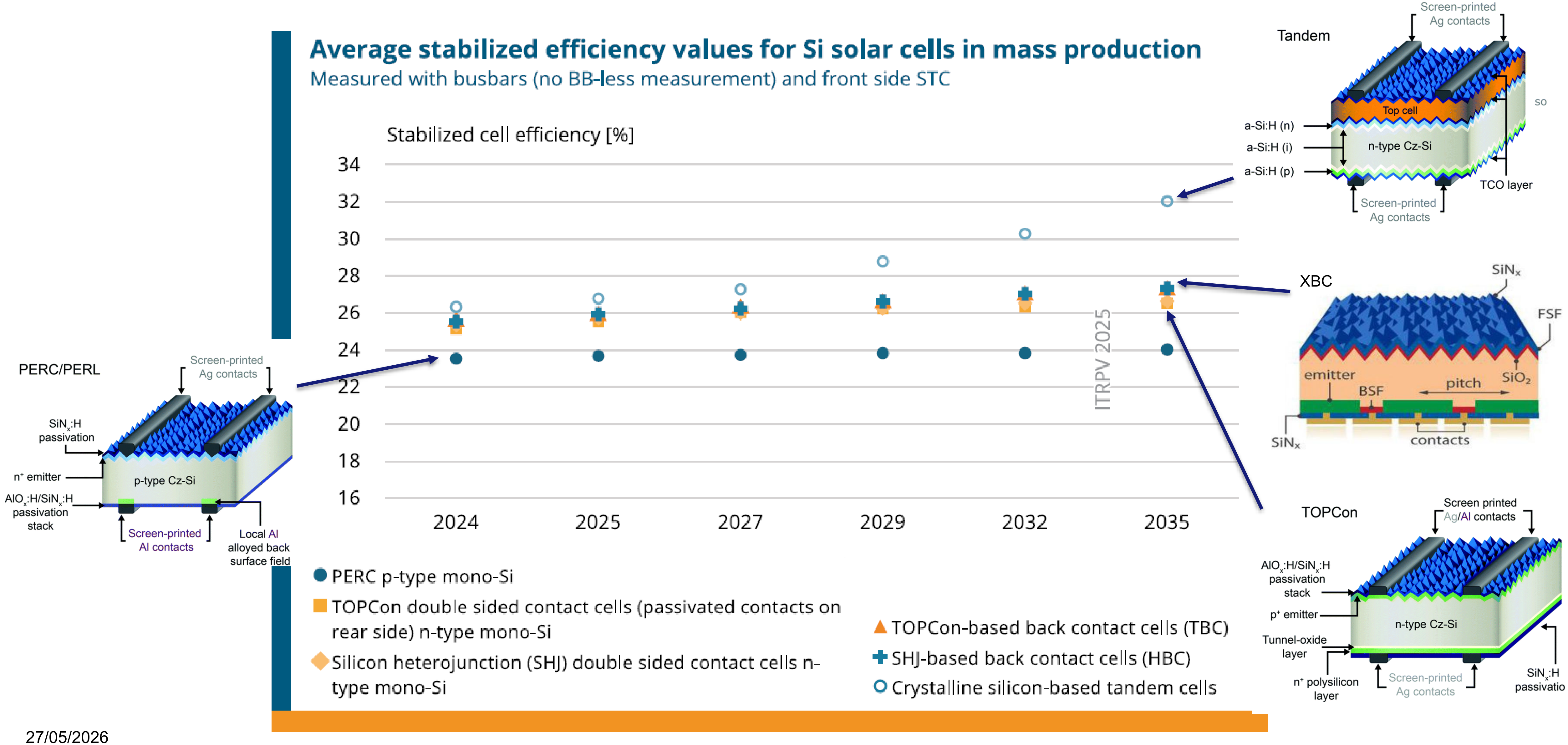


The near future lies in thin-film technology



Thin films just tens of nanometres thick!

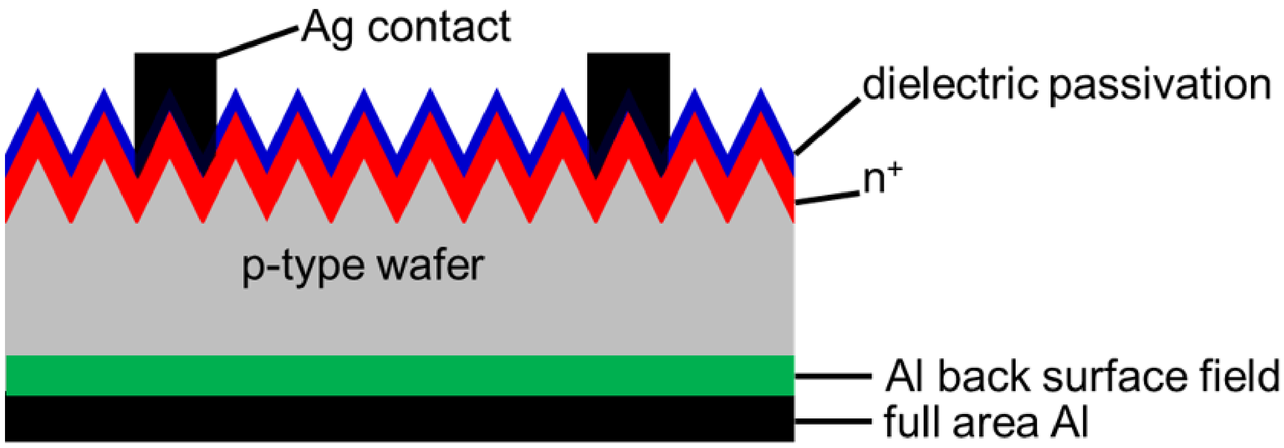
Solar Cell Evolution



First generation: Aluminium Back Surface Field (Al BSF) cell 2004–2017

Monocrystalline silicon solar cell

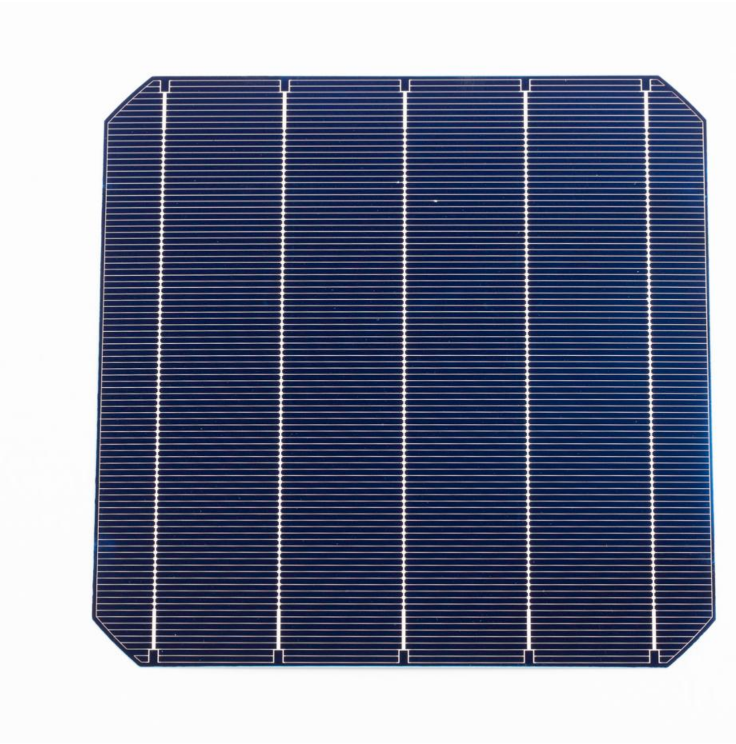
Polycrystalline silicon solar cell

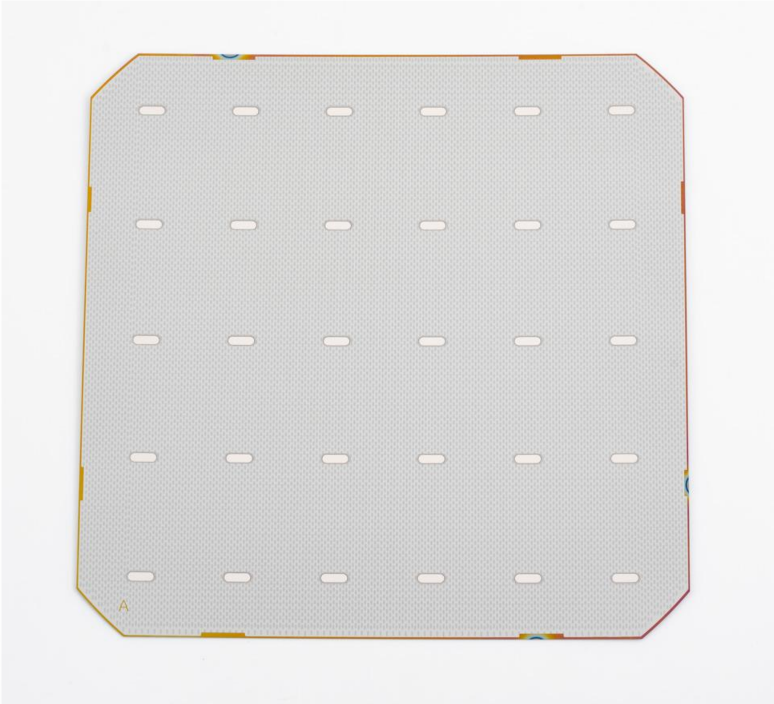


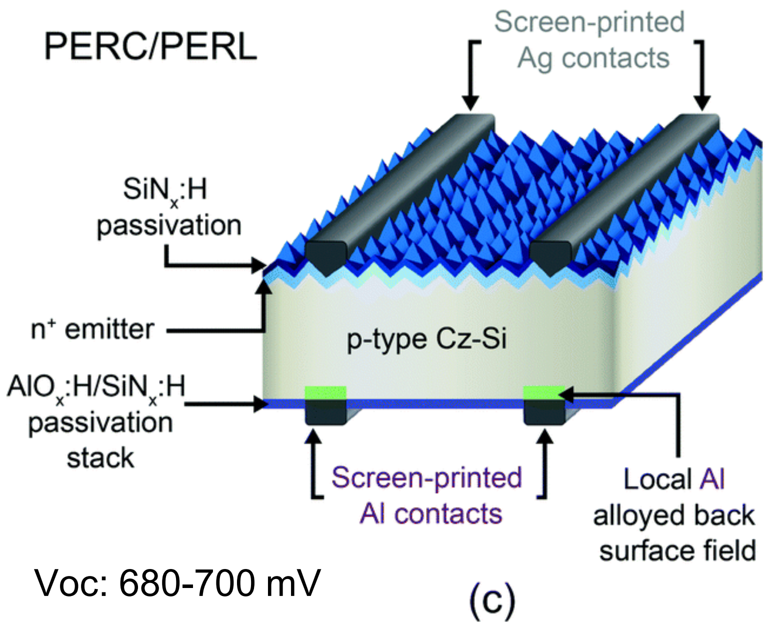
Voc: 650 mV

Thickness of the BSF aluminium layer: between 0.7 μm and 1.5 μm

Second generation: PERC (Passive Emitter Rear Cell) cell







Voc: 680-700 mV

Passivation: thickness of the passivation layer, AlOx, approximately 10 nm

PERC cell (Passive Emitter Rear Cell): limits

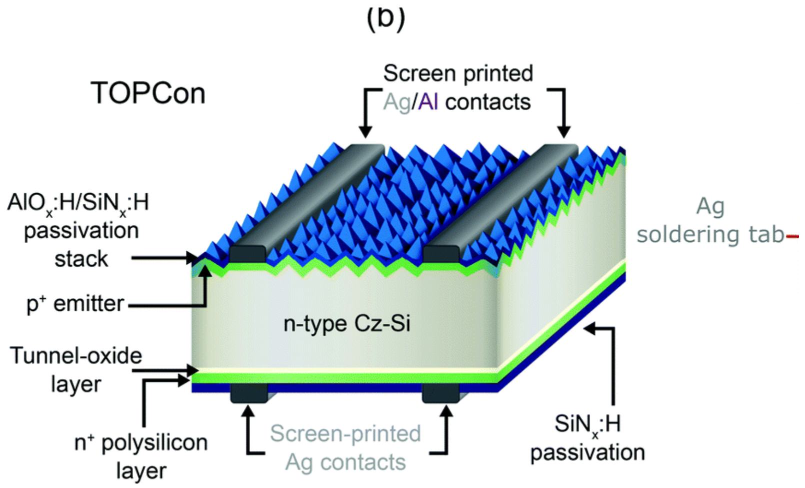
- The widespread doping of the wafer surfaces reduces recombination at the metal/silicon interface, but introduces adverse effects such as :
    - Auger recombination,
    - Absorption of free charge carriers
    - Reduction in the energy bandgap

•These phenomena limit the efficiency of traditional solar cells.

Solution: Carrier Selective Passivating Contacts (CSPC)

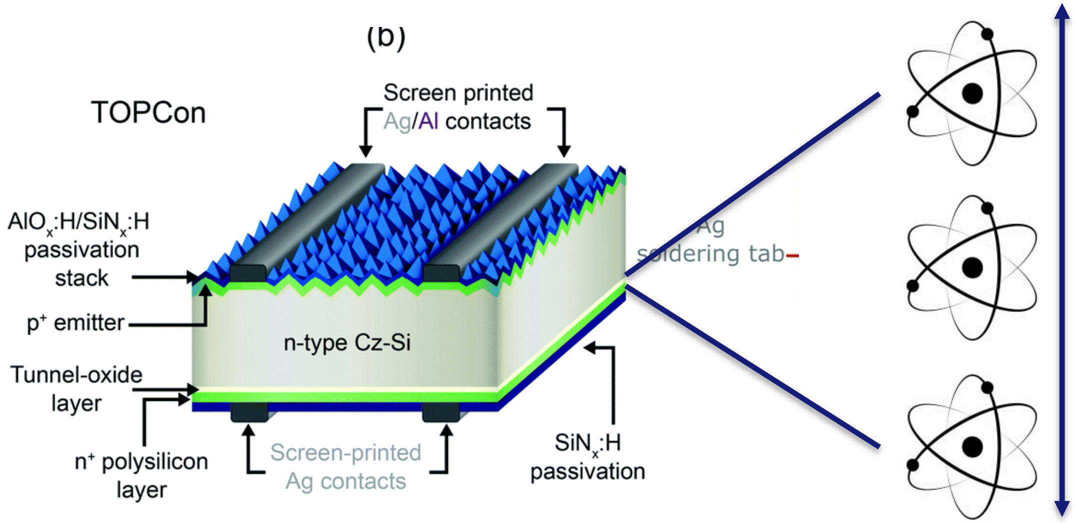
- Designed to eliminate direct metal-to-silicon contact.
- They consist of thin layers deposited on both sides of the wafer:
    - They passivate the surface defects.
    - They selectively collect the photogenerated carriers.

Third generation: TOPCON cell

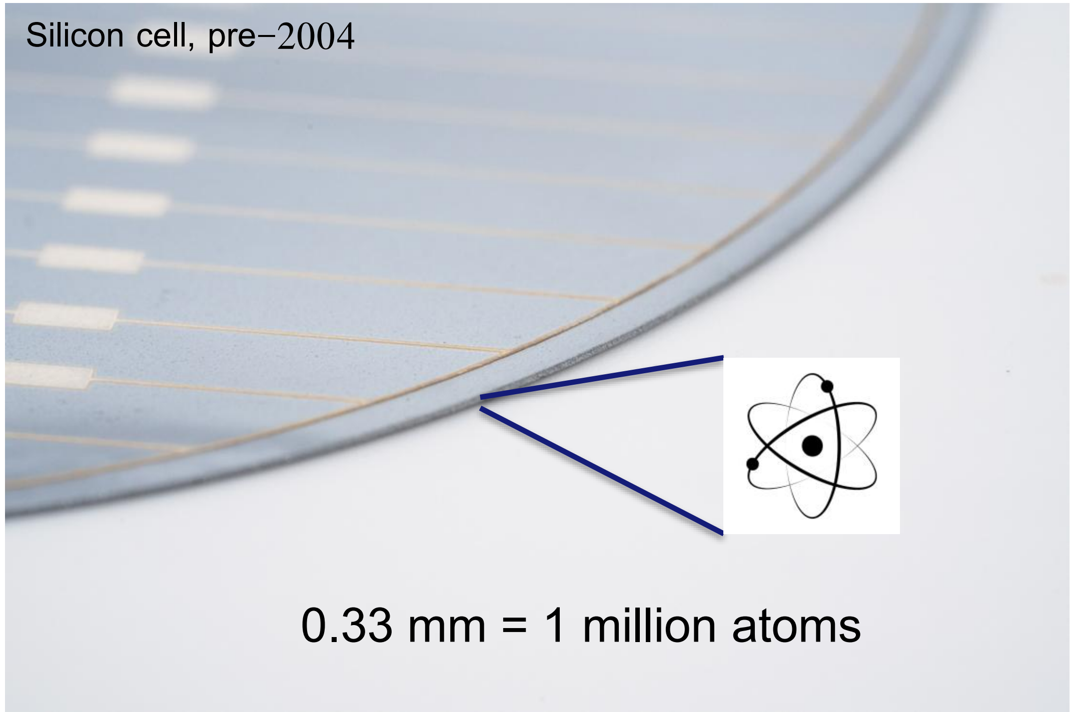


Voc: 715 mV Bifacial cell

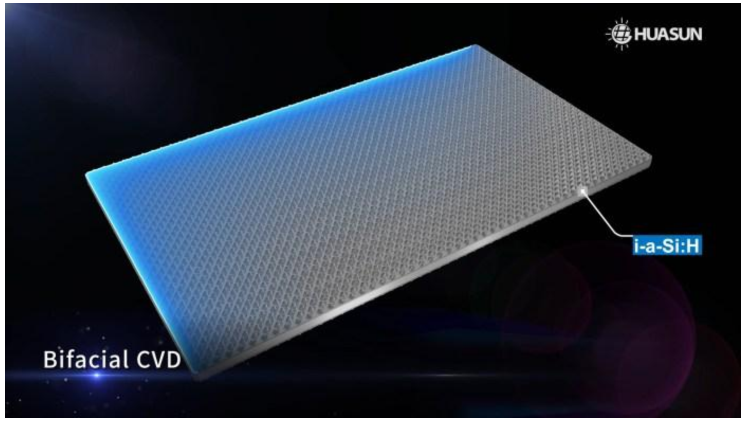
Passivation: SiOx oxide tunnel layer thickness 1–2 nm, polysilicon 50–300 nm

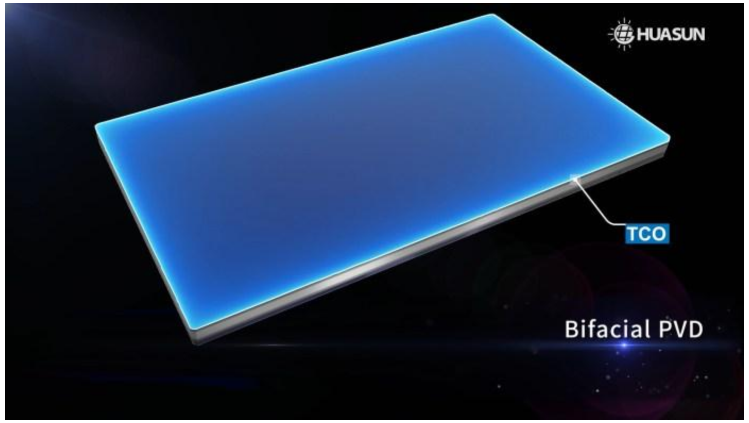

(b)
TOPCon
Screen printed
Ag/Al contacts
AlO$_x$:H/SiN$_x$:H passivation stack
p$^+$ emitter
n-type Cz-Si
Tunnel-oxide layer
n$^+$ polysilicon layer
Screen-printed Ag contacts
SiN$_x$:H passivation
Ag soldering tab

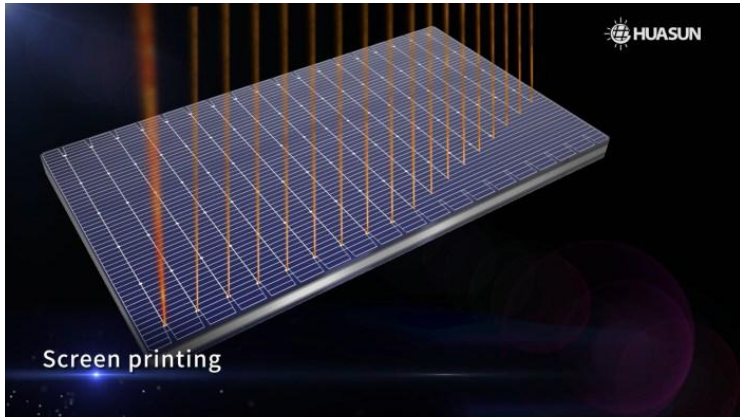
1 nm = 3 atoms

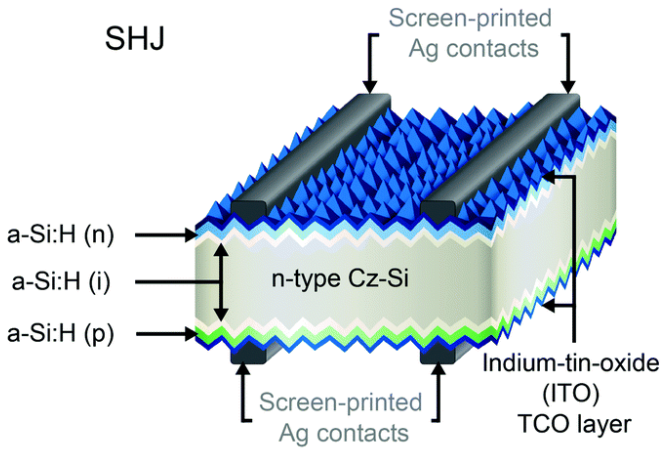

Silicon cell, pre-2004
0.33 mm = 1 million atoms

Third generation: heterojunction cells



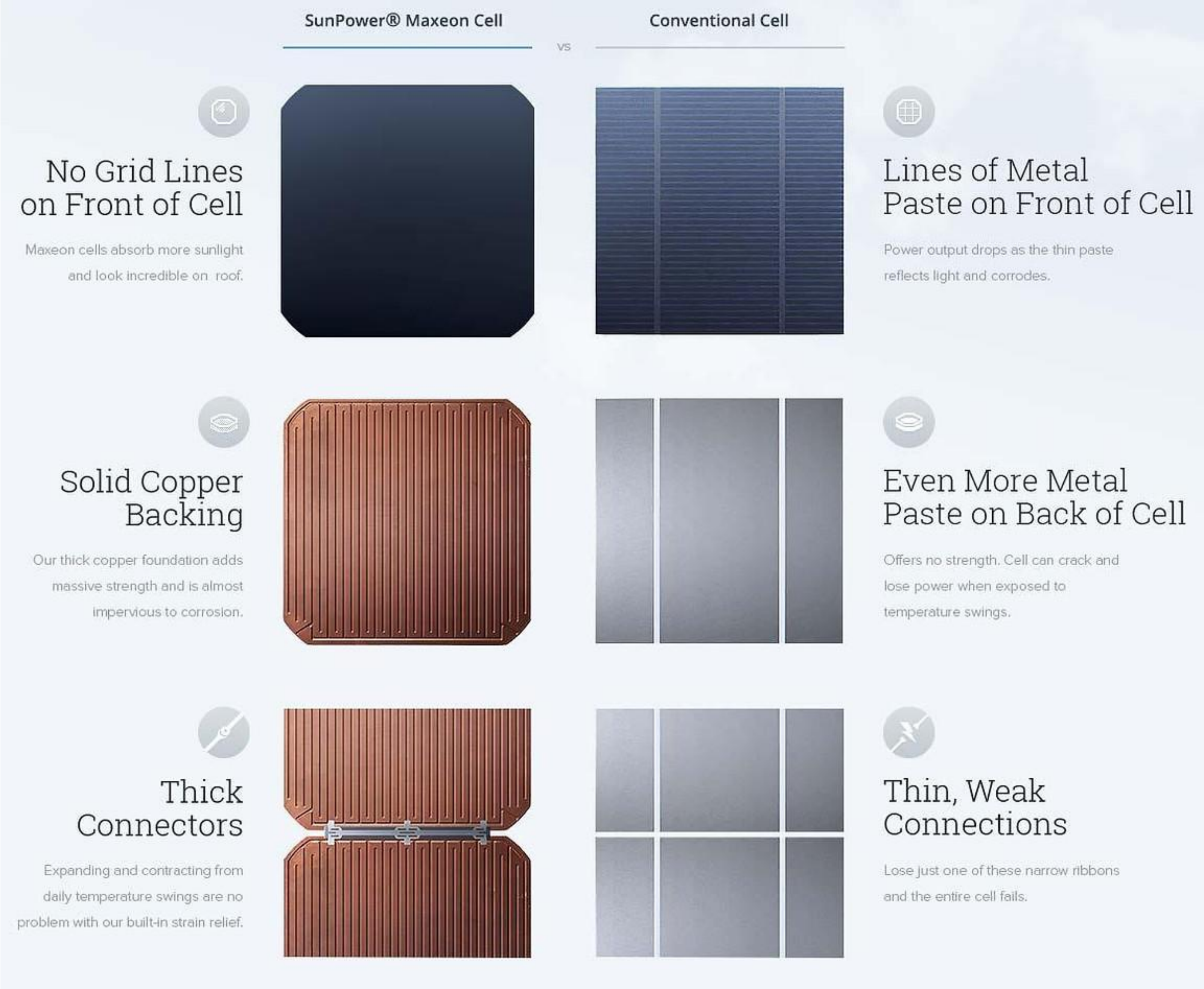


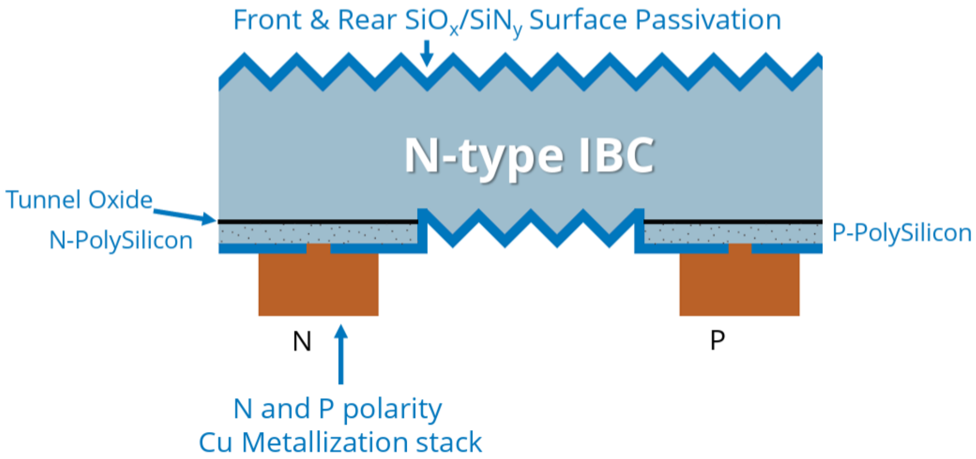




Voc: 740 mV Bifacial cell

Third generation: Interdigitated Back Contact (IBC) cells: Maxeon

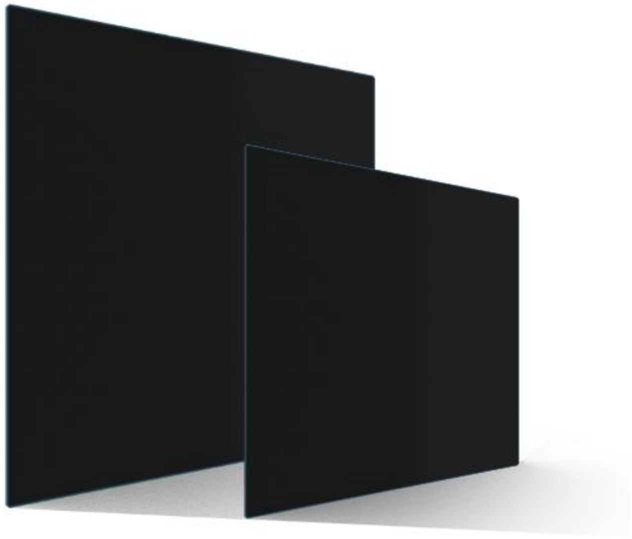


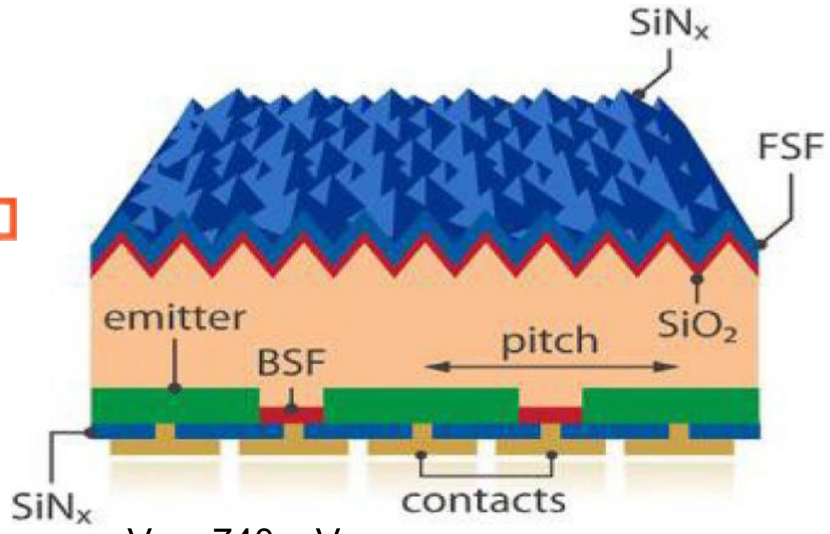


Voc: 740 mV

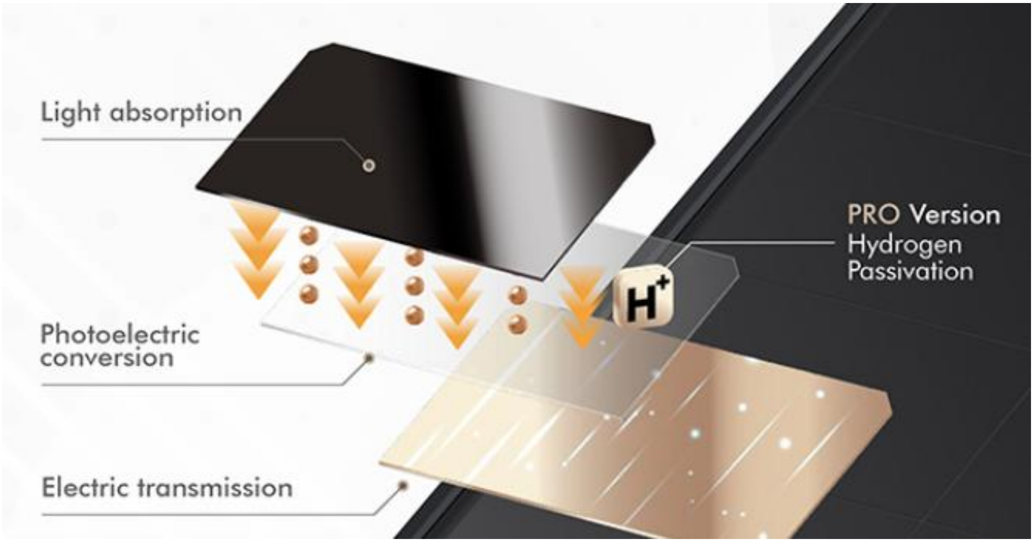
maxeon

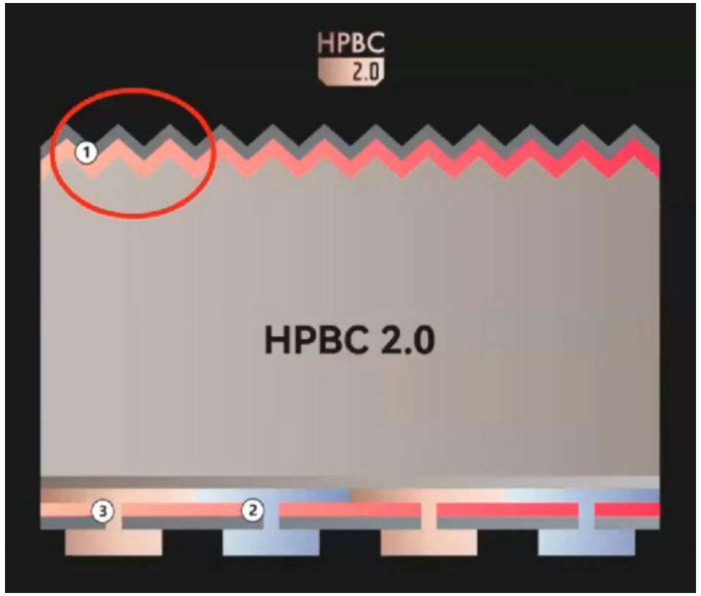
Third generation: All Back Contact (ABC) cells / Hybrid Passivation BC 2.0: AIKO / Longi





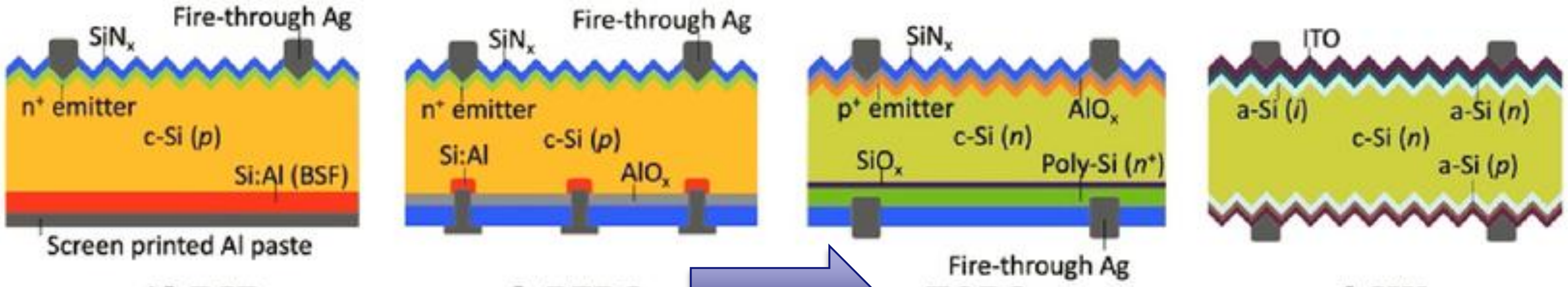
Voc: 740 mV





Third generation plus: TOPCon-compatible hybrid back-contact (THBC) / Hybrid Interdigitated-Back-Contact (HIBC) Trina/Longi

Industrial competitiveness: upgrading production lines from PERC to TOPCON



a Al-BSF	b PERC	c TOPCon	d SHJ
Texture	Texture	Texture	Texture
P-diffusion	P-diffusion	B-diffusion	a-Si:H deposition
Rear-side etch	Rear PSG removal	Rear BSG removal	ITO deposition
ARC/passivation	Rear-side etch	Rear-side etch	Screen printing
Screen printing	Selective emitter	SiO_x + poly(i)	Low-temp curing
Contact firing	Rear passivation	P-diffusion	
	ARC/passivation	Front-side etch	
	Laser opening	ARC/passivation	
	Screen printing	Rear passivation	
	Contact firing	Screen printing	
		Contact firing	

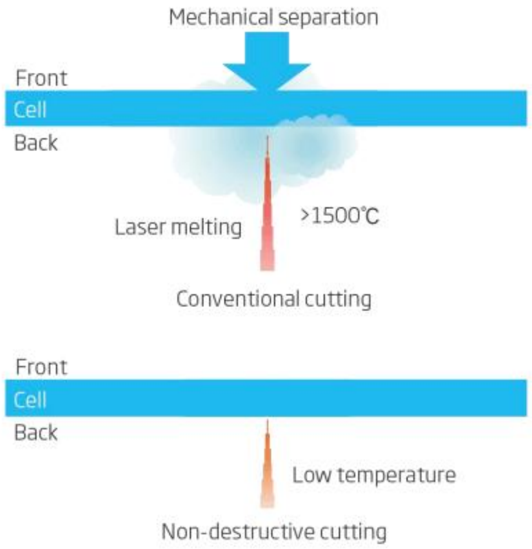
Making PV Modules…

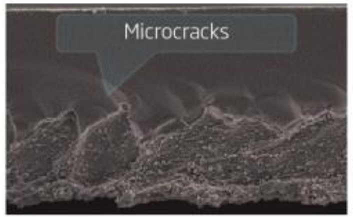
Cell cutting (Full-cell to 1/2, 1/3 and shingled cells)

Technology (*only most common ones*)	**Working Principle**	**Main Advantages**	**Main Challenges**	**Typical Applications**
Laser Scribing + Mechanical Separation	Laser creates weakened line, followed by controlled mechanical break	High throughput, mature process, cost-effective	Microcracks, heat-affected zone	Mainstream PERC / TOPCon production
Thermal Laser Separation (TLS)	Local heating and cooling generate controlled crack propagation	Very low damage, smooth edges, high mechanical strength	Higher equipment cost, slower process	High-efficiency TOPCon / HJT
Full Laser Cutting	Laser cuts completely through wafer	High precision, flexible geometries	More thermal damage and debris	Shingled cell manufacturing

Transition toward low-damage laser processes. Increasing adoption driven by:

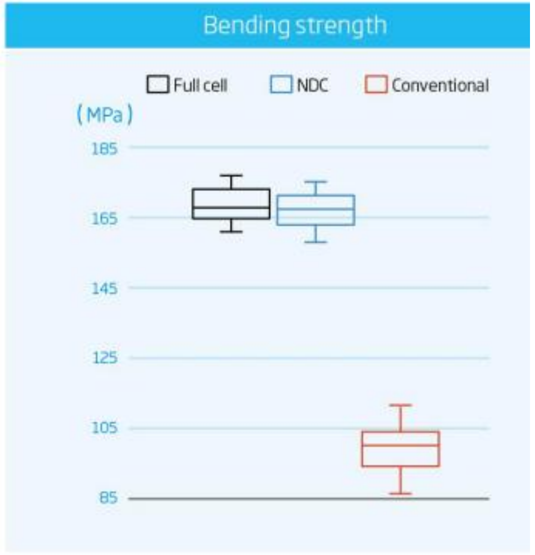
- thinner wafers
- larger wafer formats
- high-efficiency cell technologies
- shingled module architectures



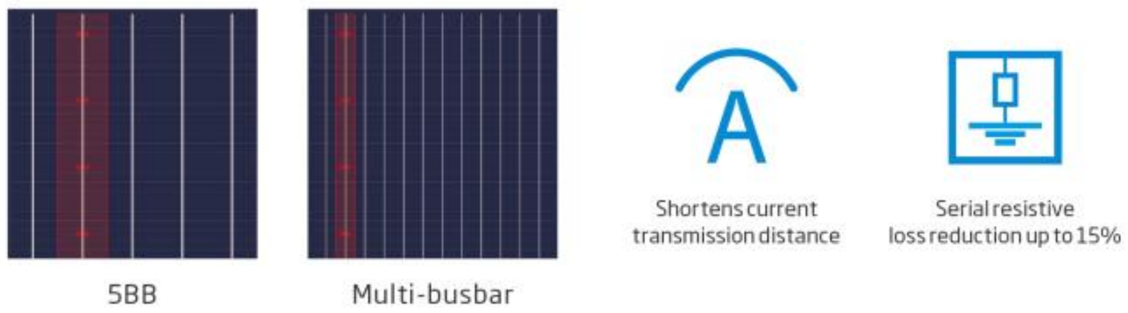


Cross-section of a solar cell from conventional cutting

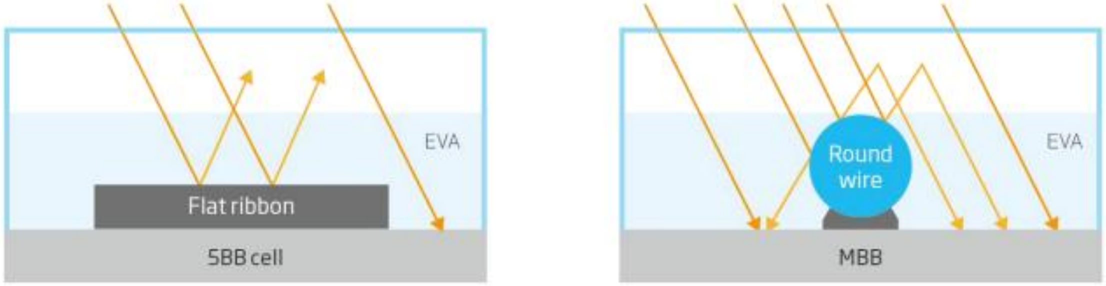
Cross-section of a solar cell from non-destructive cutting



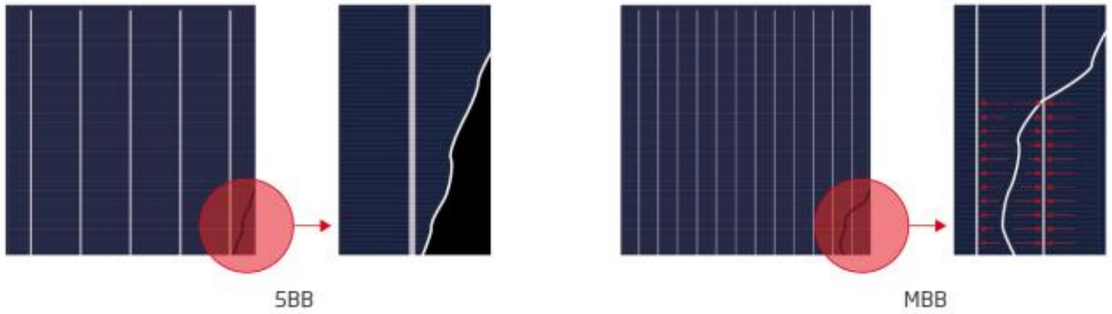
Multi Busbars



Shortens current transmission distance on the finger by more than 50%, reducing power loss due to internal resistance



Improves light utilization



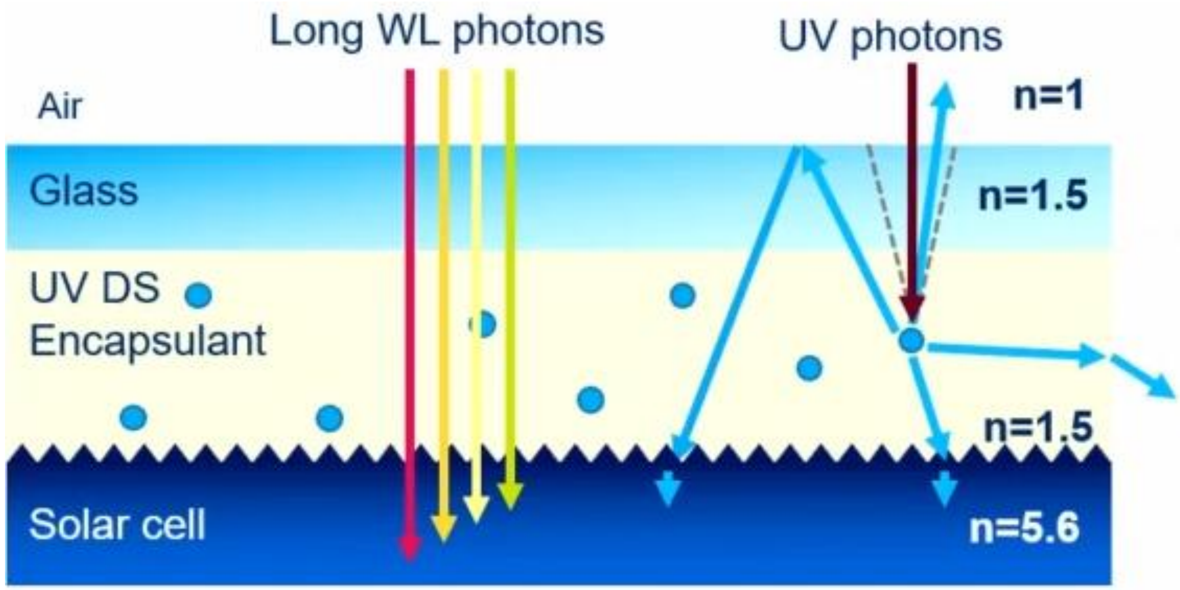
Reduces power loss caused by micro-cracks

UV-Downshifting Encapsulants

UVID Mitigation: Specifically addresses UV-induced degradation in high-efficiency c-Si cells by shifting high-energy photons to lower energies, which also reduces parasitic absorption.

Efficiency gain: Converts UV light into harmless visible light, boosting module power (increased current density)

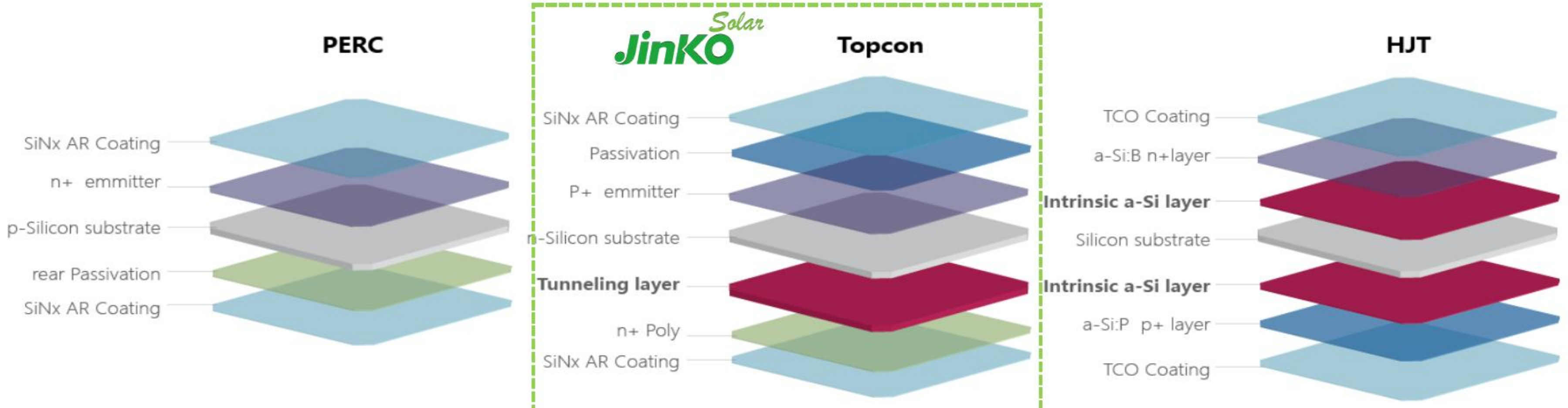
Improving both reliability and power efficiency



L. Marthey et al., EUPVSEC 2025

New cells, new materials, new modules: manufacturers’ roadmaps.

Technical Roadmap: **Why TOPCon?**

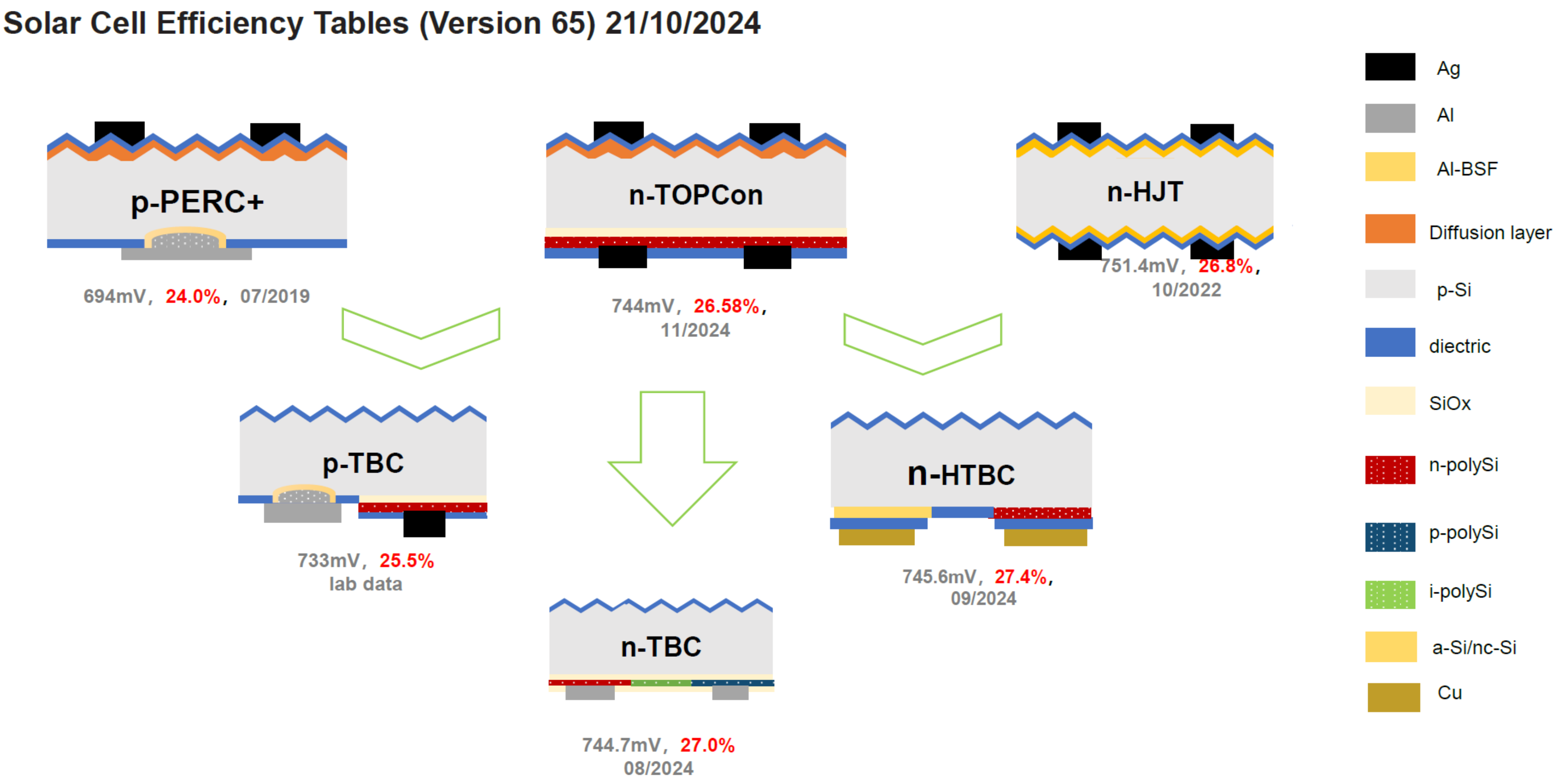


	PERC	Topcon	HJT
Theoretical Ultimate Efficiency [1,2]	24.5%	**28.7%**	28.5%
Temperature Coefficient	~-0.34	~-0.29	**~-0.27**
Bificiality	~70	~80	**~85**
PID Risk	PID-p	PID-p	PID resistant
Delamination Risk	Low	Low	High
Moisture Sensitivy	**	***	*****
Hot Spot Risk	**	**	*****
Cost	BSL	~BSL	**+~3cent/W**

[1] Brendel, R., Rienaecker, M. & Peibst, R. 2016, “A quantitative measure for the carrier selectivity of contacts to solar cells”, Proc. 32nd EU PVSEC, Munich, Germany, doi:10.4229/EUPVSEC201620162CO.4.1.
[2] Brendel, R. & Peibst, R. 2016, “Contact selectivity and efficiency in crystalline silicon photovoltaics”, IEEE J. Photovolt., Vol. 6, No. 6, pp.1413–1420, doi:10.1109/JPHOTOV.2016.2598267.

通威股份 TONGWEI CO., LTD.

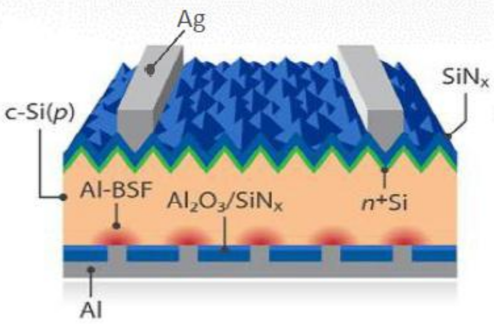
Efficiency pradox, struggle for BC future

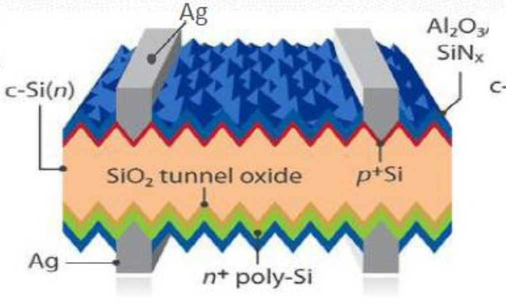


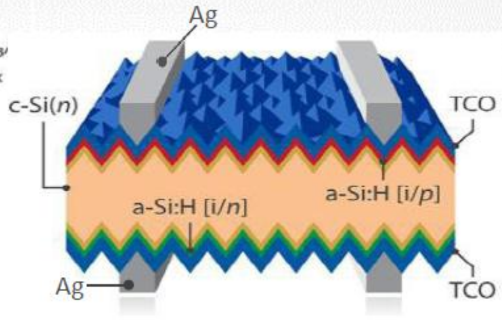
Comparison of Solar Cell Technology

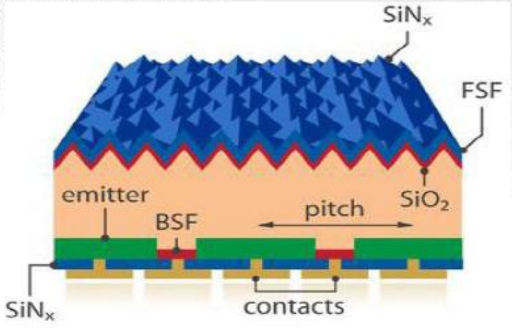
AIKO FIND YOUR POWER

Cell Topology

PERC


TOPCon


HJT


ABC


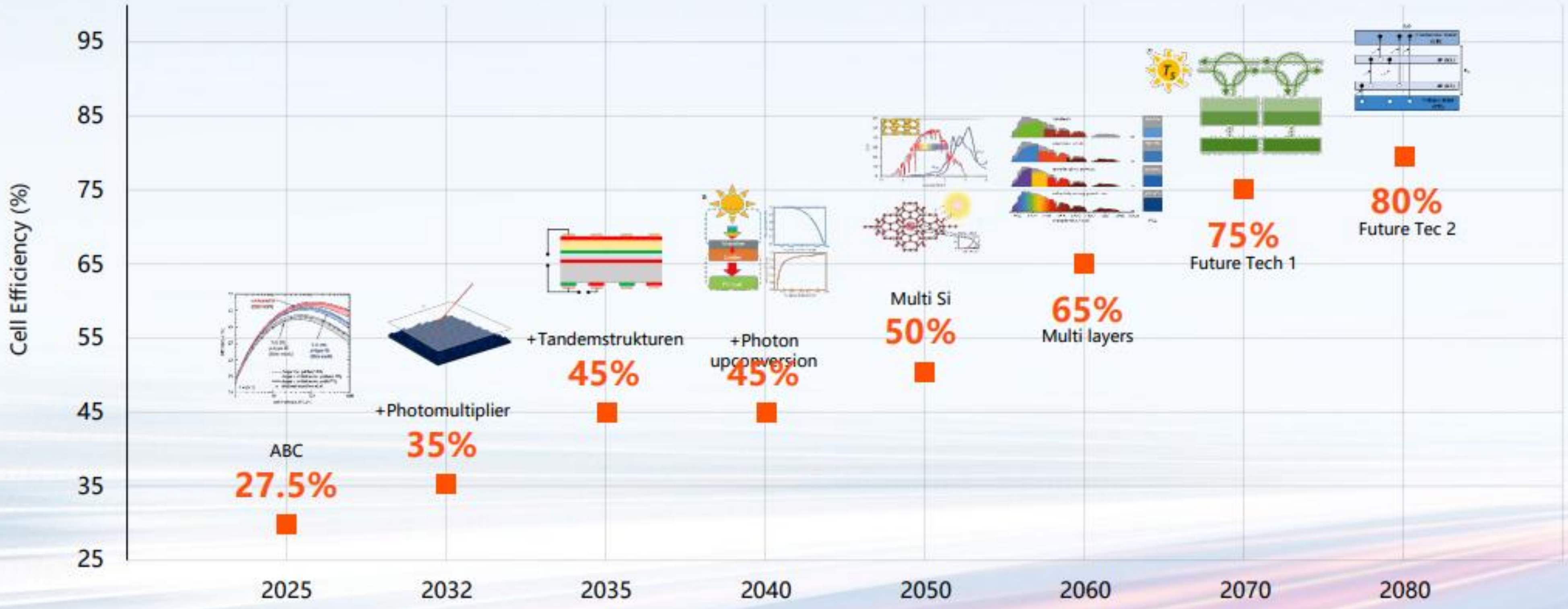
	PERC	TOPCon	HJT	ABC
Front Surface Shading	Yes (3-5% Shadings)	Yes (3-5% Shadings)	Yes (3-5% Shadings)	No (0% Shadings)
Ag-based Metalisation	Front+Back (~70mg)	Front + Back (~110mg)	Front + Back (~150mg)	No (0mg)
Metalisation Temperature	>700℃	>700℃	~200℃	>700℃
/	/	/	/	/
Voc	690mV	715mV	>740mV	>740mV
ETA Potential	23.5-24%	25-26%	25-26%	26-28%

The Next-gen PV Technology Beyond BC Era

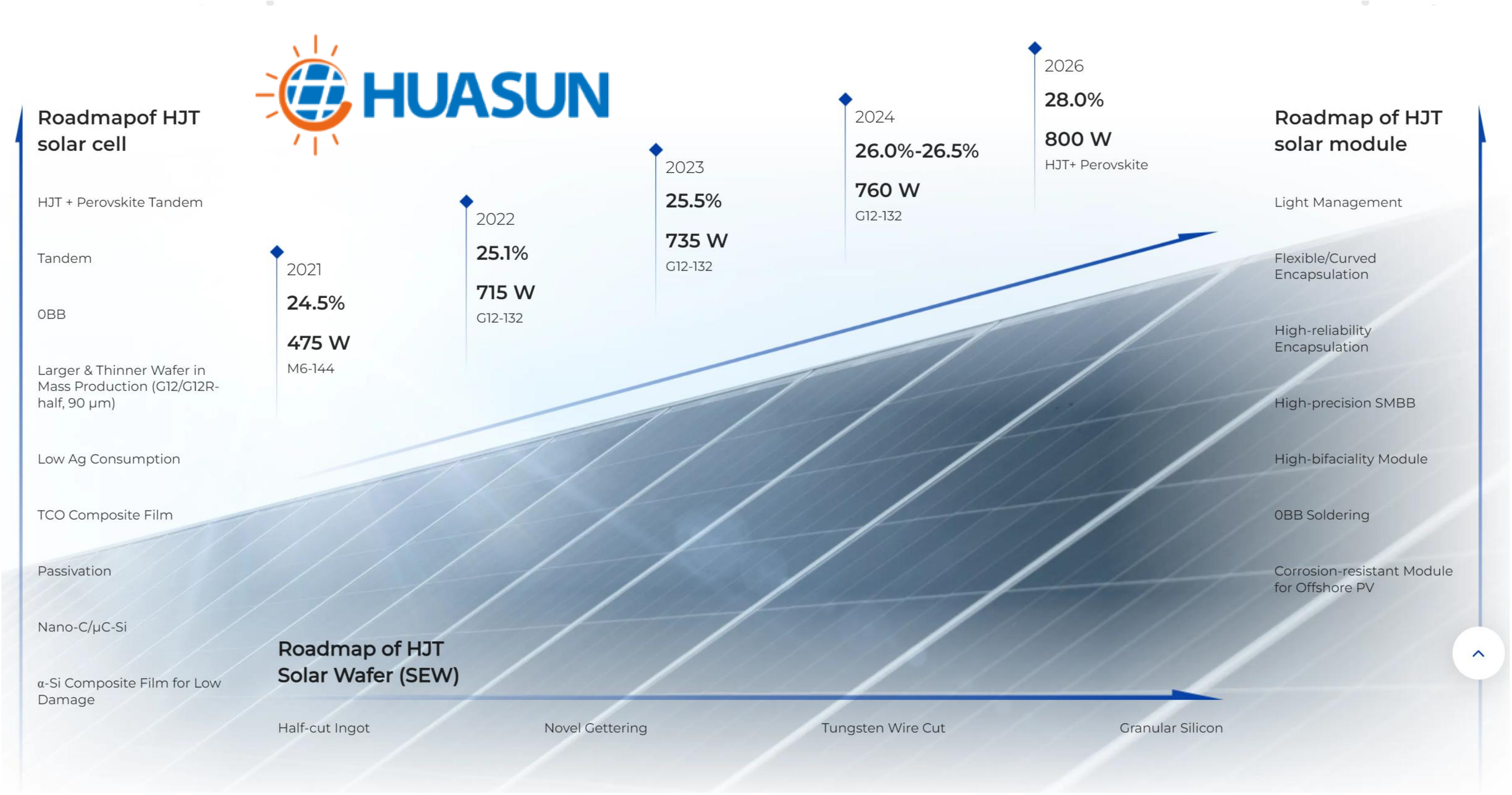
AIKO

Two directions for next-generation technology:

- Photon down conversion
- Tandem Technology



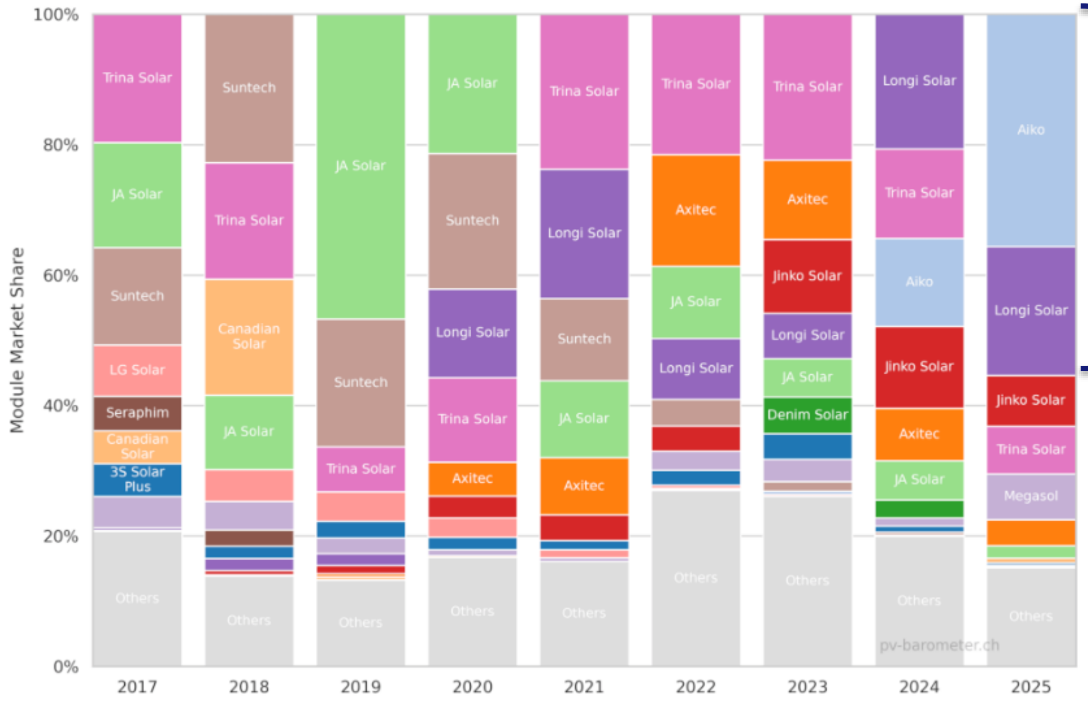

Generation Performance
BC is Able to Achieve the Highest Efficiency
P=Isc*(Voc*FF)
LONGi
Optical(Isc):
Zero
Light loss
Electrical(Voc*FF):
70% +
Reduced current loss+contact resistance1
Maximum
Technology compatibility
Light Absorption
Multi-layer anti-reflection film and absence of front busbars maximize light absorption and short-circuit current(Isc)
Photoelectric Conversion
Fully hybrid passivation to boost open-circuit voltage (Voc) and fill factor (FF)
Electric Transmission
Positive and negative electrodes connected at the back ensure stable current transmission and reduce reliability risk
29.1%
Highest theoretical cell efficiency among all Si technologies2
Note – 1- compared to TOPCon
2- single-junction crystalline Si cell technologies


HUASUN
Roadmapof HJT solar cell
HJT + Perovskite Tandem
Tandem
0BB
Larger & Thinner Wafer in Mass Production (G12/G12R-half, 90 μm)
Low Ag Consumption
TCO Composite Film
Passivation
Nano-C/μC-Si
α-Si Composite Film for Low Damage
2021
24.5%
475 W
M6-144
2022
25.1%
715 W
G12-132
2023
25.5%
735 W
G12-132
2024
26.0%-26.5%
760 W
G12-132
2026
28.0%
800 W
HJT+ Perovskite
Roadmap of HJT solar module
Light Management
Flexible/Curved Encapsulation
High-reliability Encapsulation
High-precision SMBB
High-bifaciality Module
0BB Soldering
Corrosion-resistant Module for Offshore PV
Roadmap of HJT Solar Wafer (SEW)
Half-cut Ingot
Novel Gettering
Tungsten Wire Cut
Granular Silicon

Switzerland PV Module Market Share

Solartrends, Brancheneinblicke und Analysen

Dieser Report zeigt, wie sich die technischen Eigenschaften von PV-Modulen und Wechselrichtern in den Jahren 2017 bis 2025 verändert haben. Darüber hinaus wird auch die Entwicklung von System- und Marktdaten wie Marktanteile von Herstellern oder die Anzahl Batteriespeicher analysiert. Die Daten stammen aus einer anonymisierten und mengengewichtet konsolidierten Datenbank von Eturnity und wurden gemeinsam mit dem PV-Labor der Berner Fachhochschule (BFH) aufbereitet. Es wird angenommen, dass die vorgestellten Produktdaten repräsentativ für PV-Anlagen in der Schweiz und generell für PV-Anlagen auf Gebäuden sind. Freiflächenanlagen hingegen sind in den Daten kaum vertreten.



XBC
>50%

Summarising:

- Solar cells and their efficiency are evolving rapidly and continuously: today, we have modules for residential installations with a capacity of over 500W.
- On the Swiss and European residential markets, the size of the panels is limited only by their weight: the switch to glass-to-glass solutions results in weights exceeding 25 kg, which poses a problem for handling
- The potential of IBC cells is also promising due to their intrinsic diode effect at the single-cell level: in the event of shading, losses are lower and temperatures are lower
- Topcon’s technology is based on PERC technology, which has been on the market for several years
- The potential of bifacial cells is of interest for large modules and large-scale projects, but it also influences choices in the residential market
- With so many changes, it is easy to lose sight of the factors that ensure the quality of the modules: accelerated testing, field testing, in-line quality control, and the ability to rectify errors without the risk of going bankrupt, as has happened in the past.

Thank you!