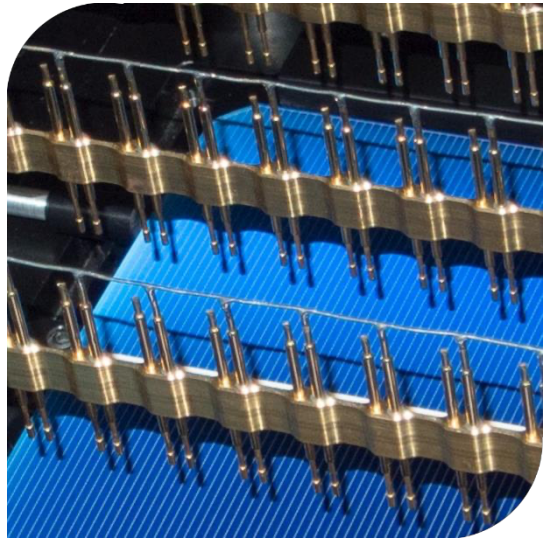



Global Solar Technology Trends
From Silicon to Modules

Dr. Radovan Kopecek, Andreas Halm et al.

ISC research for a sunny future

International Solar Energy Research Center Konstanz

Agenda

1. ISC Konstanz R&D and technology ramp-up
2. c-Si PV tech

Market forecast (outside of China, in US)

Highest efficient modules

PV value chain

a. Material (Si, ingot, wafer)

b. Solar cells

c. Modules

d. Systems

Statements in PV arena

Hot R&D topics in PV arena

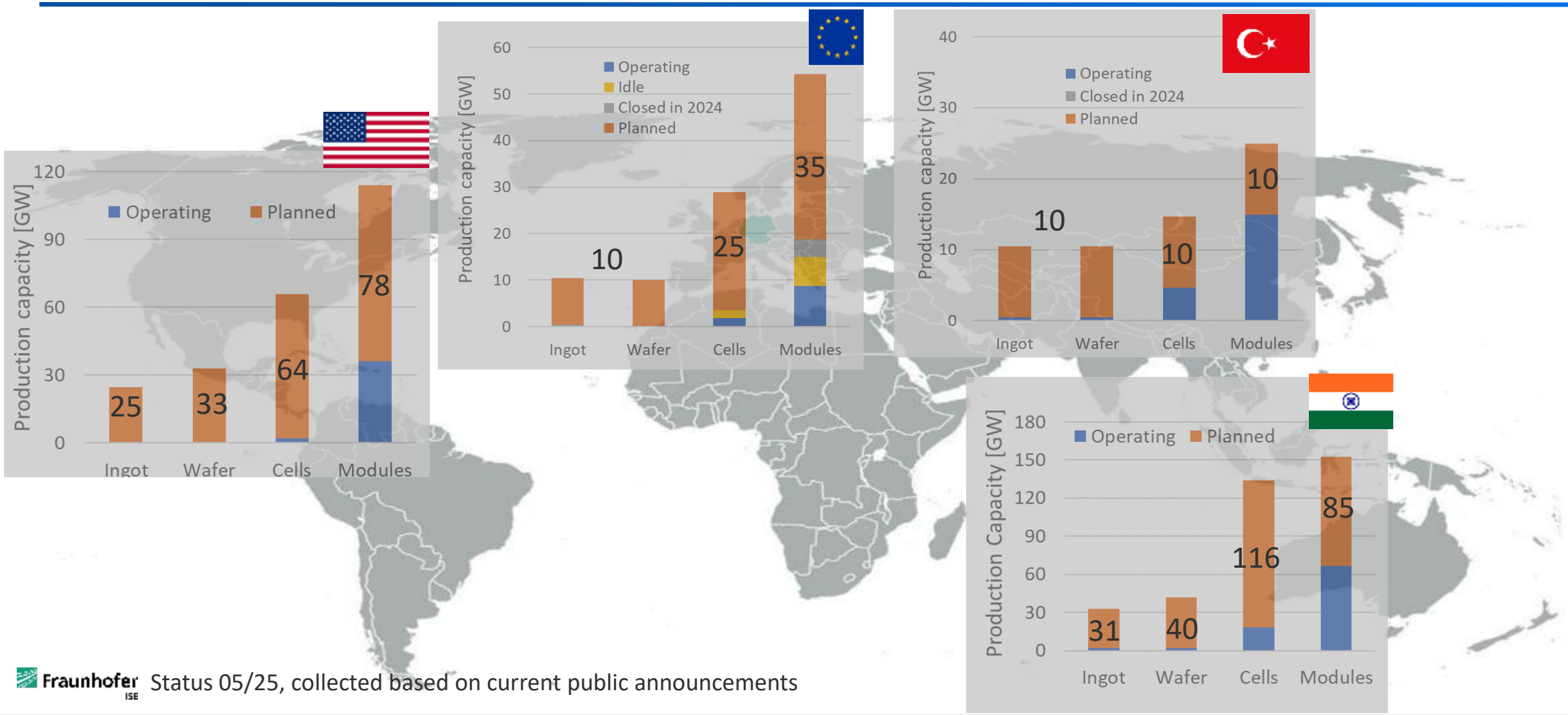
Employees at ISC Konstanz	Turnover 2025	Educated scientists	Achieved solar cell efficiency*	Transferred technology
70 ↗	8 Mio€ ↗	150 ↗	24.6% ↗ (Lab: 24.8%)	7GW ↗

*in industrial manufacturing

Technology transfer & Ramp-up service – track record

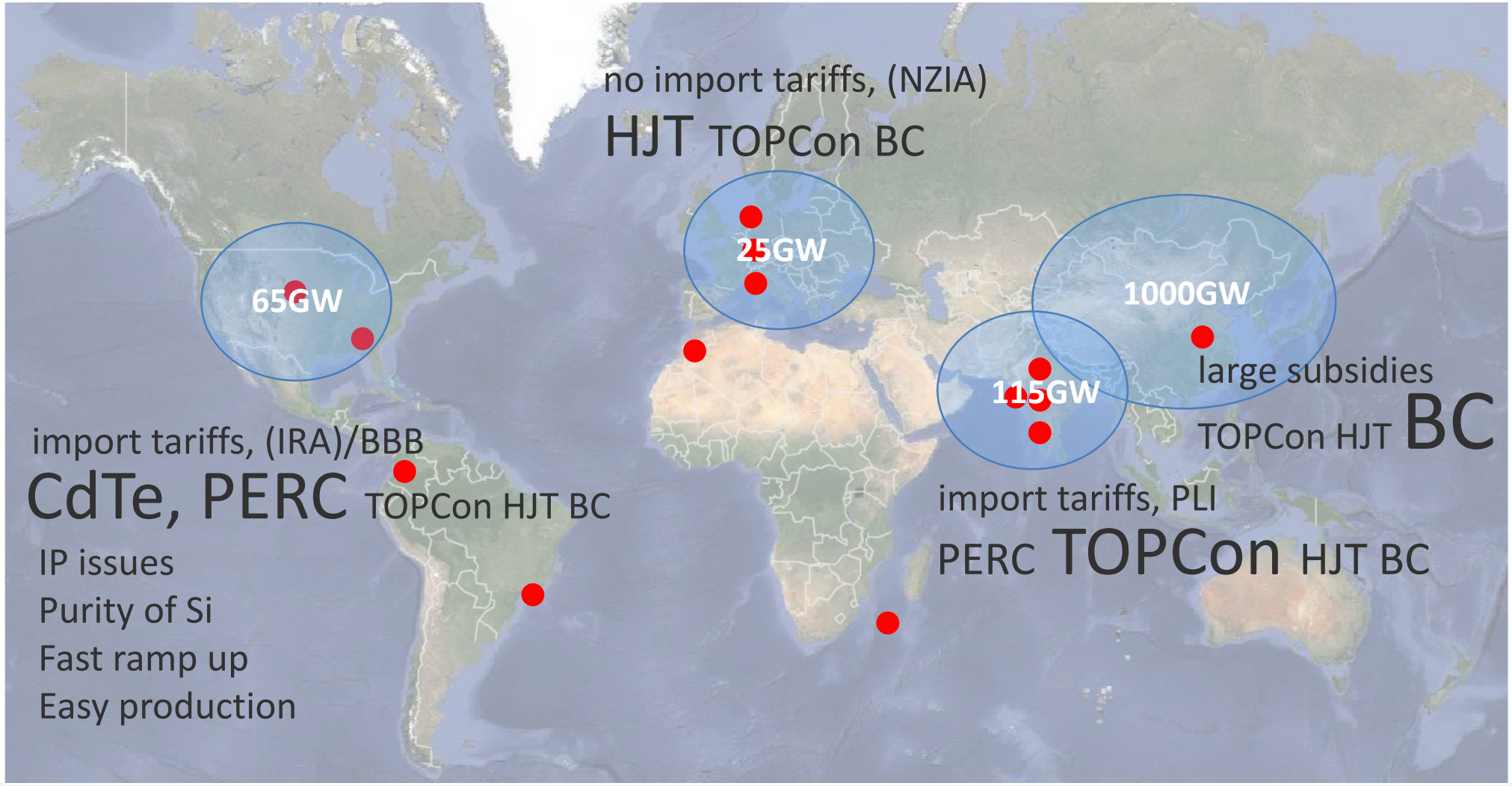
- ISC Konstanz has **20 years of experience** in development and industrialization of n-type cells concepts
- **Successful process transfers into industry:**
  - 2015 @ MegaCell, Italy → BiSoN (40MW nPERT technology successfully transferred)
  - 2017 @ Adani, India → BiSoN (80MW nPERT technology successfully transferred)
  - 2018 @ undisclosed Asian customer → BiSoN converted to !!TOPCon!!
  - 2020 @ SPIC, China → ZEBRA (200MW IBC technology transferred and in mass production)
  - 2021 @ Valoe Solar, Lithuania → ZEBRA (60MW IBC technology, ramp-up service)
  - 2023 @ Asian customer, India → PERC (2GW process optimisation on Asian process equipment)
  - 2024 @ Asian customer, India → PERC (450MW process optimisation on European process equipment)
  - 2024 @ Asian customer, India → TOPCon (2GW process optimisation on Asian process equipment)
  - Ongoing @ Asian customer, India → TOPCon (1.2GW process optimisation on European process equipment)
  - Ongoing @ Suniva, US → PERC (1GW process optimisation on European process equipment)
  - Ongoing @ Asian customer, India → TOPCon (500MW > 4GW process optimisation on European process equipment)

Total production capacity and forecast

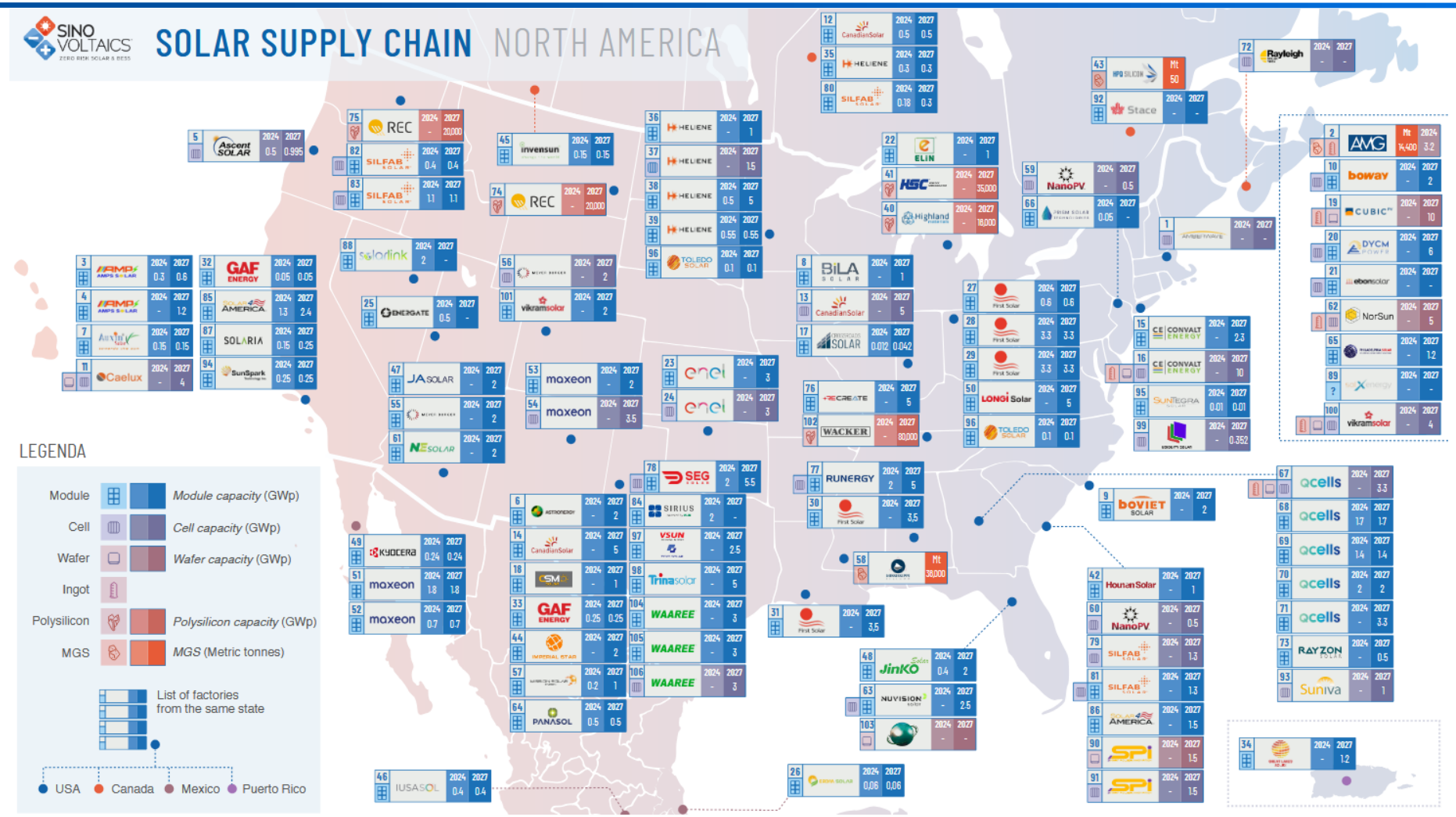


Fraunhofer ISE Status 05/25, collected based on current public announcements

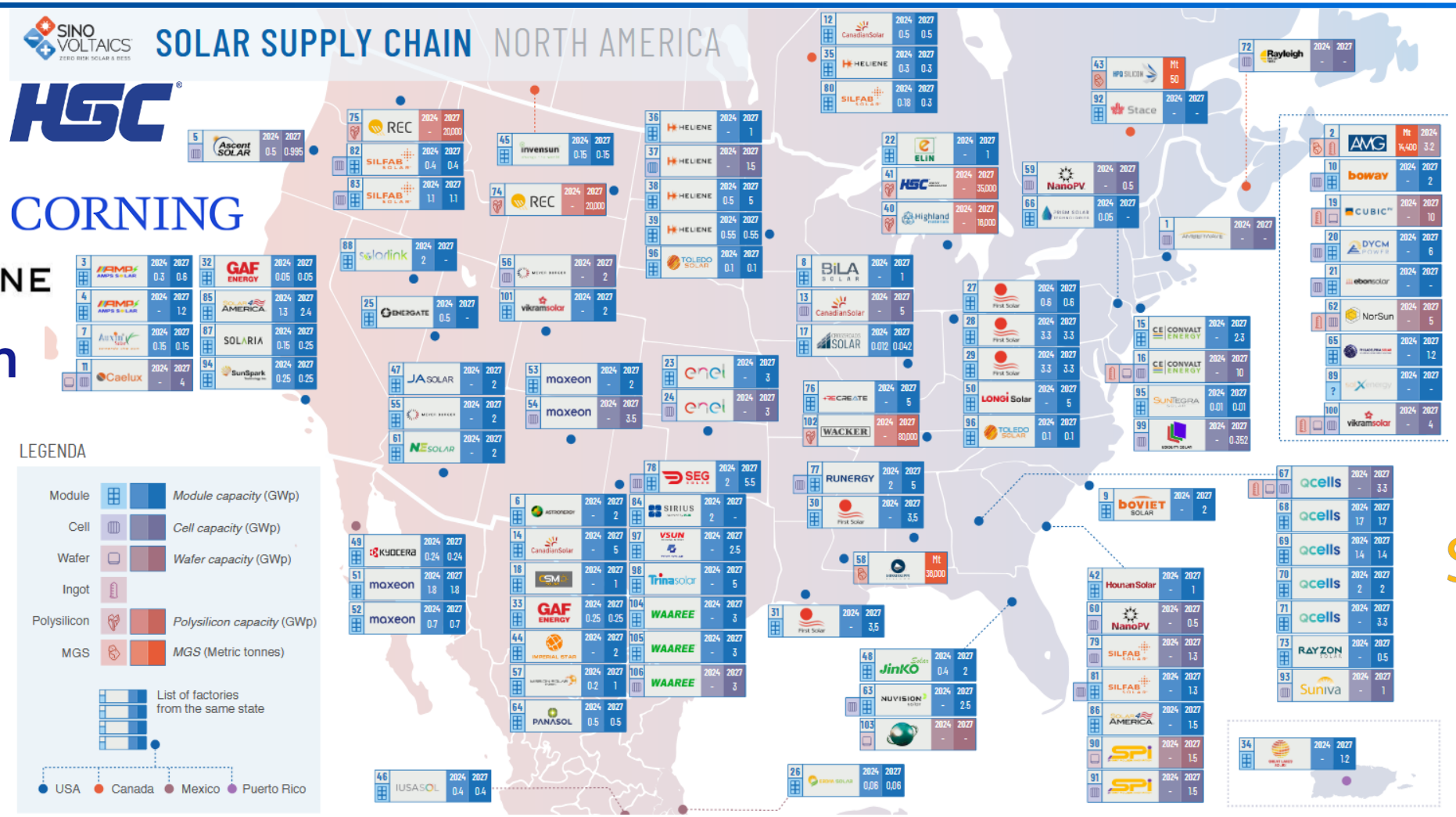
Total cell production until 2027 and ISC´s projects

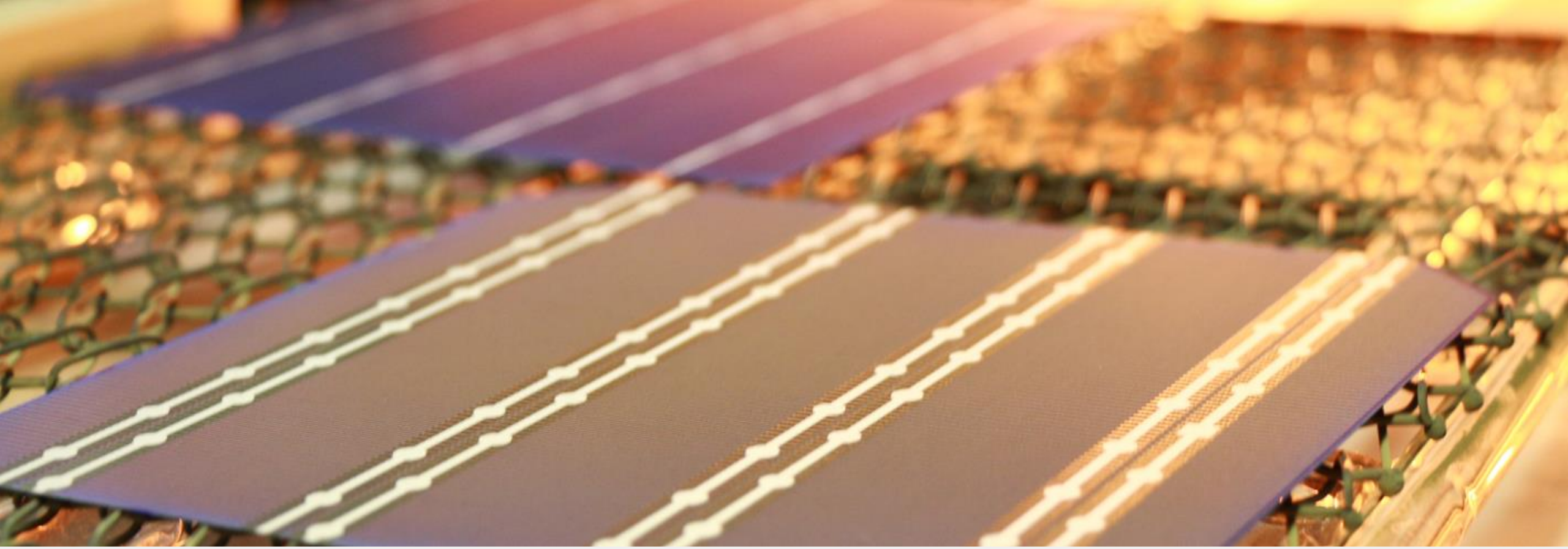


Production landscape in NA



Production landscape in NA





c-Si technology

Highest efficiency modules in August 2025

TAIYANGNEWS ALL ABOUT SOLAR POWER

TaiyangNews Top Modules: Highest Efficient Commercial Solar Modules 08-2025

Rank	Company	Series	Model	Wafer type	Cell Size	Cells No.	Cell Tech	Module Technology	Power (W)	Efficiency (%)
1	AIKO	Comet 2U	AIKO-G660-MCH72Mw	n-type	182	144	ABC	Half-cell, Back Contact	660	24.4
2	LONGi	Hi-MO 9	LR8-66HYD 635-655M	n-type	182	132	HPBC	Bifacial, Half-cell, Back Contact	655	24.2
3	Maxeon	Maxeon 7	SPR-MAX7-445-PT	n-type	125	112	IBC	Back Contact, Full-cell	445	24.1
4	HUASUN	Himalaya	HS-210-B132DS730W	n-type	210	132	HJT	Bifacial, Half-cell, MBB	730	23.5
5	JinkoSolar	Tiger Neo	JKM625-630N-66HL4M-BDV	n-type	210R	132	TOPCon	Bifacial, Half-cell, MBB	630	23.32
6	JA SOLAR	DeepBlue 4.0 Pro	JAM72D40 600/MB	n-type	182	144	TOPCon	Bifacial, Half-cell, MBB	600	23.2
7	ASTRONERGY	Astro N7	CHSM66RN(DG)/F-BH	n-type	182	132	TOPCon	Bifacial, Half-cell, MBB	625	23.1
8	Trinasolar	Vertex N	TSM-NEG21C.20	n-type	210	132	TOPCon	Bifacial, Half-cell, MBB	715	23.0
8	TW SOLAR	-	TWMHF-66HD700-715W	n-type	210	132	HJT	Bifacial, Half-cell, MBB	715	23.0
8	DMEGC	Infinity RT	DM620G12RT-B66HSW	n-type	210	132	TOPCon	Bifacial, Half-cell, MBB	620	23.0
11	Jetion Solar	Jeniüs	JT SLk(B) 690-710W	n-type	210	132	HJT	Bifacial, Half-cell, MBB	710	22.9
12	Grand Sunergy	-	GSM-MH3/132-BHDG710	n-type	210	132	HJT	Bifacial, Half-cell, MBB	710	22.86
13	TW SOLAR	-	TWMND-72HS575-590W	n-type	182	144	TOPCon	Half-cell, MBB	590	22.8
13	SPIC	ANDROMEDA 3.0	SPICN6(LDF)-60/BIH410W	n-type	166	120	TBC	Bifacial, Back Contact, Half-cell, MBB	410	22.8
15	SolarSpace	Lumina II	SS8-72HD-585N	n-type	182	144	TOPCon	Bifacial, Half-cell, MBB	585	22.65
16	REC Group	AlphA®Pure-RX	REC470AA Pure-RX	n-type	210	88	HJT	Bifacial, half-cell, MBB	470	22.6
17	GCL	-	GCL-NT12/66GDF	n-type	210	132	TOPCon	Bifacial, half-cell, MBB	700	22.53
17	中来股份 JOLYWOOD	Niwa Pro	JW-HD108N415-440W	n-type	182	108	TOPCon	Bifacial, Half-cell, MBB	440	22.53
19	risen	Hyper-ion	RSM132-8-700BHDG	n-type	210	132	HJT	Bifacial,Half-cell, MBB	700	22.5
19	DASOLAR	-	DAS-DH156NA-620-630W	n-type	182	156	TOPCon	Bifacial, Half-cell, MBB	630	22.5
19	Canadian Solar	TOPHiKu6	CS6W-570-580T	n-type	182	144	TOPCon	Half-cell, MBB	580	22.5
19	Eging PV	STAR Pro	EG-580NT72-HL/BF-DG	n-type	182	144	TOPCon	Bifacial, Half-cell, MBB	580	22.5
19	RUNERGY	-	HY-DH144N8	n-type	182	144	TOPCon	Bifacial, Half-cell, MBB	580	22.5

3 x BC 24+%

HJT 23+%

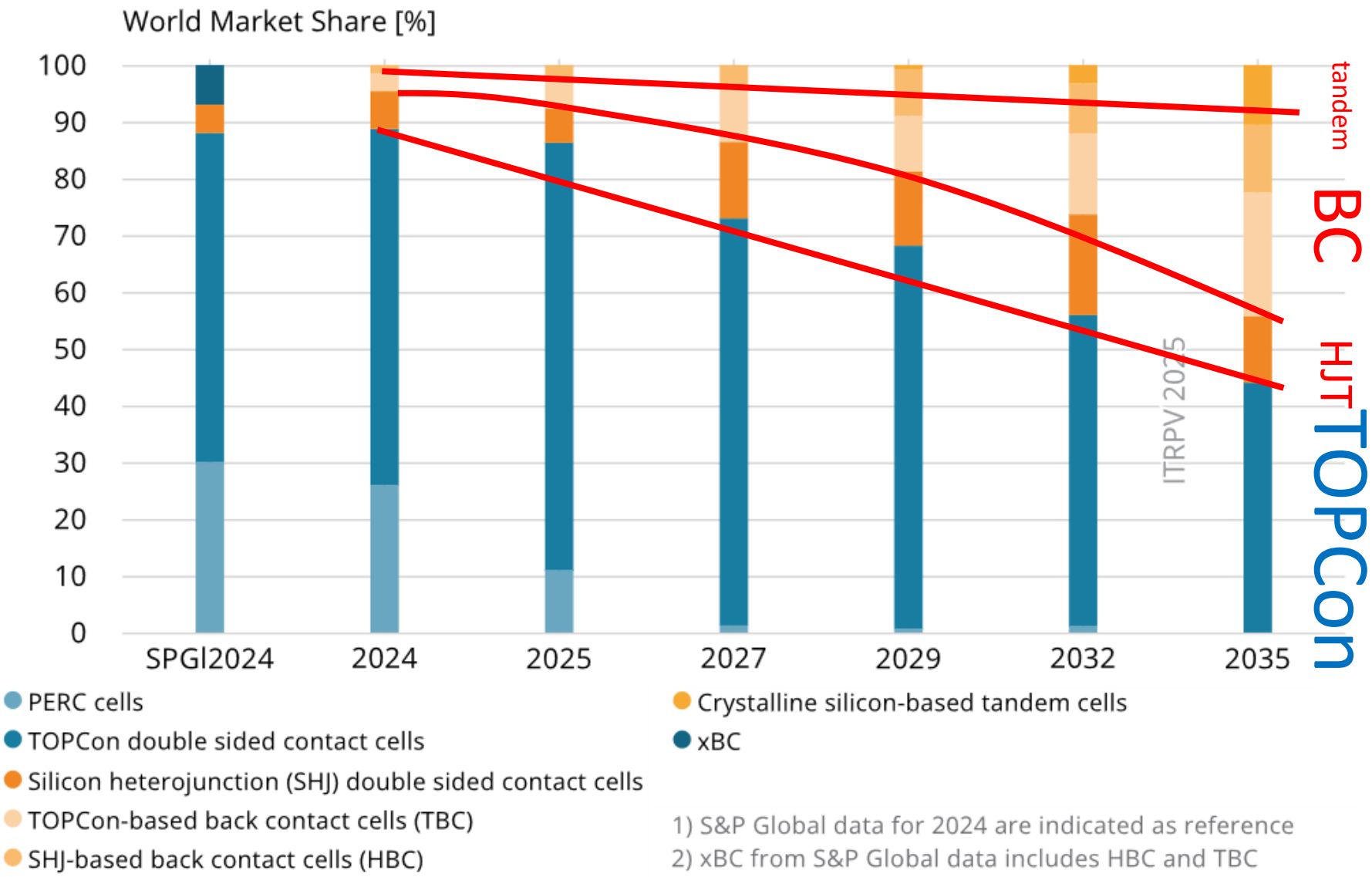
TOPCon 23+%

PERC 21.5-22%

Different cell technologies

For GW-scale device and equipment manufacturers

ITRPV | International Technology Roadmap for Photovoltaics



28+%

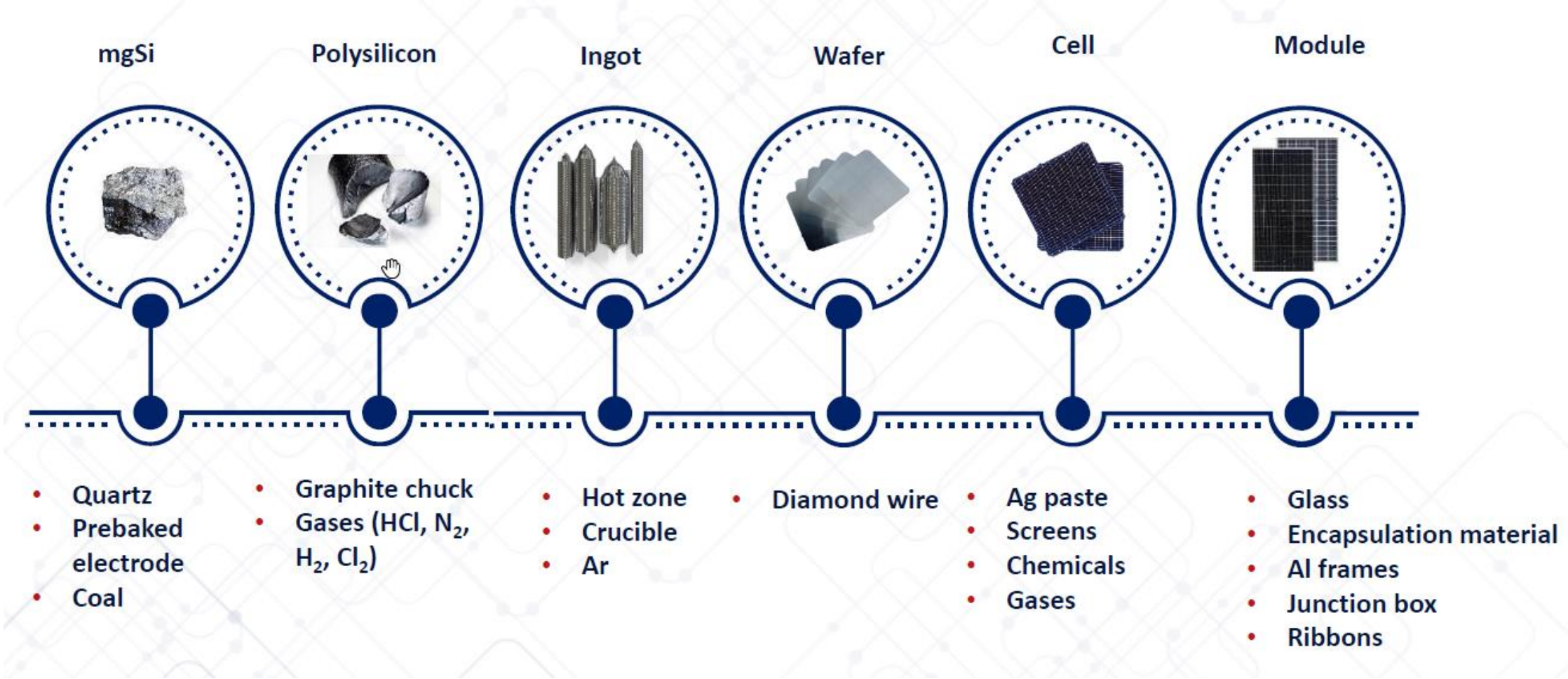
25+%

24+%

24+%

21.5-22%

c-Si PV value chain



Si material: from p-type to n-type

Poly-Si: Siemens, FBR and other (e.g. UMG-Si/Highland) > electronic grade purity necessary (10N+)

Ingot: Recharged Cz-Si, P, Sb (Tai Ray) doping, 2+ms (wafer) lifetime

Wafer: M10/G12 families, 130µm thickness direct wafer (NexWafe)

ITRPV | International Technology Roadmap for Photovoltaics

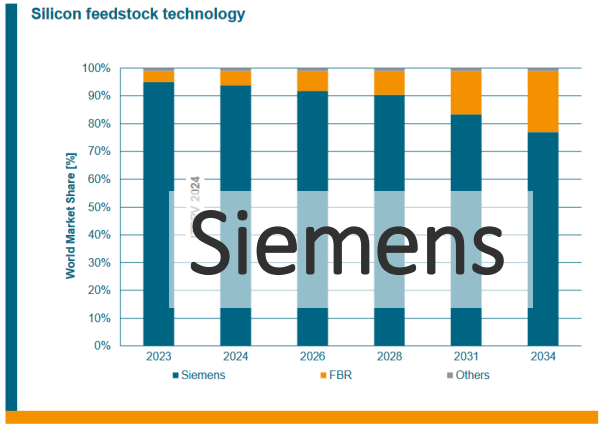


Fig. 2: Expected world market share of poly-Si feedstock technology.

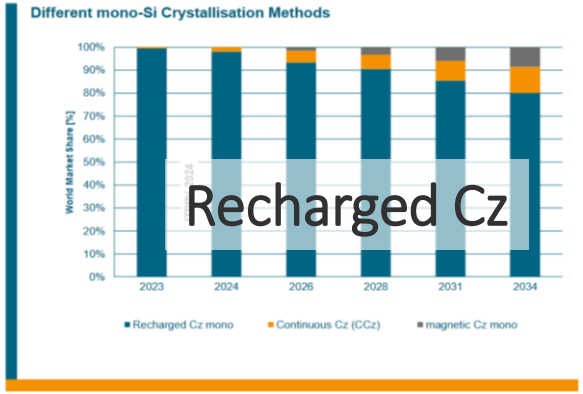


Fig. 5: Different mono-Si crystallization methods.

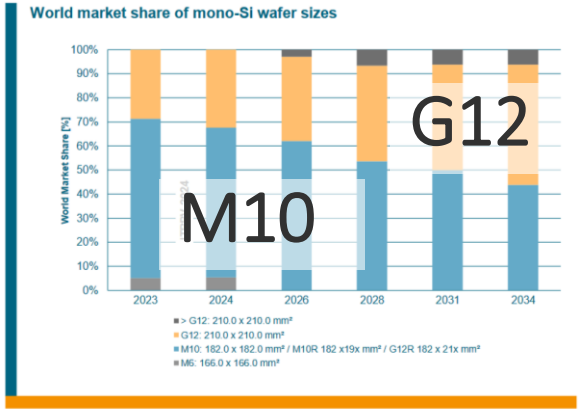


Fig. 10: Expected trend of Cz-mono-Si wafer size in mass production.

Crystalline silicon **solar cell** technology

Efficiency

26%

25%

24%

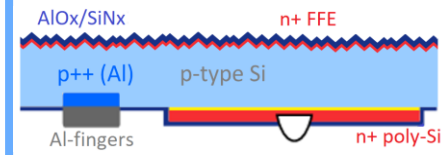
23%

p-type

n-type

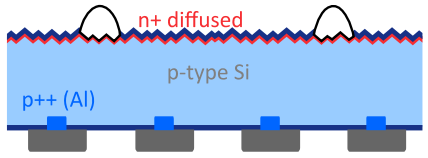
3.5 TBC solar cells

TOPCon-p-IBC (720 mV)



3.1 Al-BSF &PERC solar cells

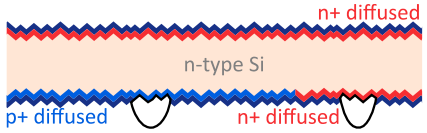
PERC (690 mV)



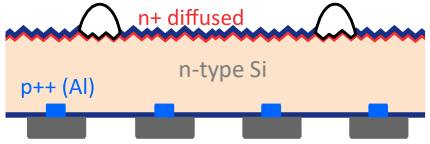
3.5 IBC solar cells

3.2 nPERT solar cells

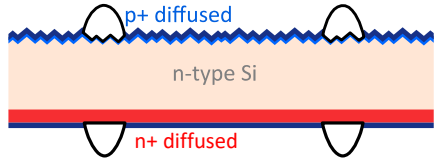
IBC (705 mV)



nPERT RJ (705 mV)



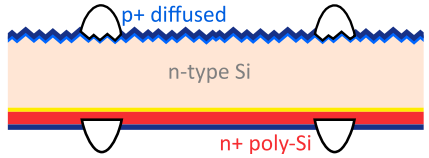
nPERT FJ (685 mV)



3.3 TOPCon* solar cells

LECO

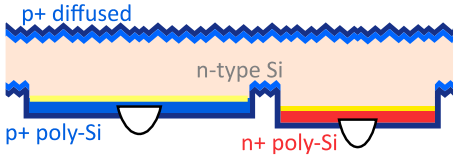
TOPCon-like (738 mV)



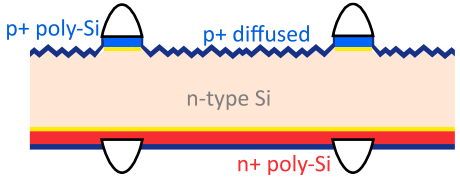
3.5 TBC solar cells

3.3 TOPCon*-2 solar cells

TOPCon-n-IBC (740+ mV)



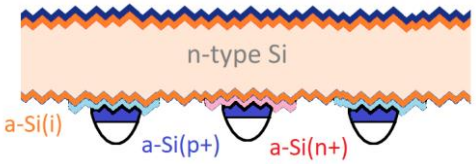
TOPCon-like 2 (740+ mV)



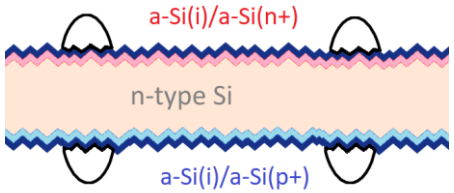
3.5 HBC solar cells

3.4 SHJ solar cells

SHJ-IBC (740+ mV)



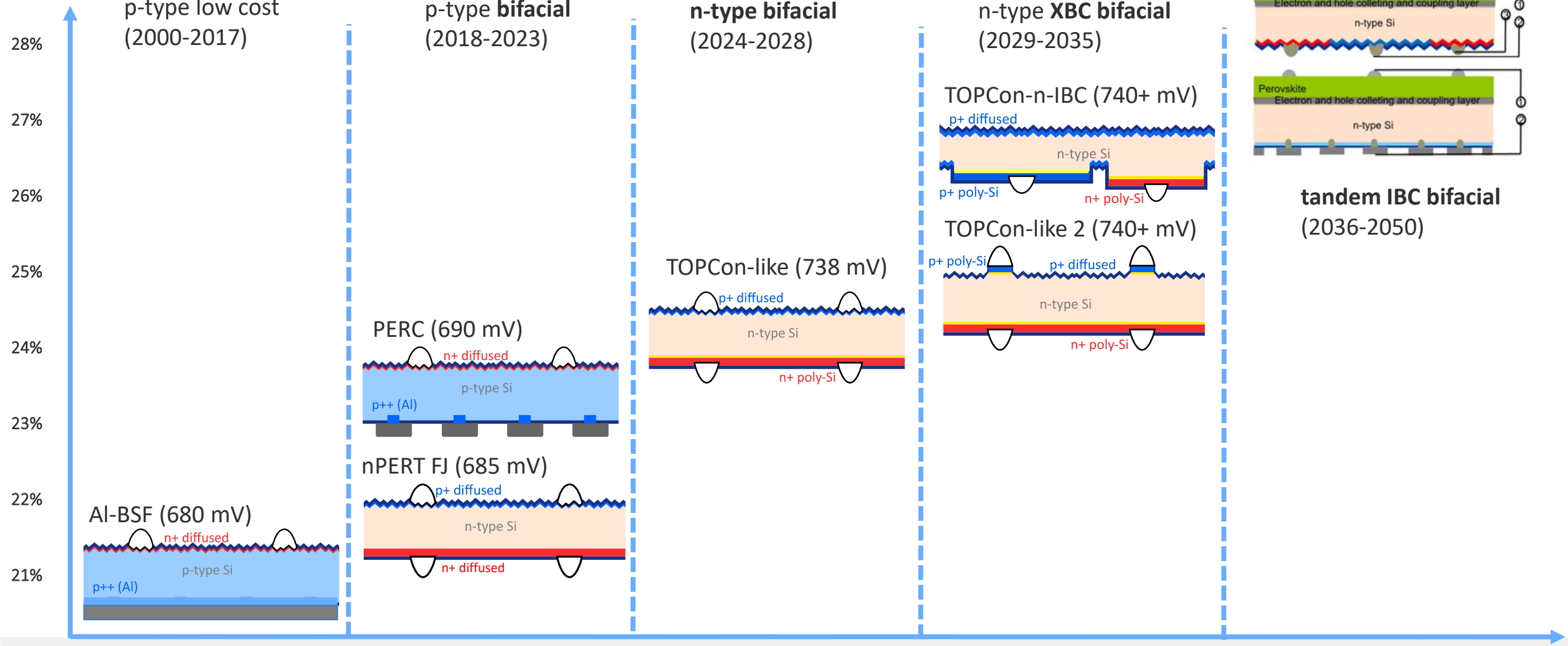
SHJ (740+ mV)



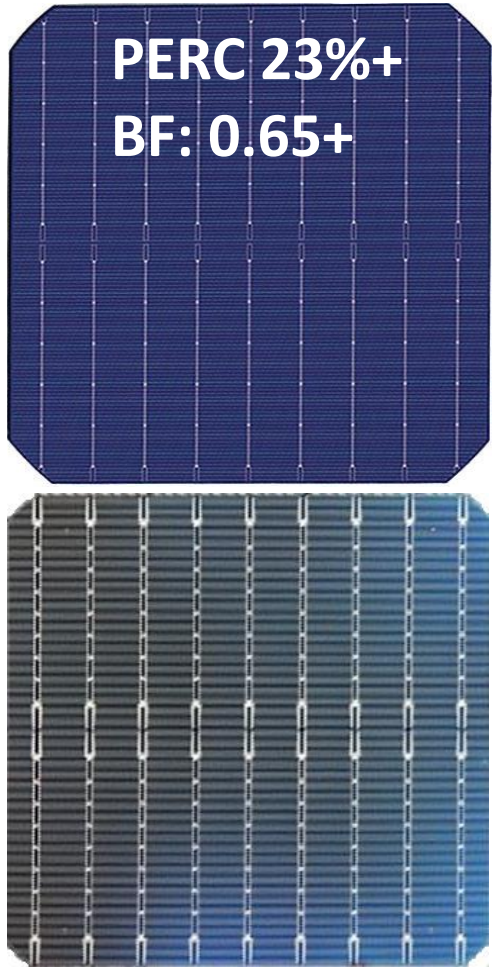
**TOPCon refers to cells with poly-Si/SiO_x passivated contacts. The « tunnel » SiO_x layer is represented by a yellow line.*

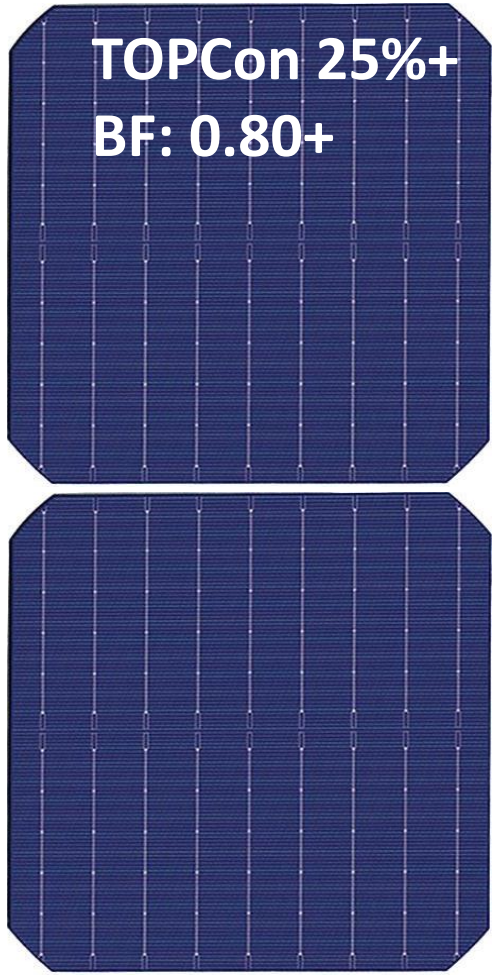
Improvements of surface passivation

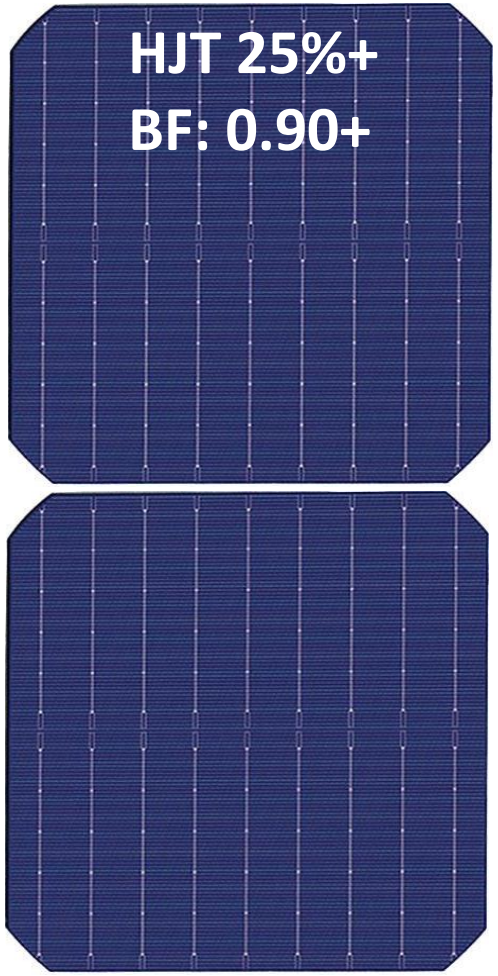
Crystalline silicon **solar cell** technology



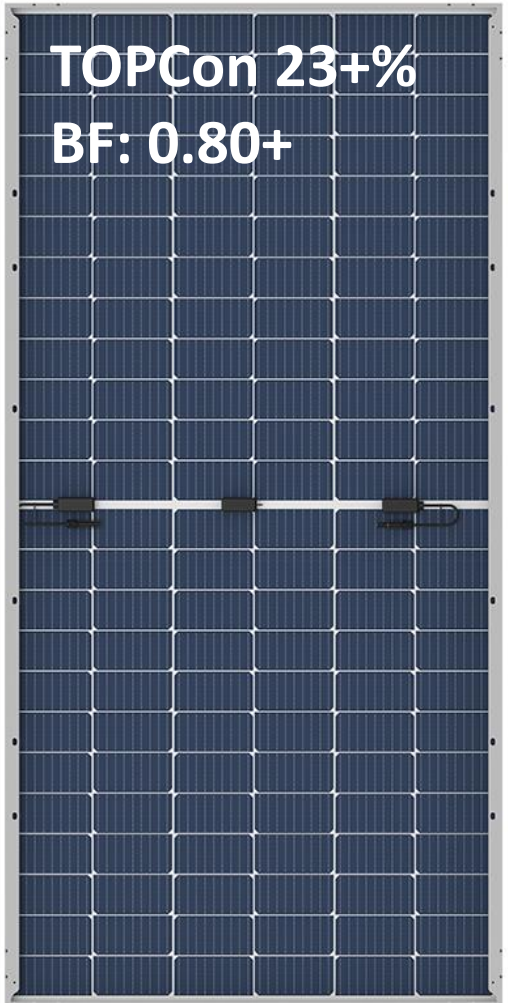
Solar cell pictures of PERC, TOPCon, HJT and IBC

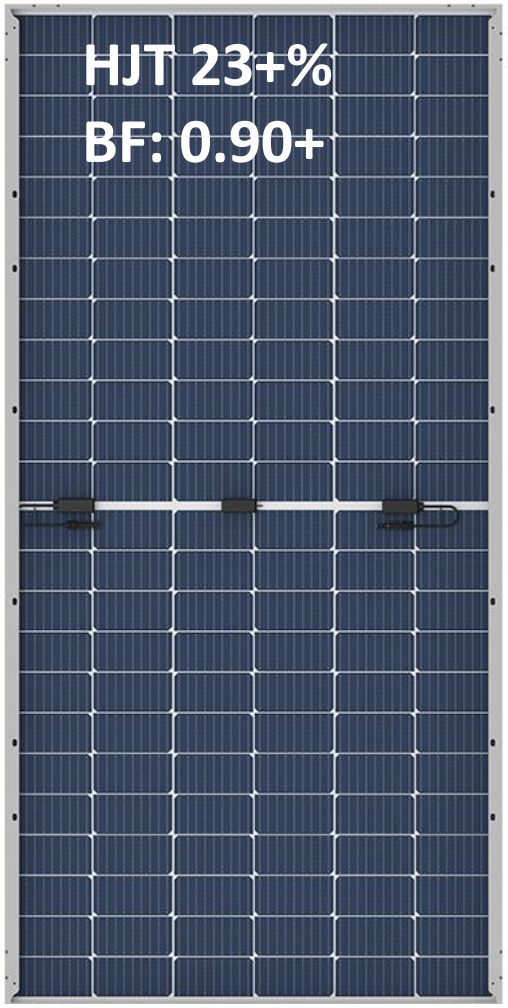


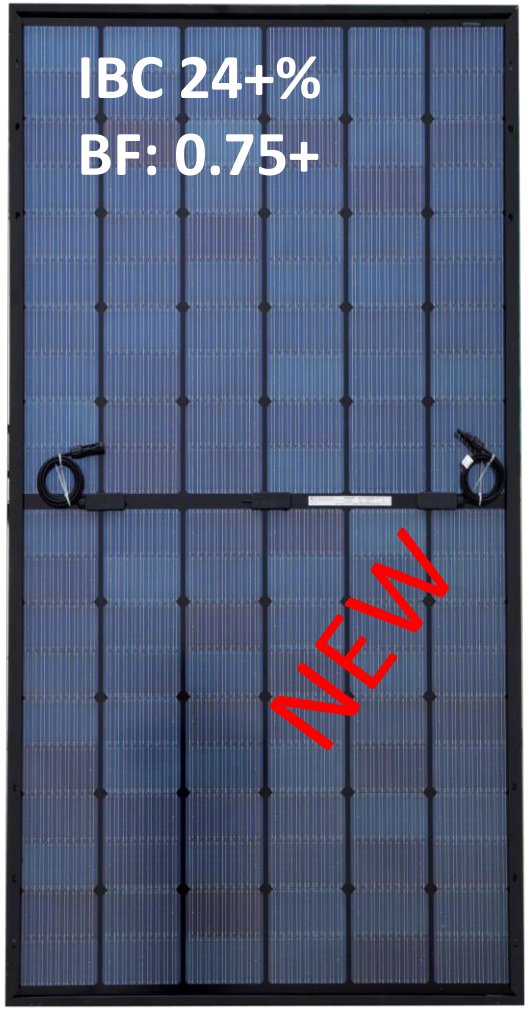




Rear side **module pictures** of PERC, TOPCon, HJT and IBC







Module technology: what is the trend?

half cell, 1/3 cell technology

negative gap

OBB technology

bifacial BC

led free (gluing instead of solder)

Cu metallization

from 3mm to 2mm glass

Laser processing

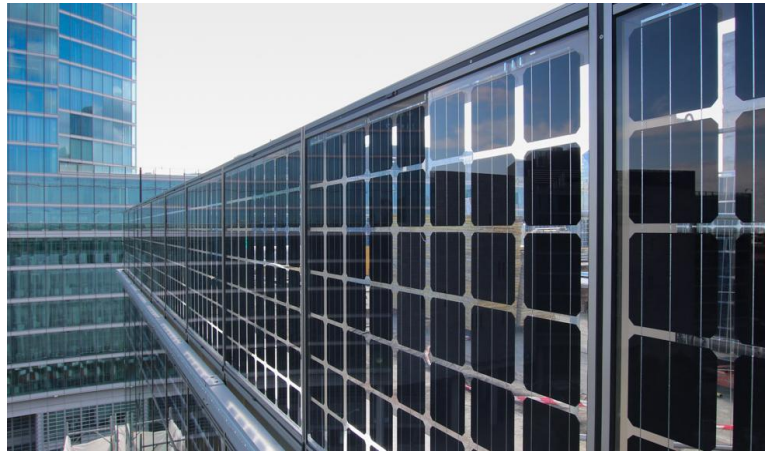
smart modules

large “floppy” modules

steel frames

PV systems: applications

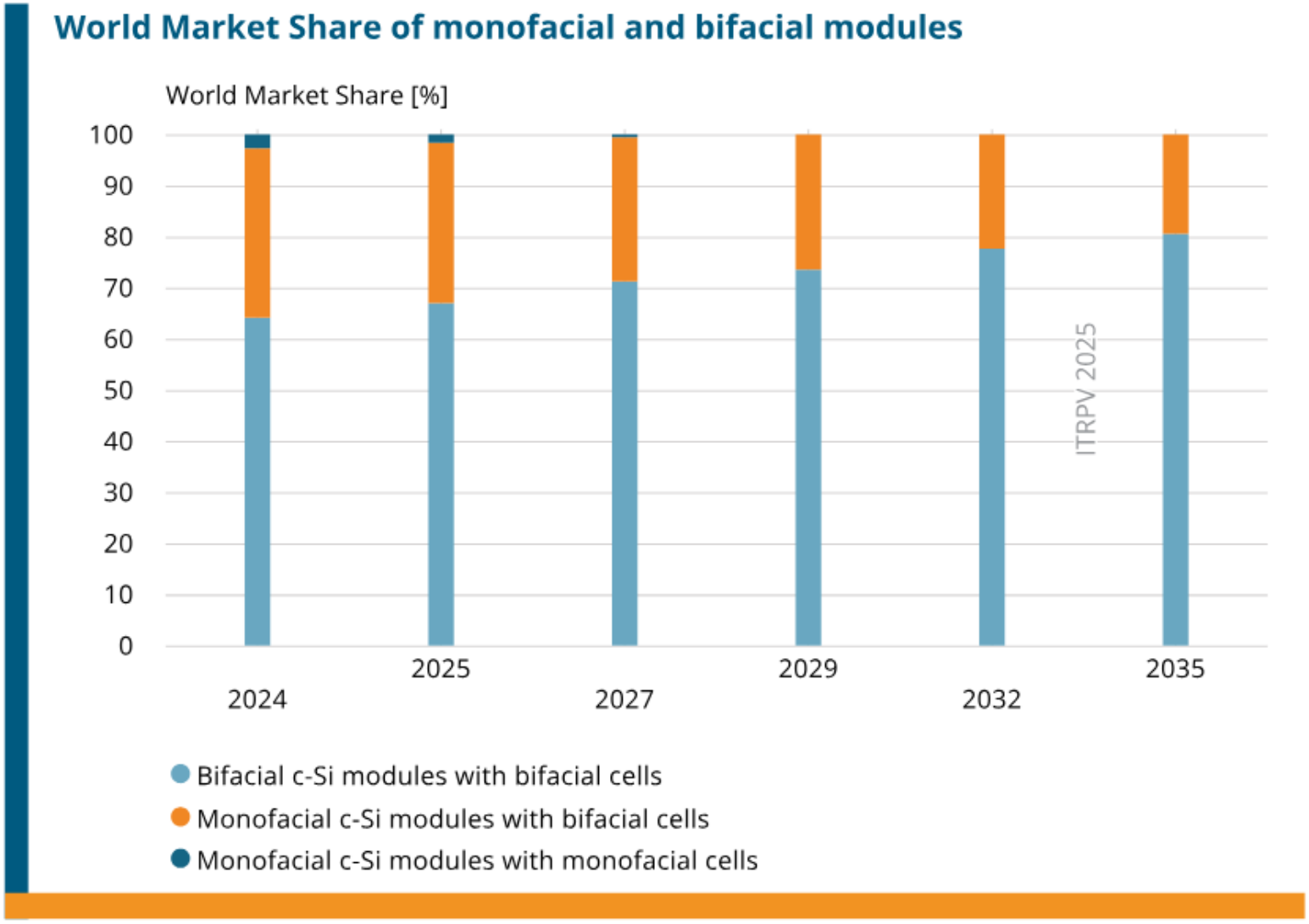






PV systems: applications



PV systems: bifacial applications and gains

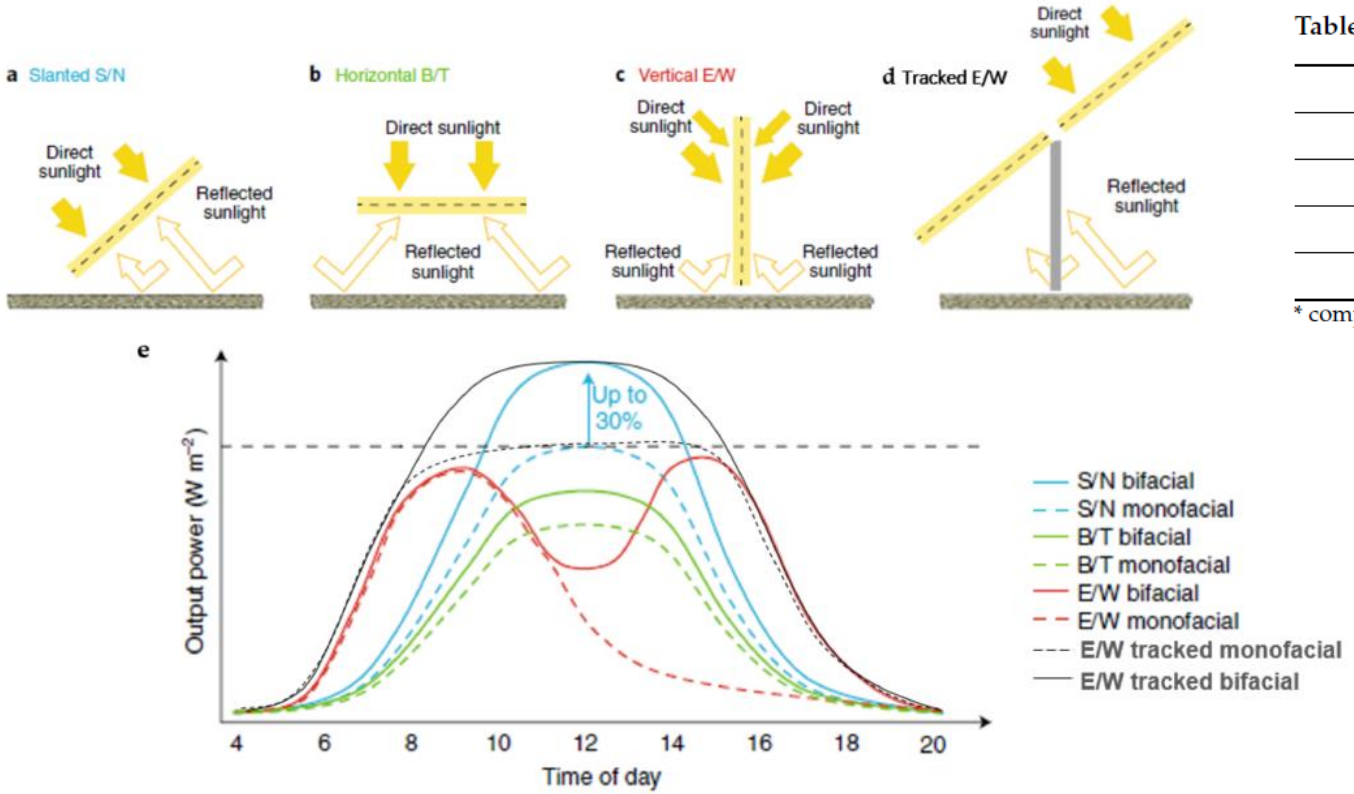


Figure 5. (a–d) possibilities for installations of bifacial modules and (e) comparison of power generation curves for monofacial and bifacial modules [16]. S/N means South/North, B/T is Bottom/Top and E/W is East/West.

Table 2. Energy gains in systems using tracking and bifacial modules [20].

Installation Geometry	Monofacial [%]	Bifacial [%]
Fixed tilt (flat roof)	100	105–115
Fixed tilt (utility scale)	100	107–130
Vertical (utility scale)	40–50	95–140 *
HSAT	110–122	117–145

* comparison with monofacial fixed tilt.

bifacial gains of 5-30%

R Kopecek; J Libal, Towards large-scale deployment of bifacial photovoltaics Nature Energy 3 (6), 443-446, **2018**

R Kopecek; J Libal, Bifacial Photovoltaics 2021: Status, Opportunities and Challenges, Energies, 14, 2076, **2021** https://doi.org/10.3390/en14082076

Statements in PV arena

"For new cells Siemens and FBR material purity must be **electronic grade**."

"TaiRay is the future!"

"PV developed from low cost Si-material and Al-BSF to electronic grade material/wafers and selective processes."

"Laser tech is the future."

"LECO killed HJT!"

"TOPCon with **LPCVD, PECVD, PVD** is similar."

"The last step to TBC as mainstream is the development of low cost effective insitu p-poly!"

"Tandem will need much more time for large GW scale!"

"Energy transition will be driven by c-Si tech with 80TW total installations until 2050!"

"AI is the future."

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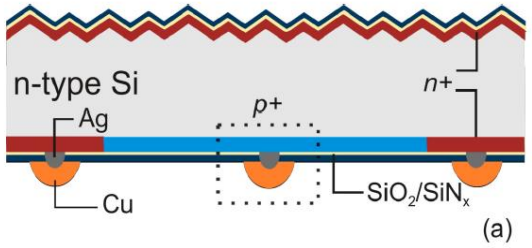
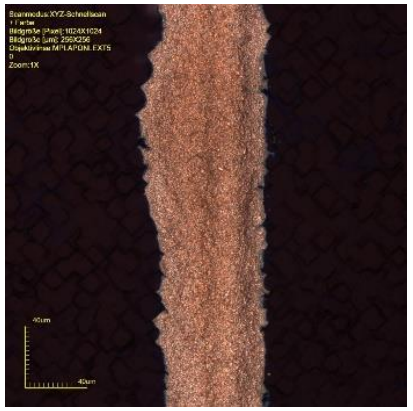
LOW COST BATTERY STORAGE IS A TOTAL GAME CHANGER!!!

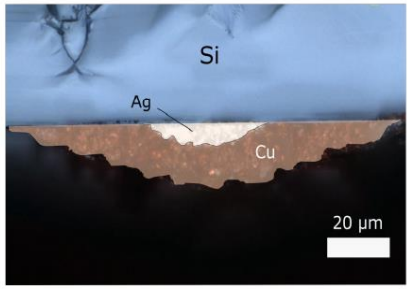
Hot R&D topics in PV arena

- Direct wafer
- Edge passivation
- Additives for advanced chemistry
- Cu metallization
- Bifacial BC technology
- Tandem technology
- Shingling tech
- Conductive adhesives
- Laser module production
- **c-Si space cells and modules**



(a)





(b)

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RE+ / Taiyang News Conference

ISC research for a sunny future

Thank you for listening

More information: www.isc-konstanz.de