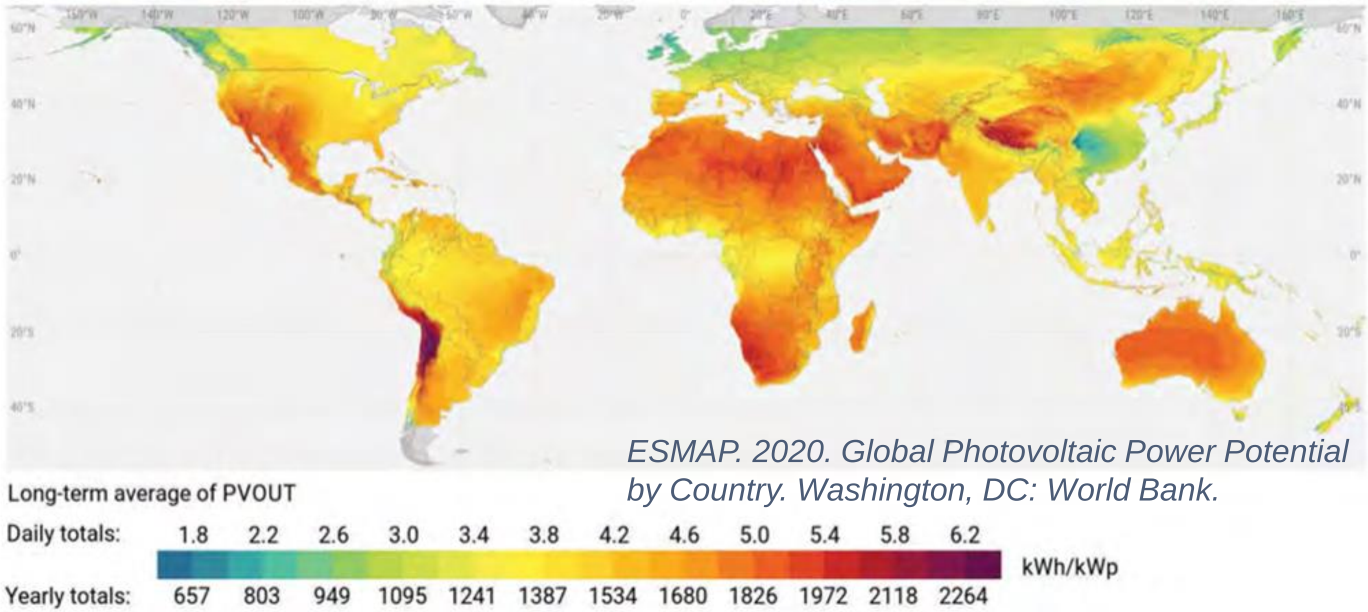
SOLAR ENERGY

Joint EPS-SIF International School on Energy 2023

FIGURE 3.4: PRACTICAL SOLAR PV POWER POTENTIAL: LONG-TERM YEARLY AVERAGE OF DAILY/YEARLY SUMMARIES (LEVEL 0)



ESMAP. 2020. Global Photovoltaic Power Potential by Country. Washington, DC: World Bank.

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Presentation outline

Basics of conversion of light into electricity - working principles of photovoltaic cells

The silicon solar cells – past, present and emerging technologies

From PV cell to PV module – electrical characteristics of PV modules

Industrial fabrication processes - from ‘sand’ to module

From module to PV plant – production of useable electricity

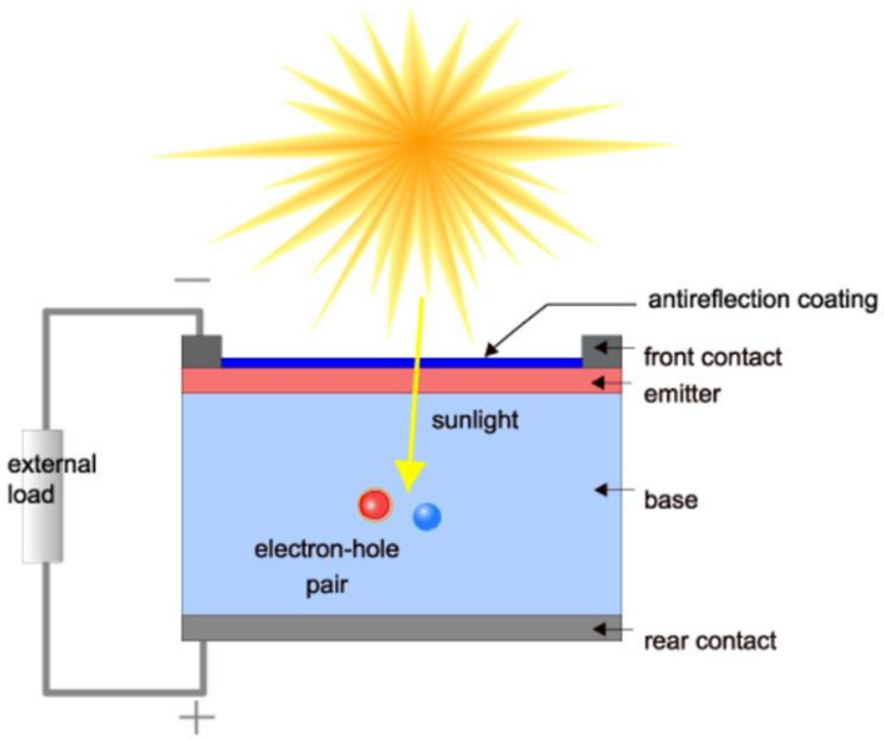
Market and cost elements of PV

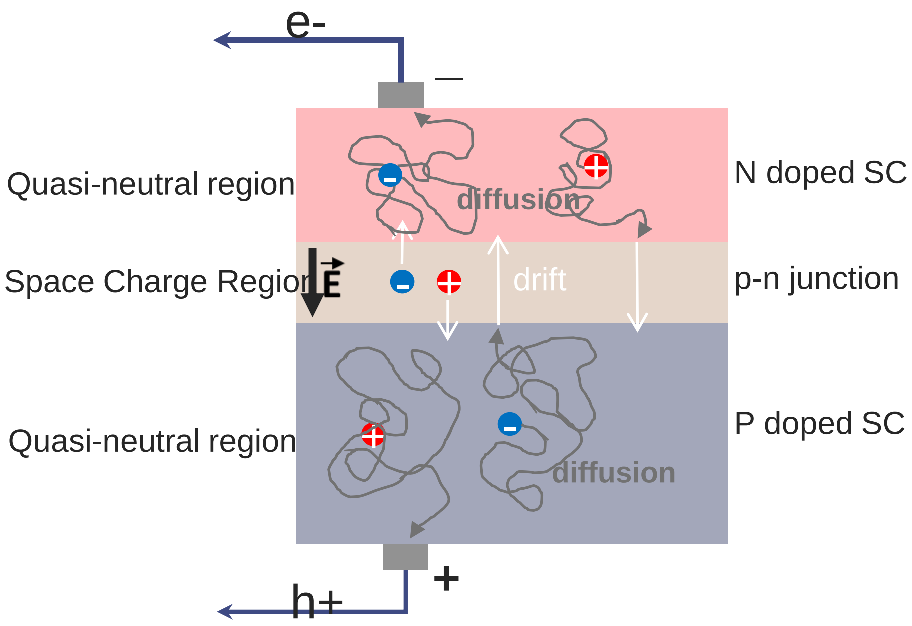
Carbon intensity and energy pay back time

Integration of PV in the electricity mix

Useful resources:
https://www.pveducation.org/
https://www.vdma.org/international-technology-roadmap-photovoltaic
https://www.irena.org/Publications
https://iea-pvps.org/publications/

Basic working principle of a silicon solar cell

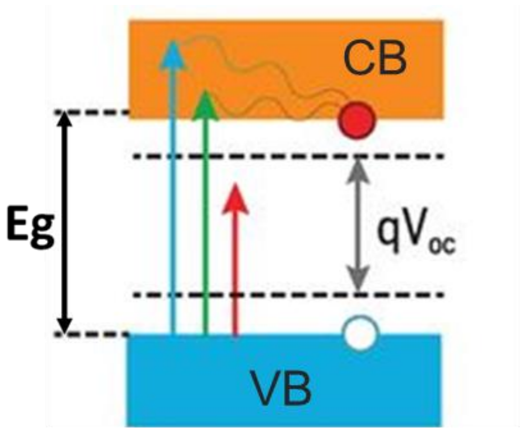




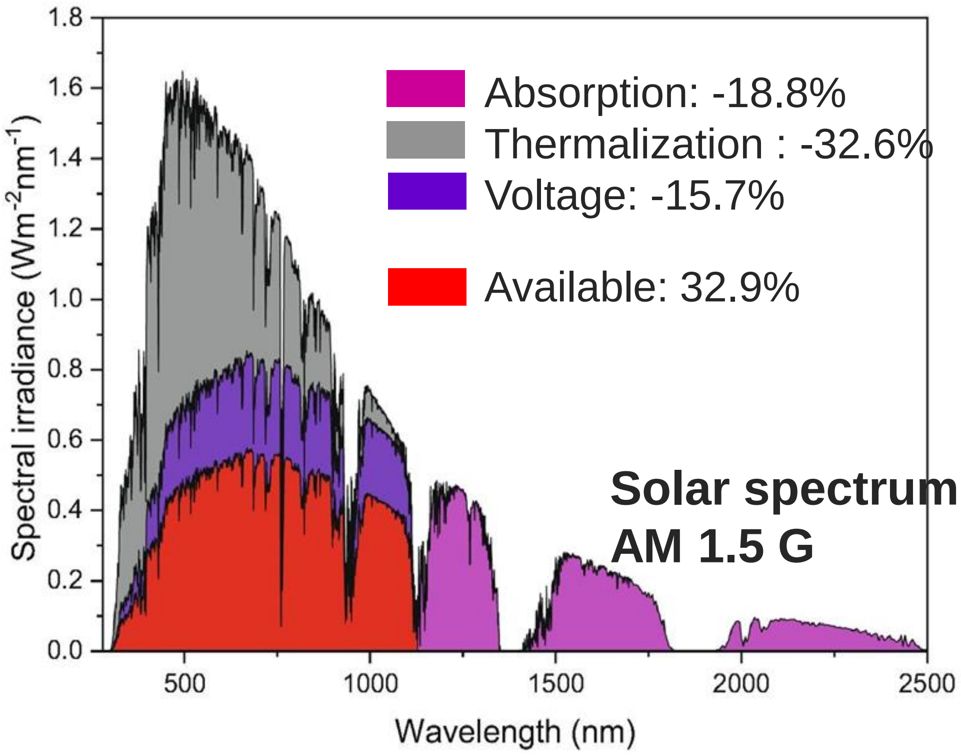
Core material creating charge carriers upon irradiation is a semi-conductor (Si, AsGa, CdTe, CIGS, ….)
Electrons and holes are separated away by a p-n junction; electrons in the n-type SC and holes in the p-type SC
Electrons and holes flow in the external circuit and recombine

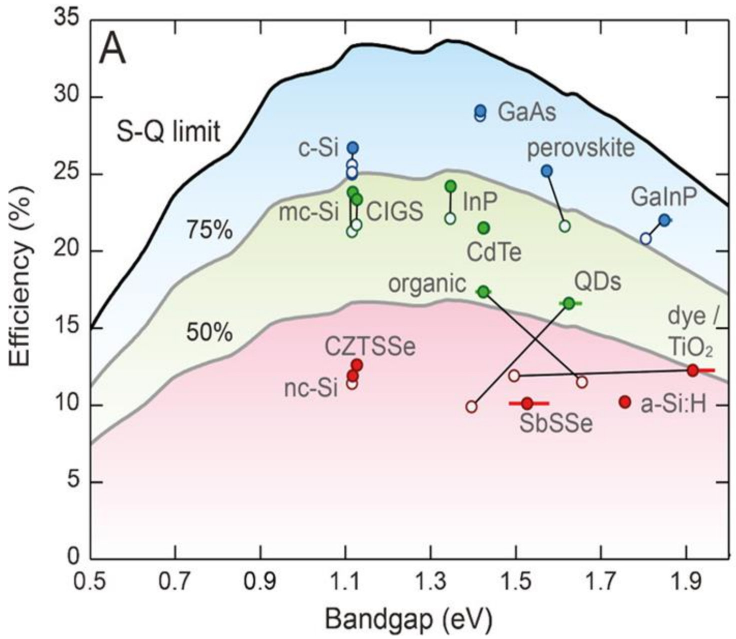
Fundamental limits of solar cells

Light harvesting and energy losses



Schematics of solar cell energy features



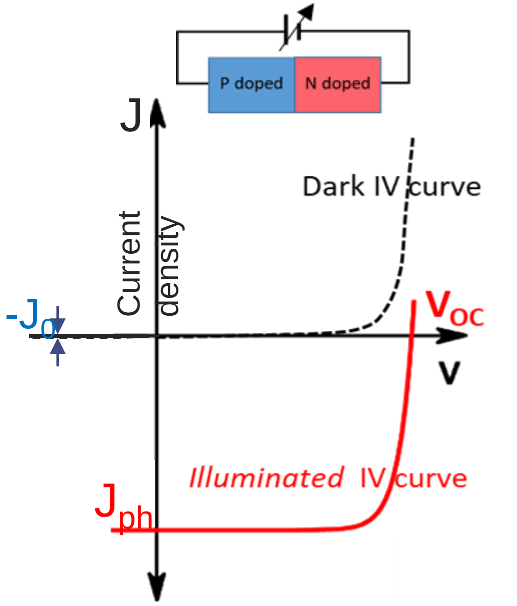


Shockley – Queisser limit vs energy gap (simple model) and single-junction solar cell efficiencies as of 2020

Practical efficiency limited by:

- ❑ Light management : part of photons *(above Eg)* absorbed
- ❑ Carrier management: part of charge carriers extracted
- ❑ Resistive losses

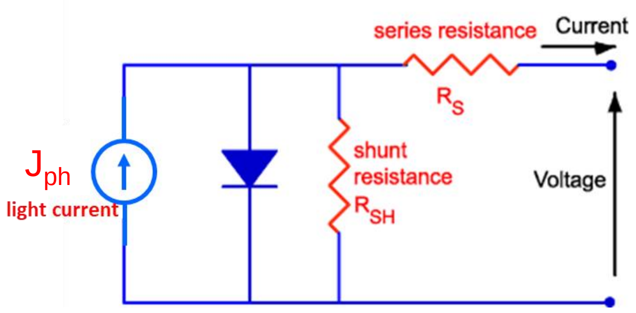
Electrical characteristics of solar cells



$$V_{OC} = \frac{kT}{q} Ln(\frac{J_{ph}}{J_0} + 1)$$

J_0 : saturation current in reverse bias
(measure of the recombinations in the solar cell)

V_{OC} increases with lower recombinations

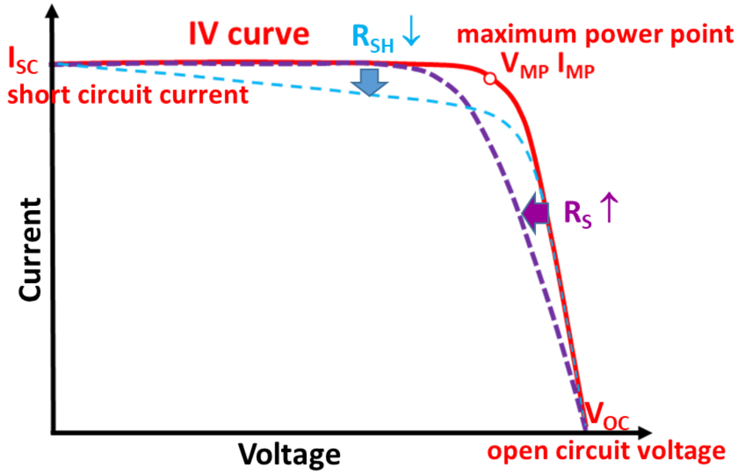


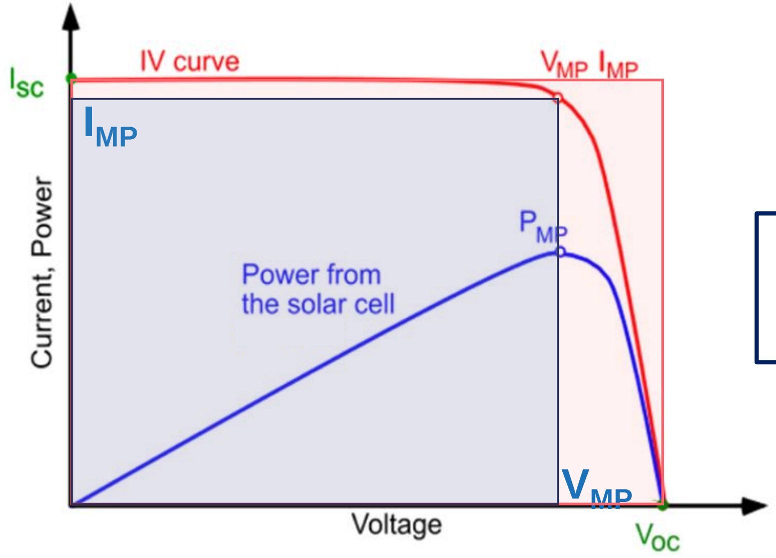
Simplified equivalent circuit

R_S: internal to base and emitter, contact metal-SC, metallizations (top + rear)

R_{SH} : alternate current paths inside the solar cell; due to manufacturing defects

Standard representation of IV curve

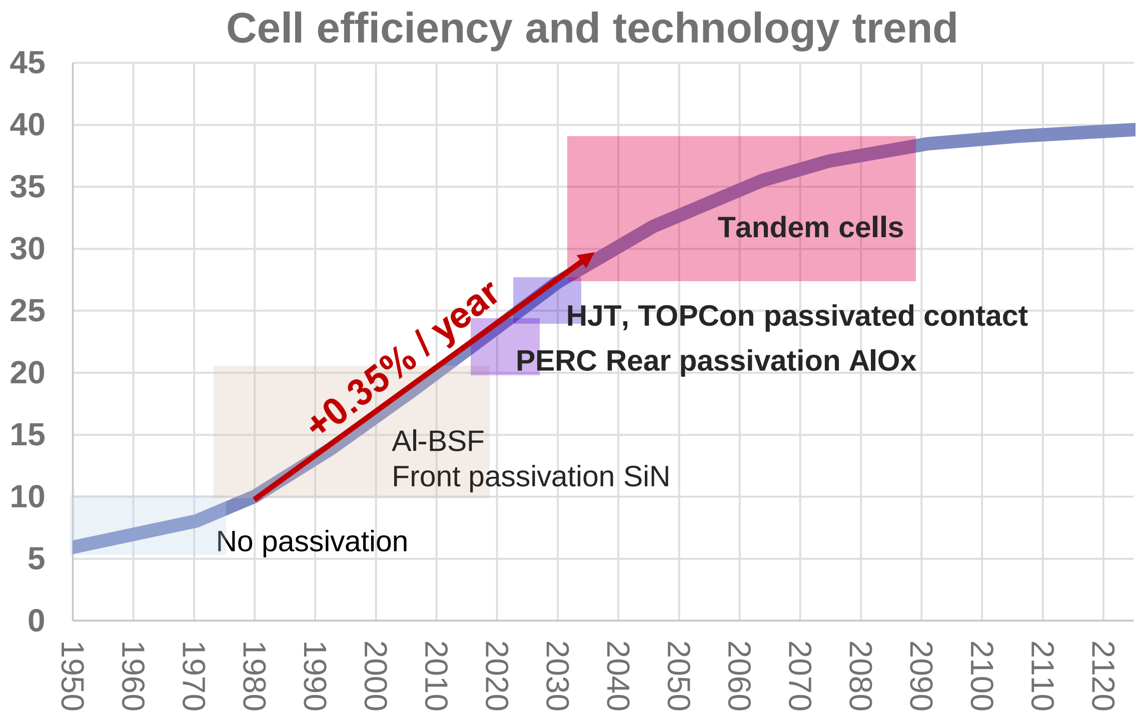




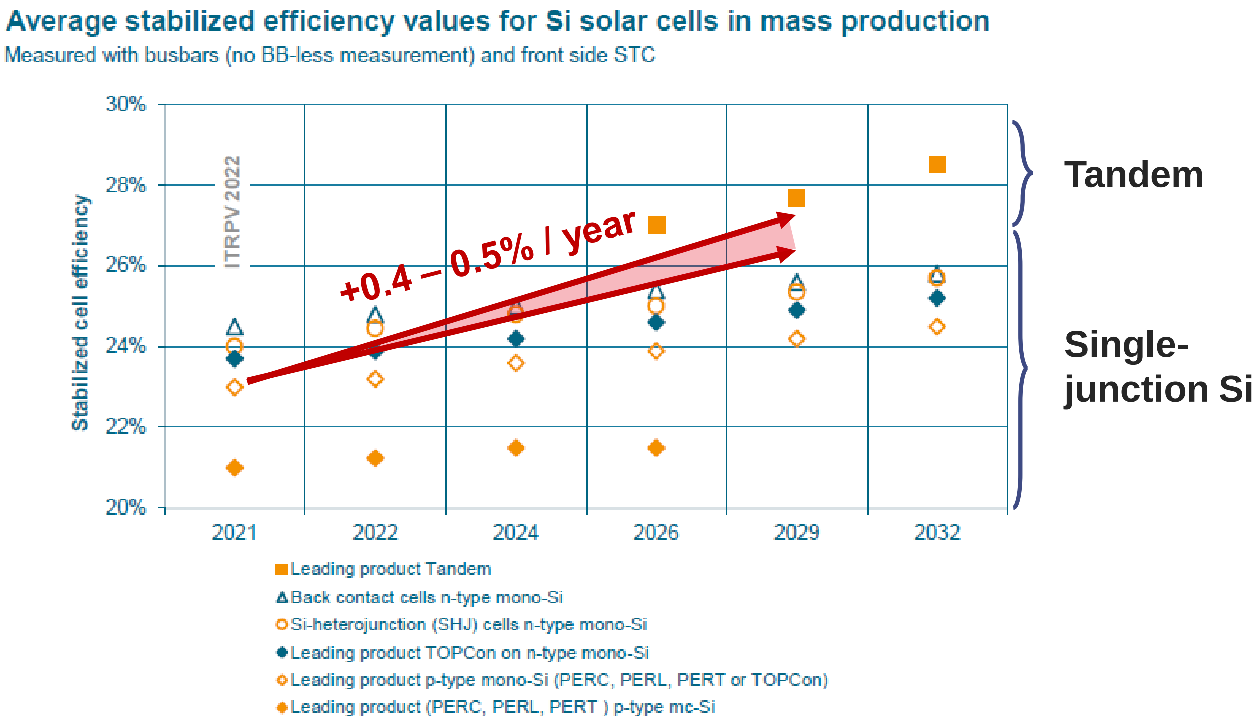
$$P_{MP} = V_{MP} \times I_{MP} = V_{OC} \times I_{SC} \times FF$$

Historical and future trends in PV cell efficiency

Focus on mainstream technologies

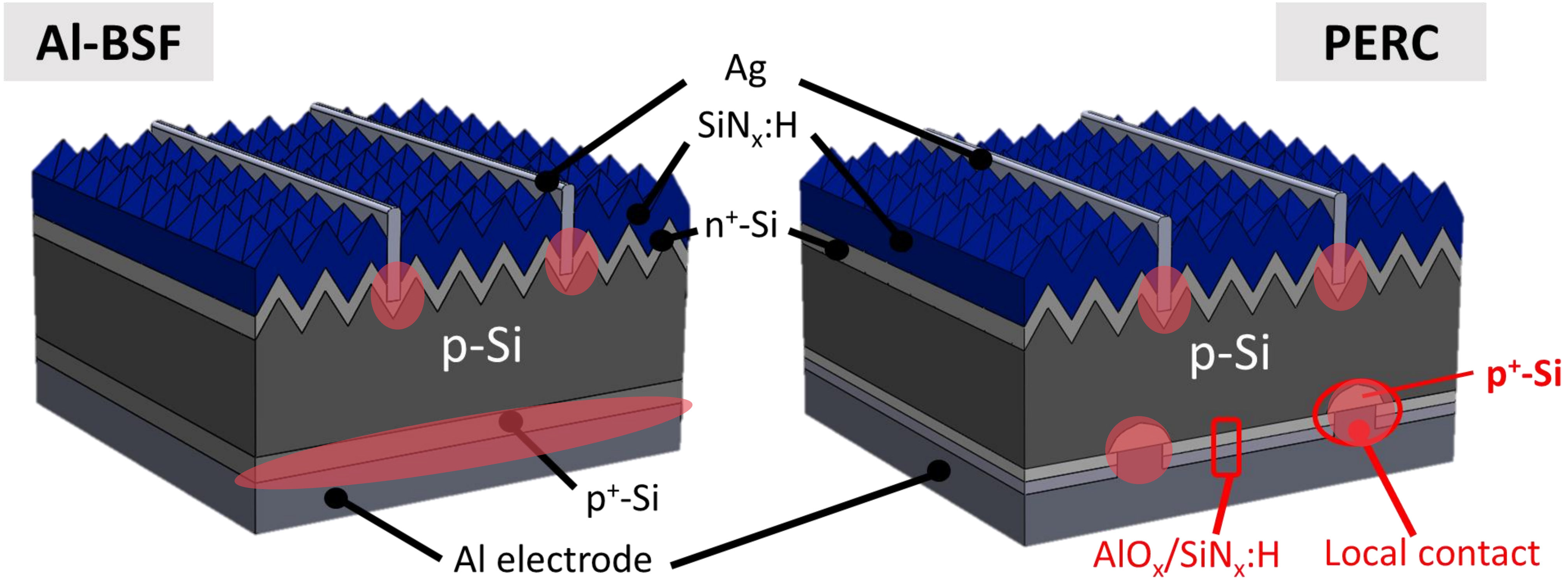


Adapted from W. Hoffmann et al; Proc. 36th EUPVSEC (2019)



First real practical use of solar cell:
satellite Vanguard 1 (1958)
cell efficiency: 9%

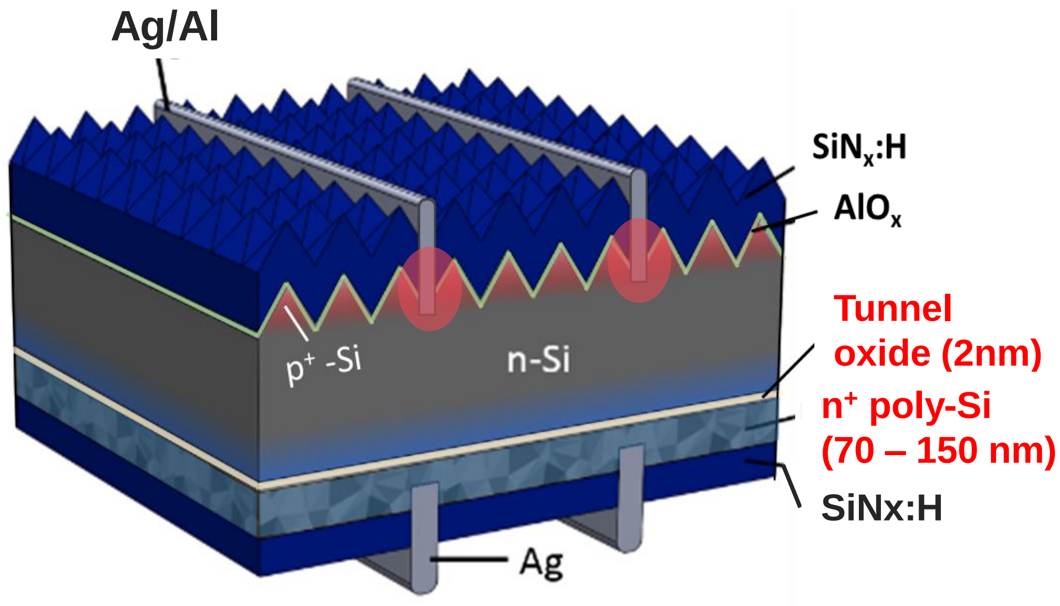
Successive generations of solar cells



- ❑ Hydrogenated SiN provides chemical passivation of the front surface + anti-reflection
- ❑ p+ doped layer at the rear provides back surface field, repelling electrons
- ❑ Limit of Voc ≈640 mV

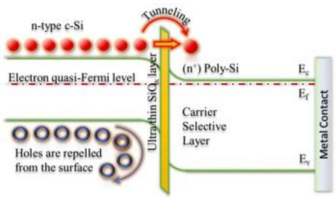
- ❑ Reduced area of direct contact metal-silicon
- ❑ AlOx/SiN:H provides chemical passivation + field effect
- ❑ *Local p+ area done by laser opening and diffusion of Al during firing of electrodes*
- ❑ Remaining direct contact metal-c-Si limits Voc ≈690 mV

TOPCon

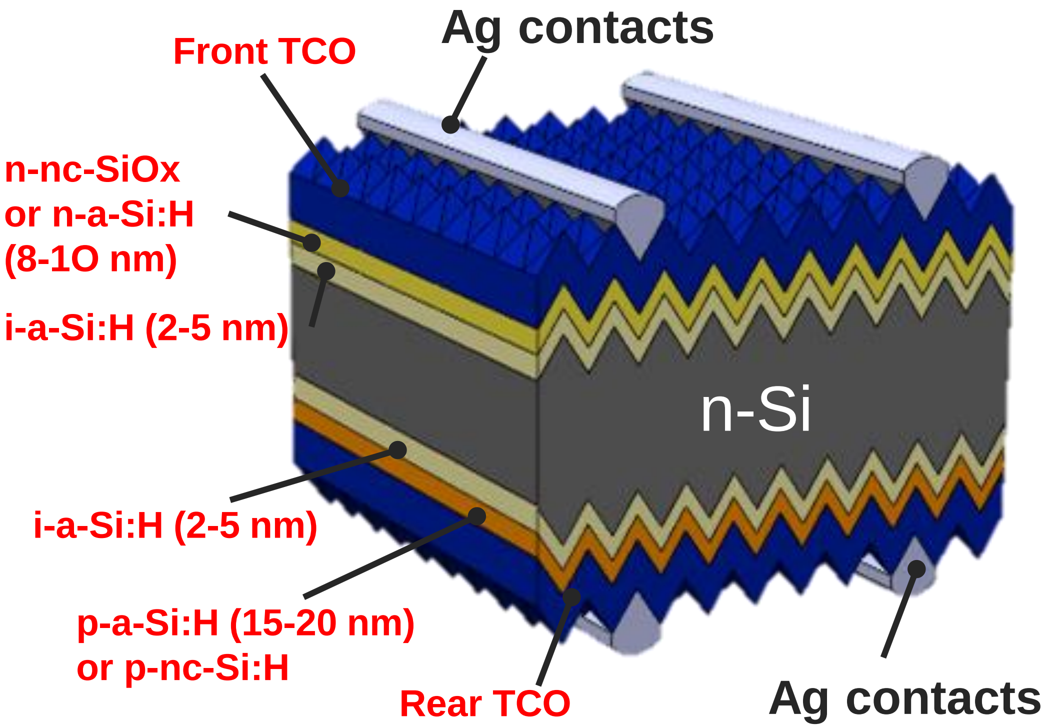


- Chemical passivation of c-Si by tunnel oxide + strong field effect by n^+ poly-Si *(SiN$_x$:H at the rear provides hydrogen at the SiO_x/c-Si interface)*
- Remaining direct contact metal/c-Si at the front
- TOPCon at the rear due to absorbance of ‘thick’ poly-Si
- High Voc up to ≈725mV (in prod.)

Schematic representation of field effect

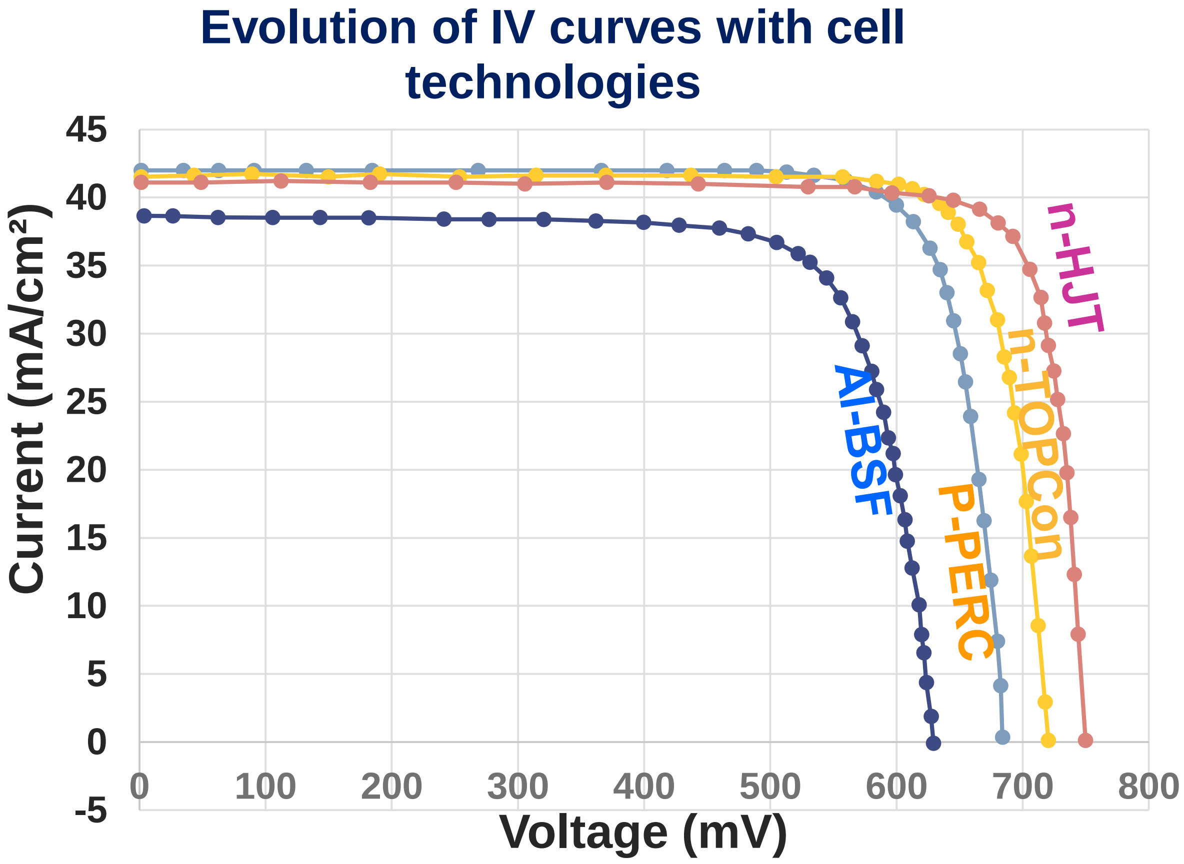


HJT



- Full area chemical passivation of c-Si by a-Si/H
- Strong field effec by doped amorphous or nano-crystalline silicon layers
- Absence of contact metal/c-Si
- Presence of TCO (Indium content)
- High Voc up to ≈745 mV (in prod.)

Evolution of IV characteristics with cell technologies

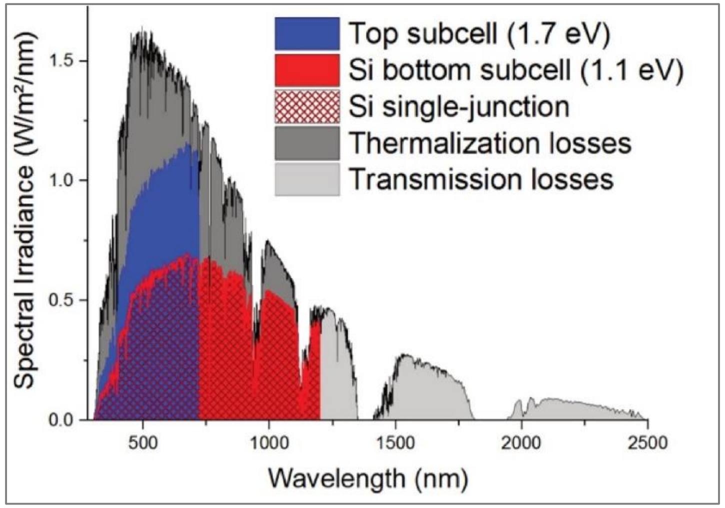


- 1st jump in efficiency due to the introduction of the passivated contact concept + improved optical properties at the rear
  Al-BSF to PERC: +Isc, + Voc
- 2nd jump (now) due to the introduction of the passivated contact concept
  PERC to TOPCon & HJT: + Voc
- N-type silicon is the preferred option for high efficiency cells due to longer lifetime of minority carriers (lower J_0, higher Voc)
- HJT and TOPCon cells are seen to have similar industrial performance potential

The future of PV: tandem cells

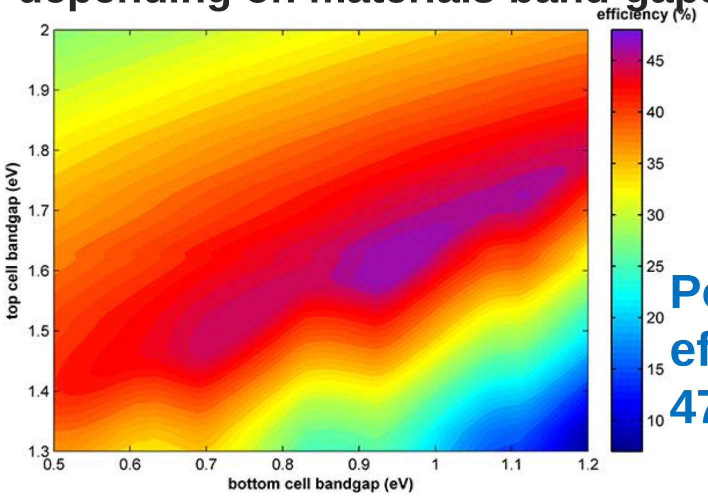
Basic working principles of tandem cells

Light harvesting and energy losses



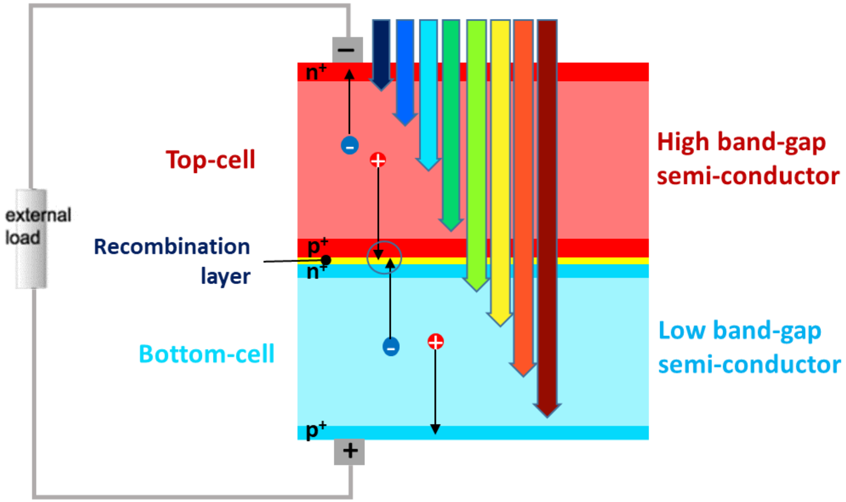
Less thermalization losses in the high band gap material

Tandem cell maximum efficiency depending on materials band-gaps



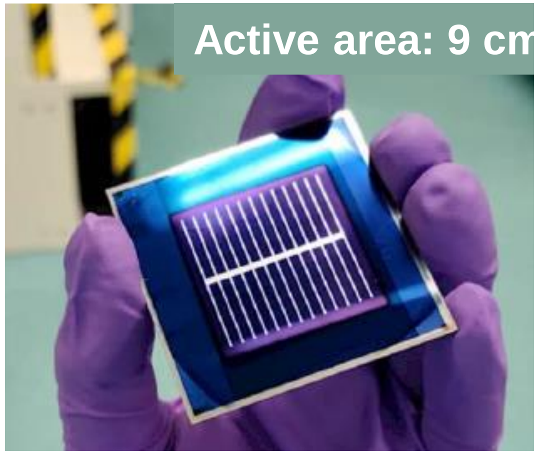
Potential efficiency up to 47%

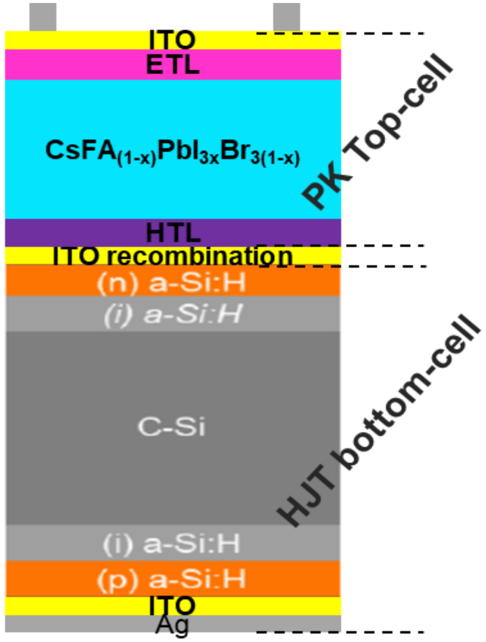
Tandem cell architecture and carrier flow

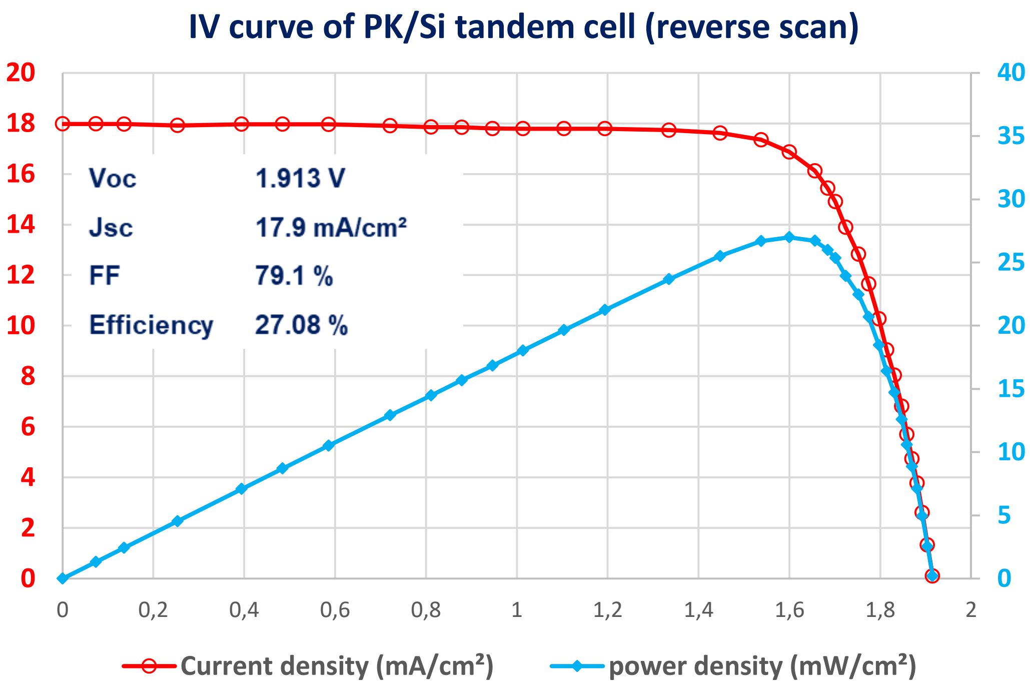


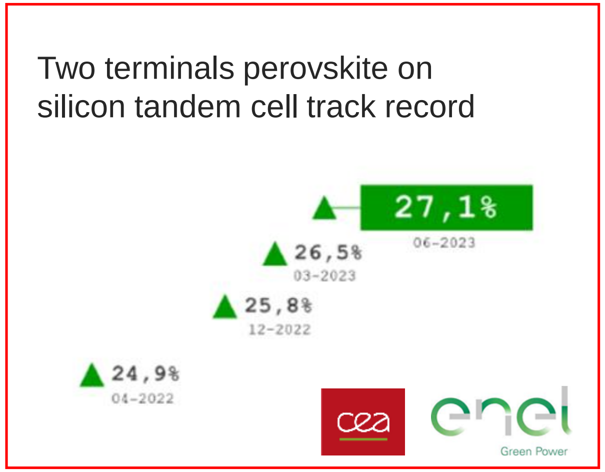
Perfect matching of charge carrier 'generation-collection' in the two sub-cells

Illustration of the potential of PK/Si technology







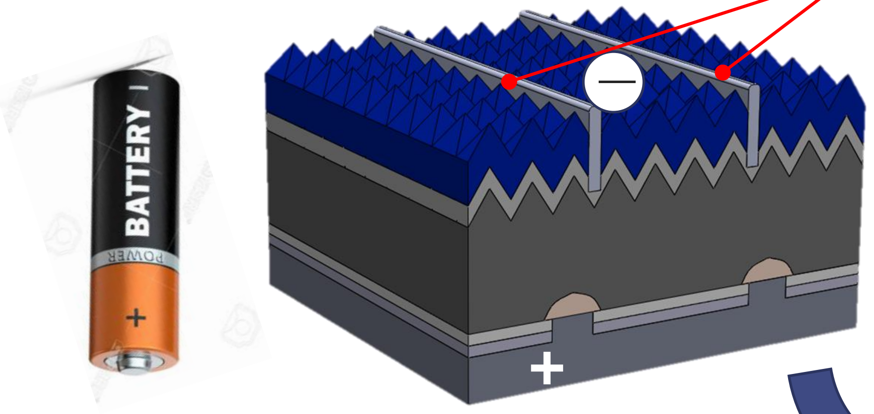


- First pilot line in Europe: Oxford PV on M6 wafers; ready in 2023
- Record efficiency in Europe on industrial wafer size: 28.6% by Oxford PV
- World record on industrial wafer size: 33.5% by Longi (size?)
- Research Lab world record: 33.7% by KAUST
- Many announcements of pilot lines in China
- Intensive work on Industrial process development (cell and module) and stability issues

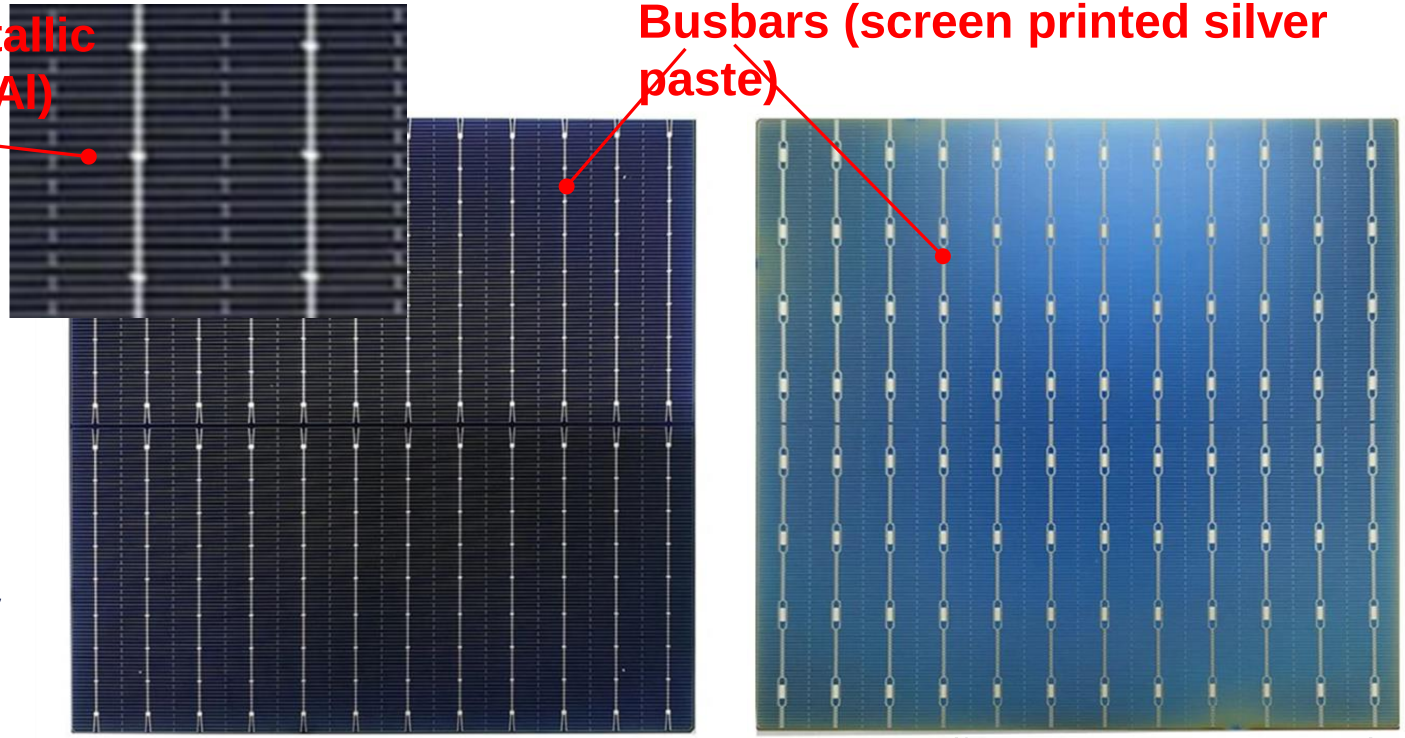
Silicon PV cell

Fingers (screen printed metallic paste: Ag, Ag/Al, Al)

Busbars (screen printed silver paste)



Schematic drawing of <u>monofacial</u> PERC cell



Front (left) and rear (right) side of G12 (210 mm) <u>bifacial</u> PERC Cell

(from DS New Energy website)

ELECTRICAL PARAMETERS at STC						
Eff(%)	Pmpp(W)	Umpp(V)	Impp(A)	Uoc(V)	Isc(A)	FF(%)
23.0	10.14	0.579	17.517	0.679	18.325	81.51
22.9	10.10	0.578	17.471	0.678	18.297	81.4[illegible]
22.8	10.05	0.578	17.394	0.678	18.24	81.3[illegible]
22.7	10.01	0.577	17.348	0.677	18.211	81.19
22.6	9.97	0.576	17.302	0.675	18.187	81.18

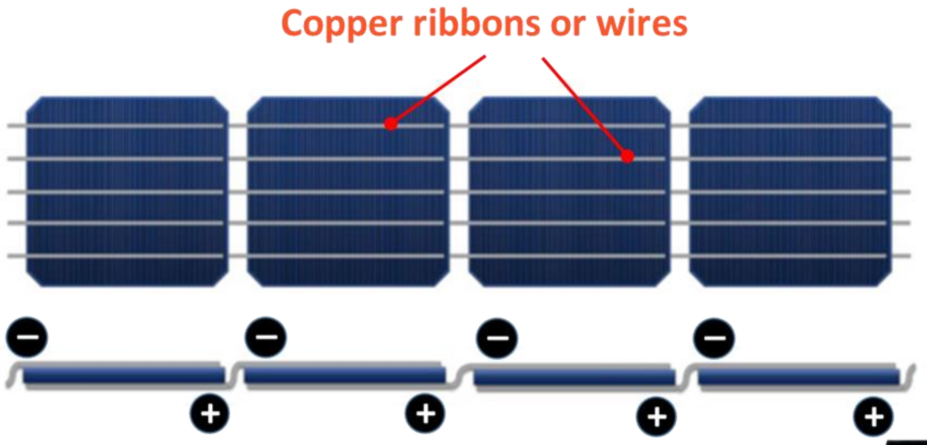
STC: Standard Test Conditions (Irr: 1000W/m², AM1.5; Temp: 25°C)

Size: Up to 210 mm x 210 mm (G12)

Thickness: 160 -180 µm in standard

From PV cell to PV module

Series connection to obtain a useable voltage



Analogy with series connected batteries

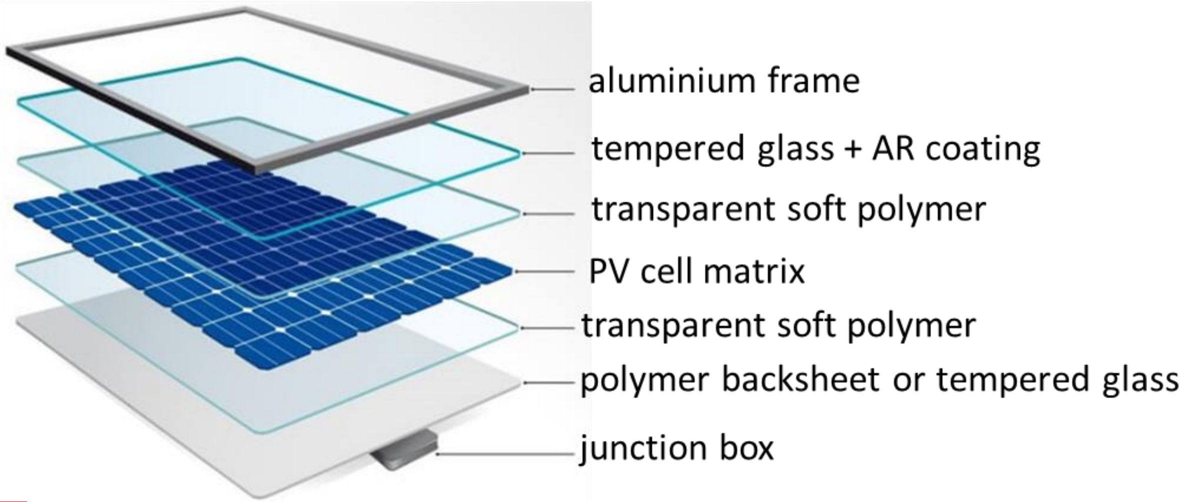
Electrical characteristics

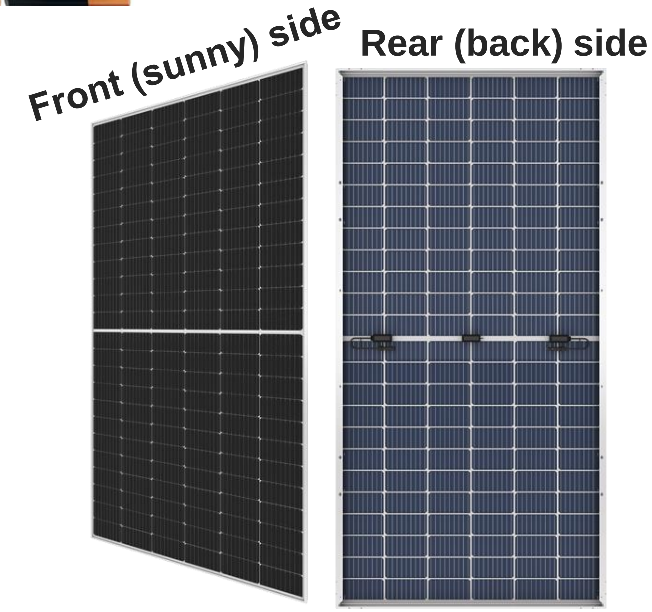
Isc ≈18.3A (limited by the lowest Isc value of all connected cells)

Voc = n x 0.68V (addition of the open voltage)

FF < 81.5 (small loss due to added series resistance from copper ribbons)

Protection from atmospheric and mechanical stress





144 half cells (2 parallel sets of 72 ½ cells in series)

$Voc_{max} \approx 72*0.68 = 49$ V

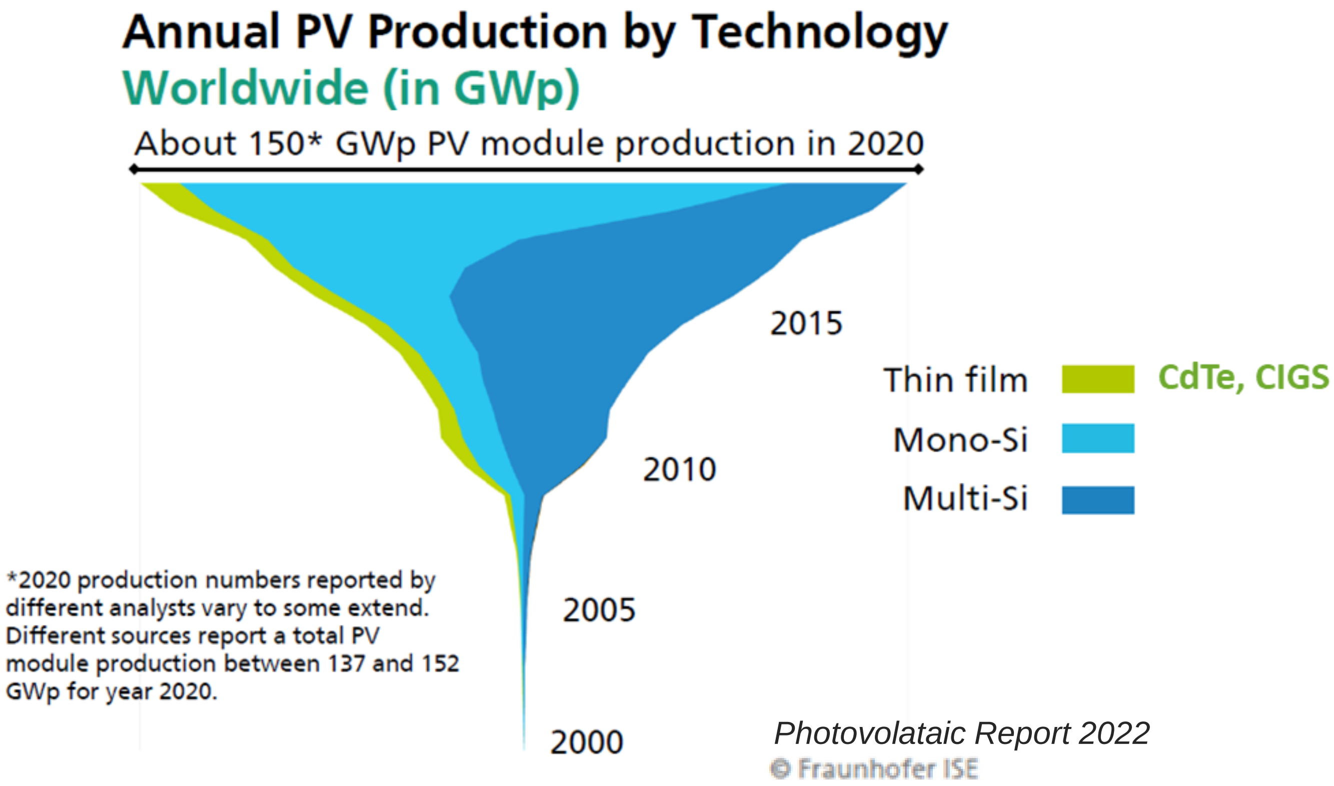
$Isc_{max} \approx 18$ A

$FF_{max} \approx 0.8$

$\mathbf{P_{max} \approx 700}$ **W**

Silicon PV technologies

Crystalline silicon technologies = 95% of market share

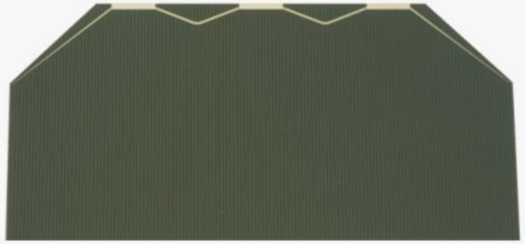


Photovolataic Report 2022

- ❑ **Share of multi c-Si in rapid decrease from 2015-2016 (<4% in 2022)**
- ❑ **All thin film technologies count for <5% of PV market**

III/V thin film multijunction

32% Quadruple Junction GaAs Solar Cell
Type: QJ Solar Cell 4G32C - Advanced



AlInGaP/AlInGaAs/InGaAs/Ge on Ge

Space applications

Organic PV

5-7% printed on PET

Novartis pavillon Basel 2022 by ASCA

Architectural & consumer applications

Silicon PV: from quartzite to PV module

2' 17''

47''

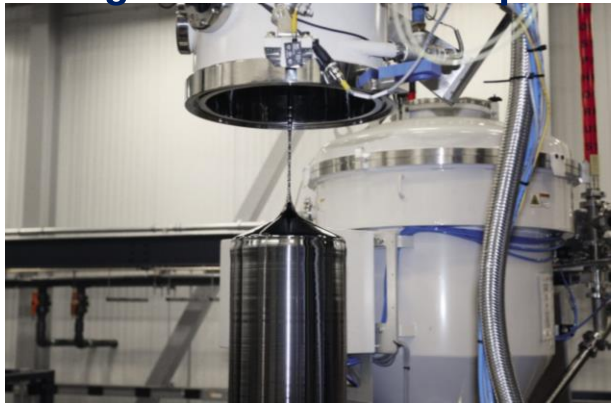
2' 16''

[redacted]ld

[redacted]

5'28''

Lingot Cz en sortie de puller



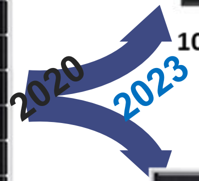
Cz ingot fabrication unit(25 GW; 160 pullers)

Poly-Si fabrication unit (30.000 MT)

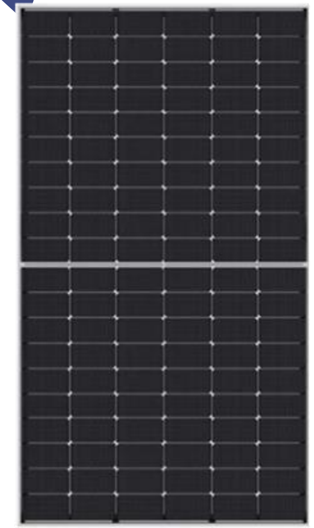
Tongwei's new 30,000-ton polysilicon plant in Baotou, Inner Mongolia came on stream in October 2018 – Image: Xin

Evolution of PV module market: higher efficiency and segmentation

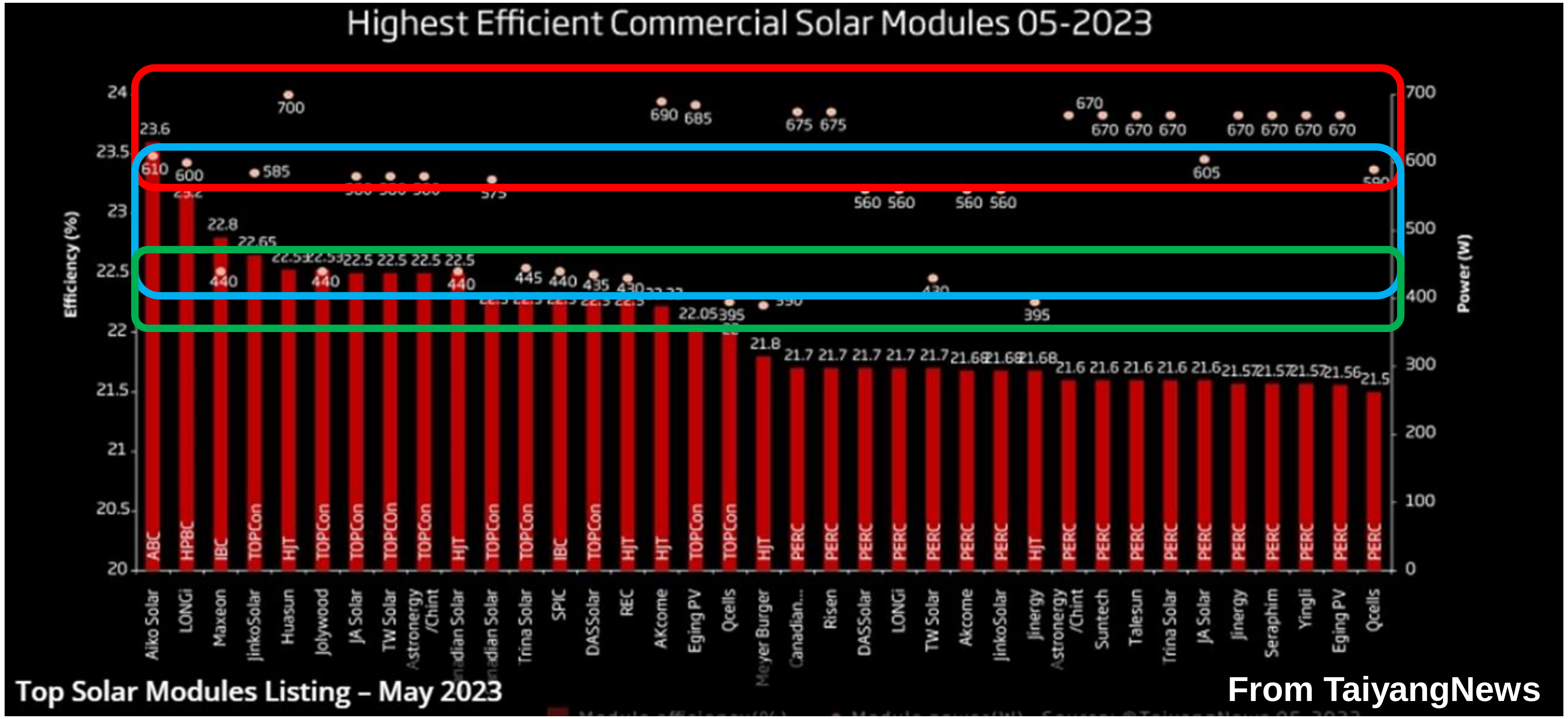
72 cells M2
199 x 100 cm
400 W
≈20% eff.



108 half-cut cells M10
172 x 113 cm
430 W
≈22% eff.



132 half-cut cells G12
238 x 130 cm
695W
≈22.5% eff.



Utility scale — Commercial & Industrial — Residential

Main market trends

PERC modules up to 21.7% eff.
TOPCon and HJT from 21.8 up to 24% eff.

Bifacial modules → utility scale
Monofacial modules → residential + C&I

Module power
- \> 600 Wp → Utility scale
- < 440 Wp → residential
- 400 Wp < > 600 Wp, → C&I

PV systems


Ground mounted


Floating PV


Residential
PV


Commercial & industrial PV


Crédit photo © Sun'Agri
Agrivoltaics

Ground mounted power plants

Main components:
Modules, fixed structure or **trackers**, **anchoring system, cables, inverters,** transformers, sensors and information system

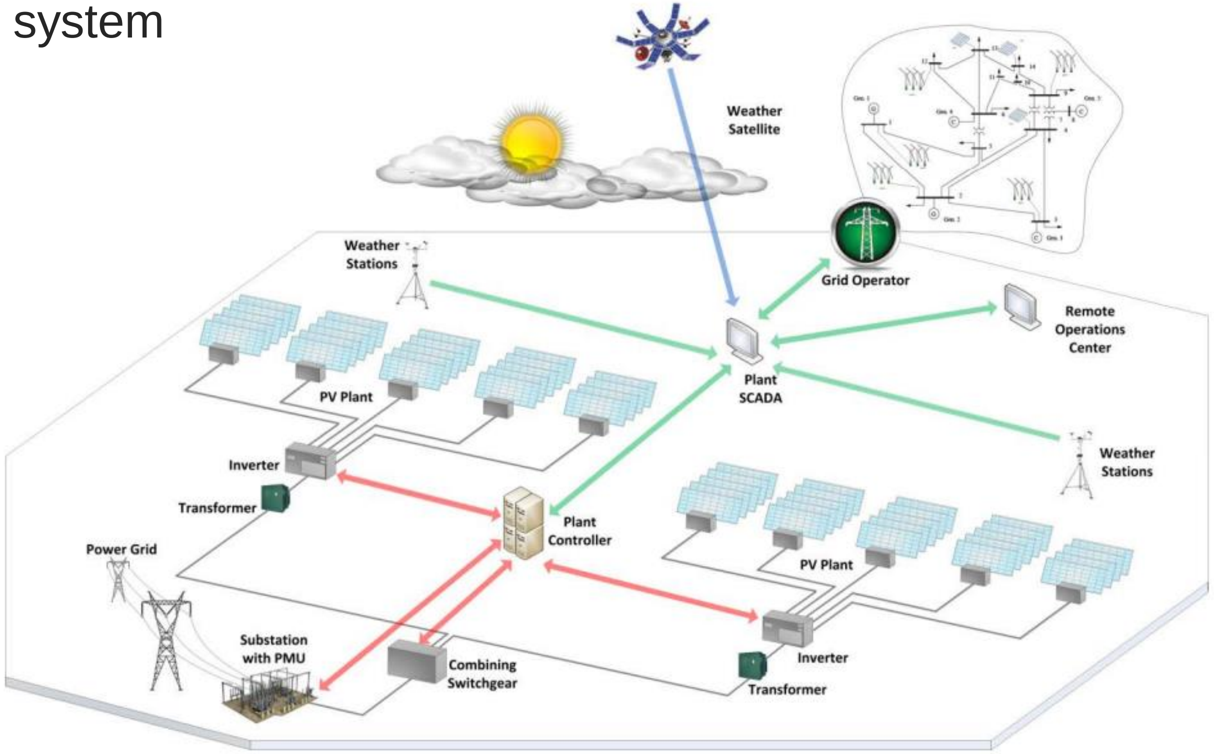
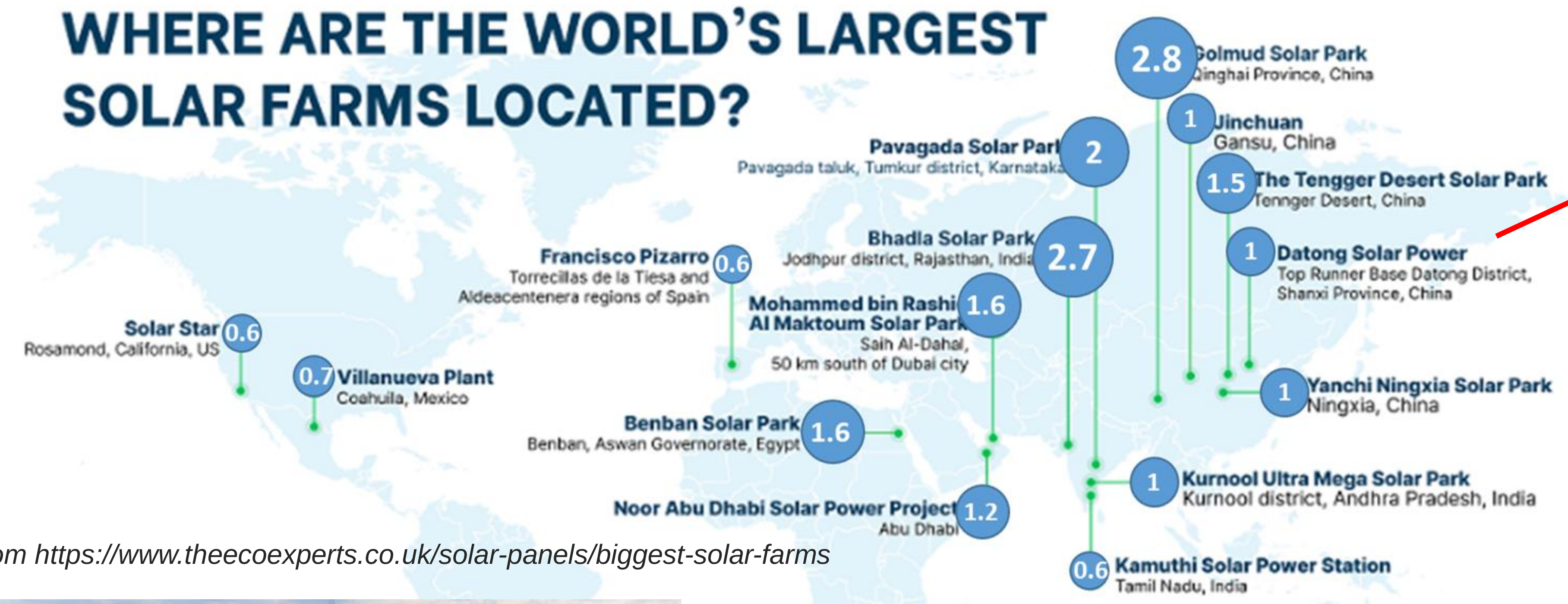


Figure 1. Components of a typical utility-scale PV power plant. *Image from NREL*

Photon –> electron dc –> electron ac: reduced number of components
Surface power density ≈1 MW/ha

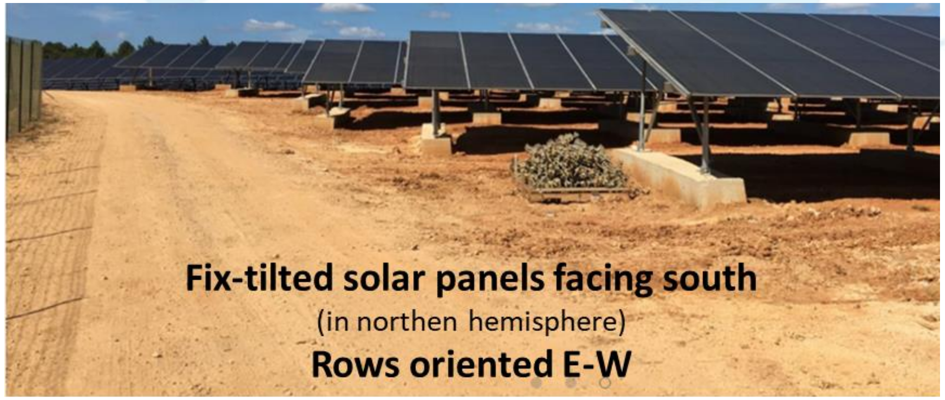
Ground mounted PV plants



from https://www.theecoexperts.co.uk/solar-panels/biggest-solar-farms

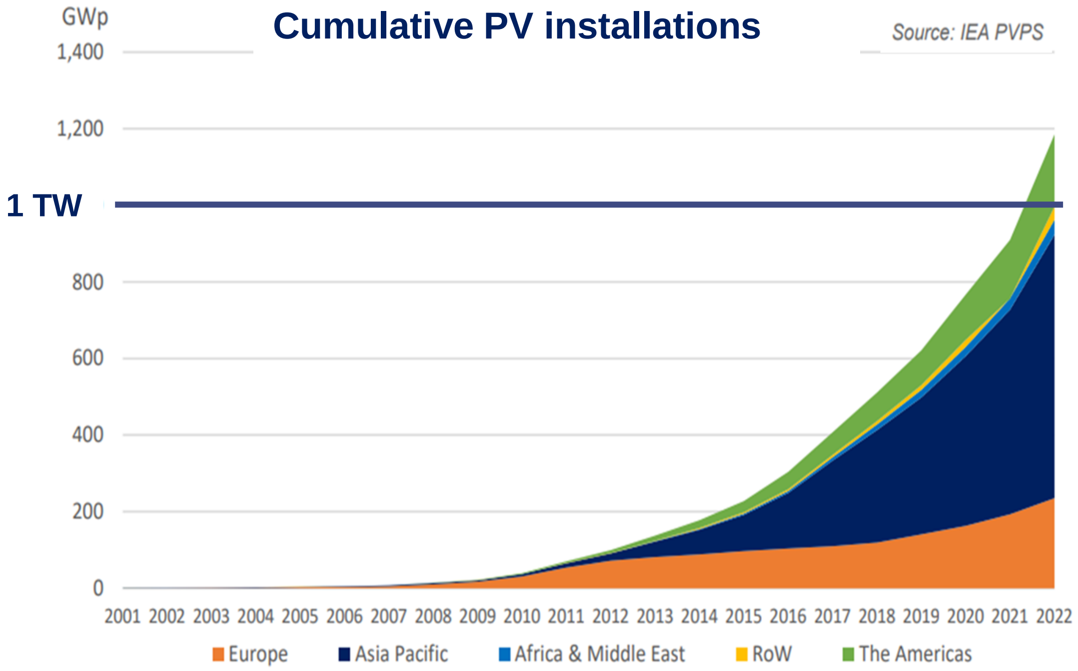
x Installed power (GWp)

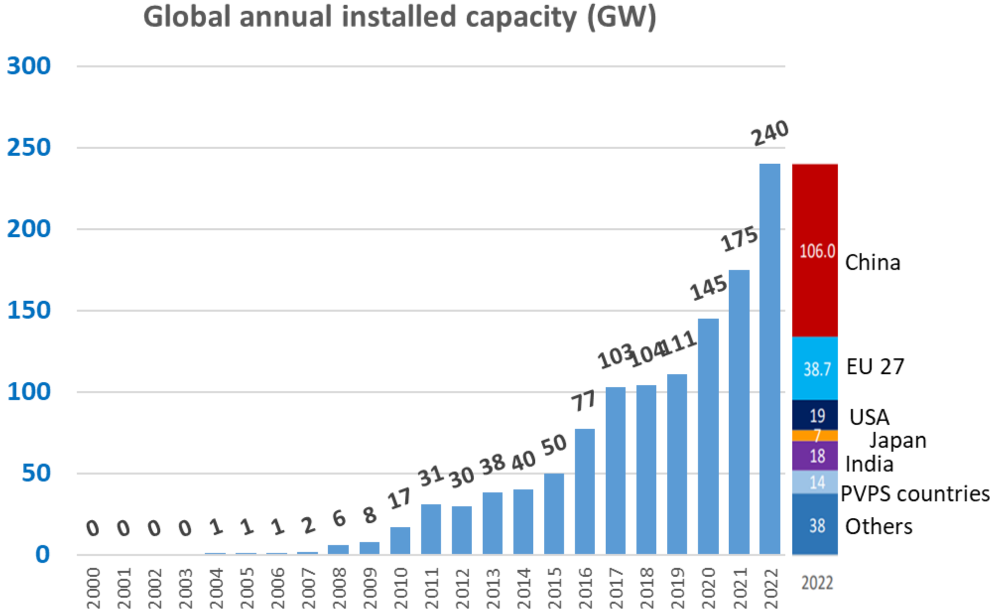
Solar panels mounted on single-axis trackers
(follows the daily sun course from east to west)
Rows oriented N-S

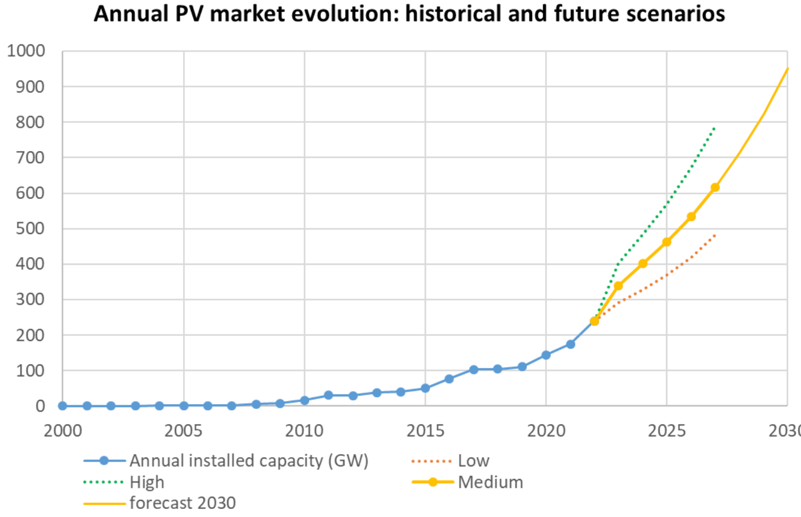


Fix-tilted solar panels facing south
(in northen hemisphere)
Rows oriented E-W

Trend of PV installations worldwide

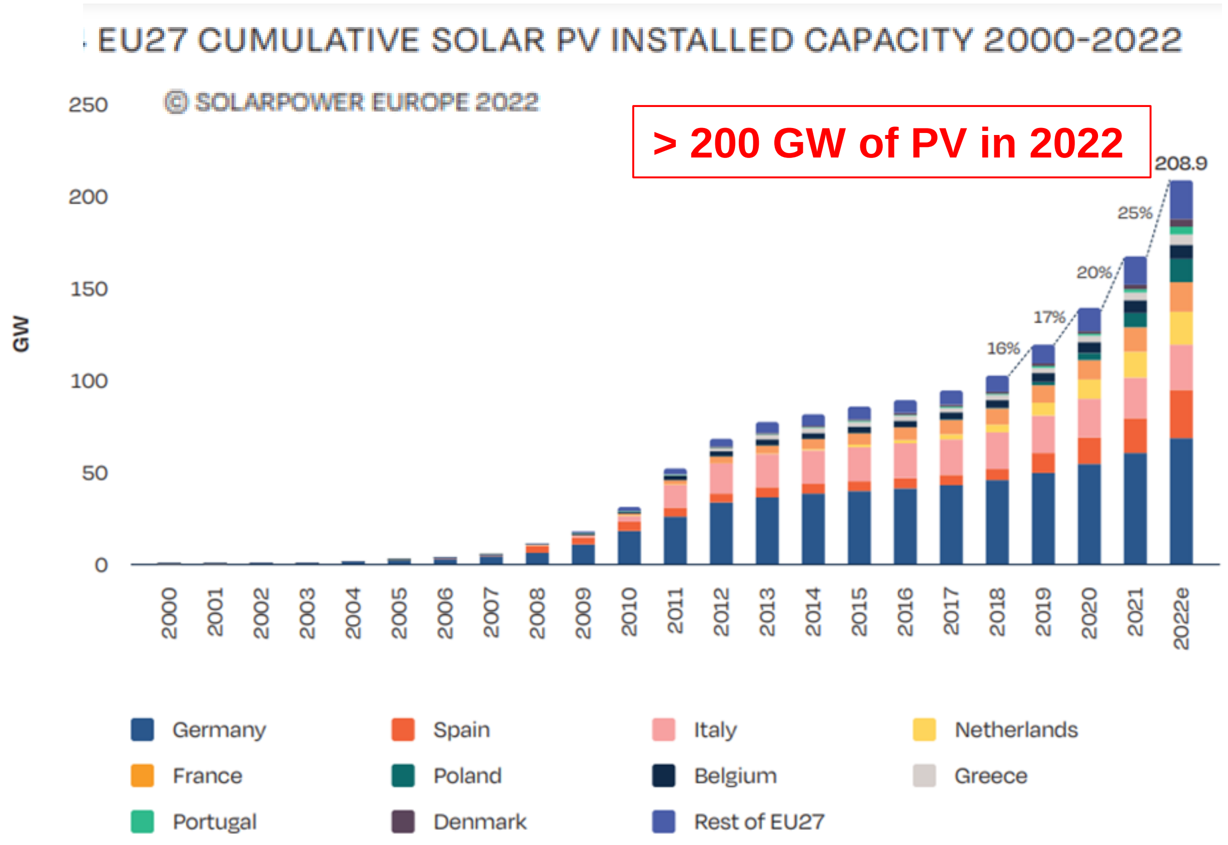


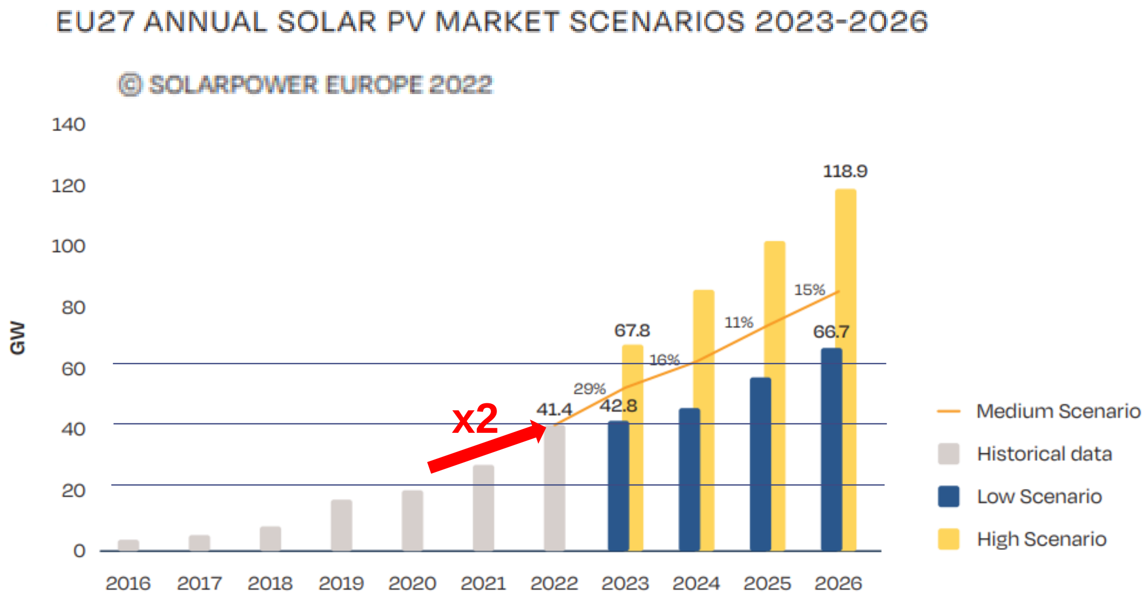




- ❑ **Cumulative PV installations pass 1 TW in 2021**
- ❑ **Mean annual market growth over 10 years: 20% (period 2013-2022)**
- ❑ **Annual market to grow up to 1 TW by 2030 (from various sources)**

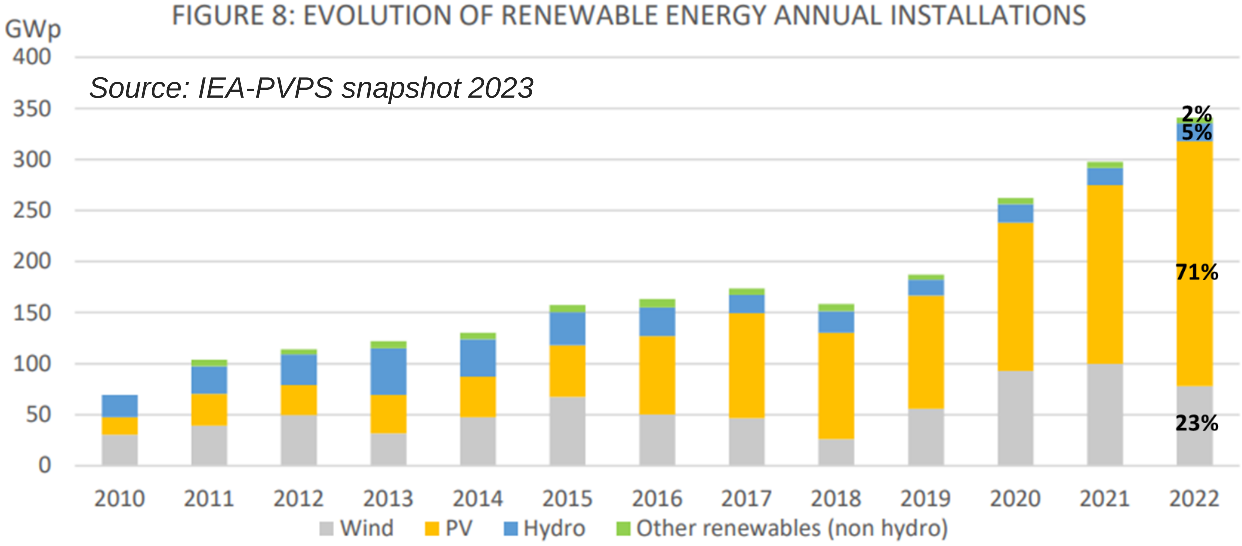
Trend of PV installations in EU





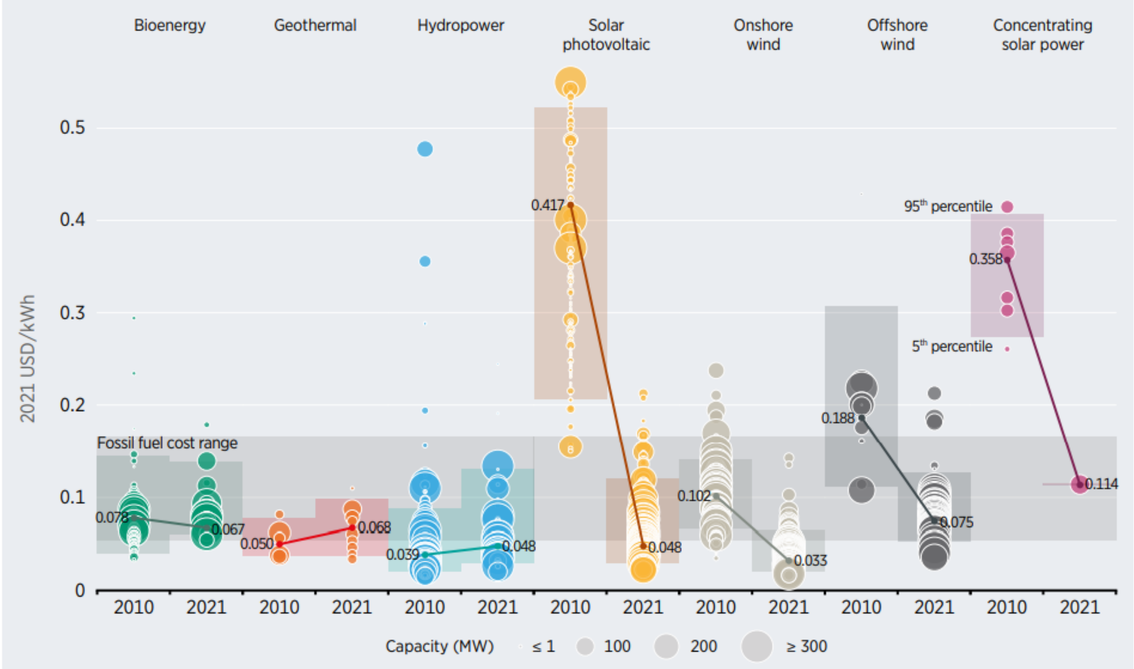
- **EU 27 is accelerating the pace of PV installations since 2020**
  Geo-political context , carbon neutrality in 2050, FIT for 55 (-55% of GEG in 2030 vs 1990) + REPower EU, EU Solar Energy Strategy
- **60 GW annual capacity addition in sight (2024 at the latest)**

Cost and market share of Renewable Energy sources



The share of renewables in total power generation capacity growth reached 81% in 2021, up from 79% in 2020

Figure 1.2 Global weighted average LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2021



Source: IRENA, RENEWABLE POWER GENERATION COSTS IN 2021

- ❑ **PV is the most installed RES worldwide (availibilty of the resource, short installation time, low cost)**
- ❑ **Global weighted LCOE of hydro, PV and onshore wind (33-48 €/MWh) below fossil fuels range**
- ❑ **Global weighted LCOE of PV reduced by 88% from 2010 to 2021**

Evolution of LCOE of PV

Levelized Cost od Electricity (Energy)

$$\mathbf{LCOE} = \frac{\textbf{Total cost for the whole PV plant lifetime } (€)}{\textbf{Total Energy prodution for the whole PV plant lifetime } (\mathbf{MWh})}$$

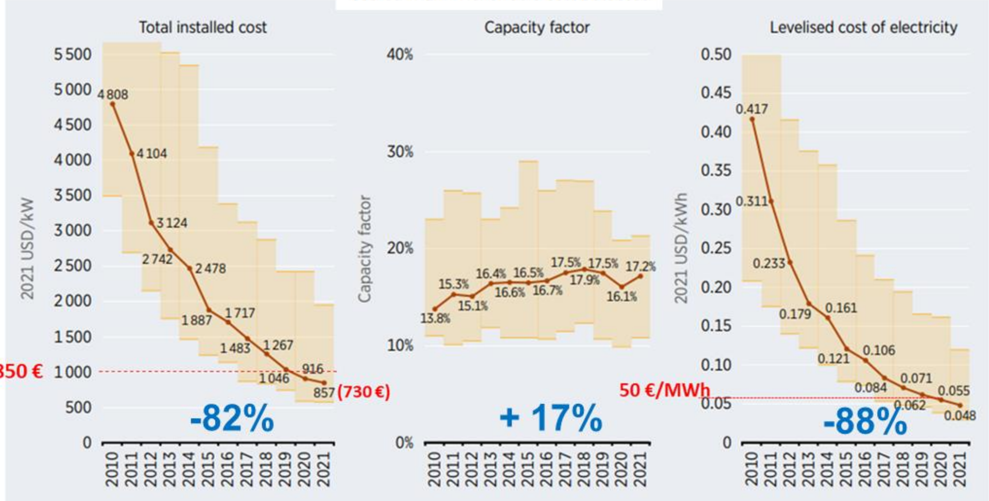
LCOE is one simple metric to evaluate the cost of the energy produced by a given production mean

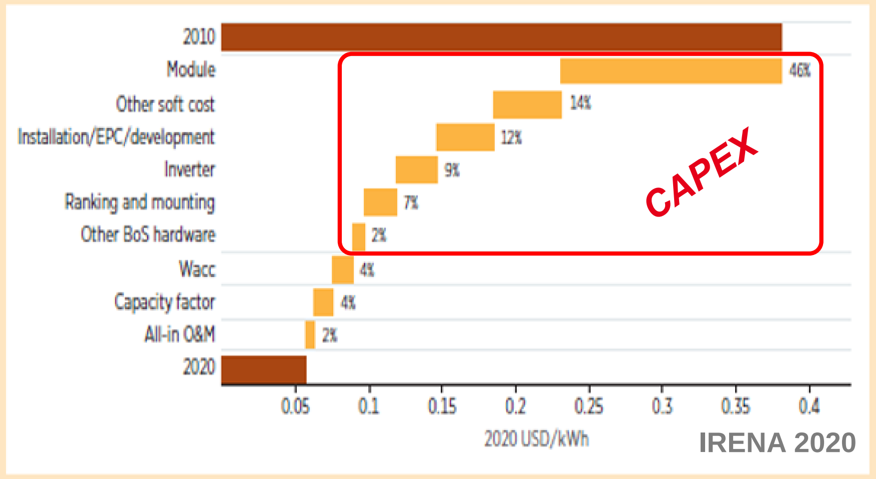
$$\mathrm{LCOE} = \frac{\mathrm{CAPEX} + \sum_{t=1}^{n} \frac{\mathrm{OPEX}(t)}{(1+r)^t}}{\sum_{t=1}^{n} \mathrm{Yield}(0) * \frac{(1-\mathrm{Degr})^t}{(1+r)^t}}$$

CAPEX = Capital expenditure
OPEX = Operation expenditure
Yield = Energy producible at t0 (ex: 1st year)
Degr: Degradation rate
r : Discount rate

Figure 3.1 Global weighted average total installed costs, capacity factors and LCOE for PV, 2010-2021

Source: IRENA Renewable Cost Database.

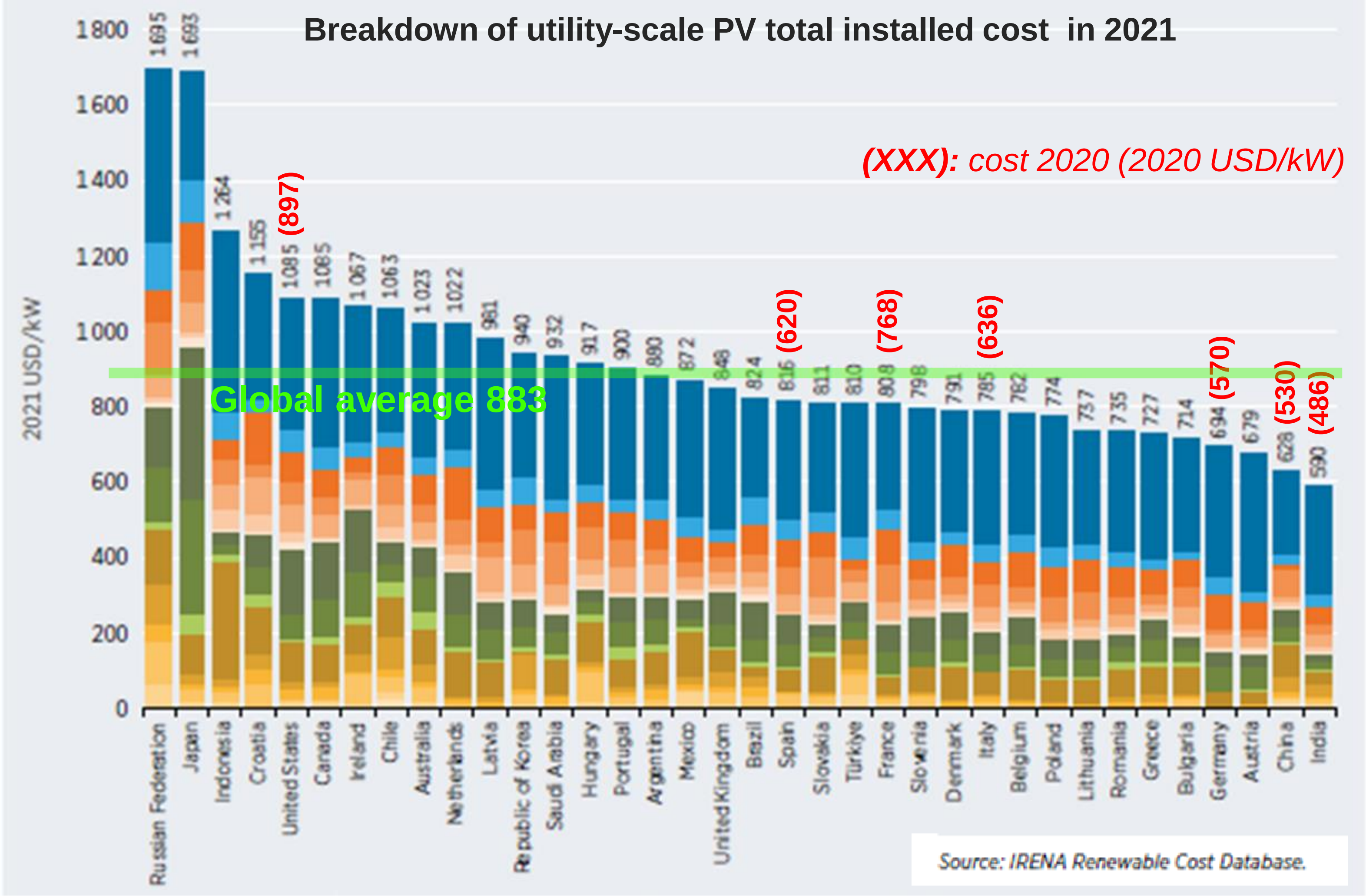


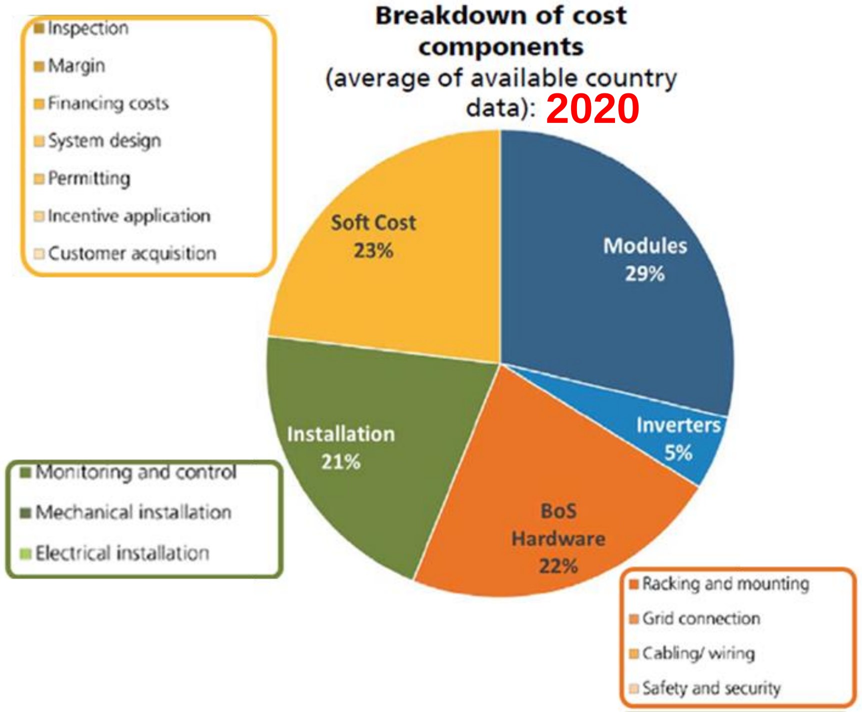


- ❑ **Fall of LCOE mainly due to large decrease in CAPEX (first, module price)**
- ❑ **Increase of CF contributes to energy production**

LCOE of PV ≈ 50 €/MWh

Installation cost of utility scale PV



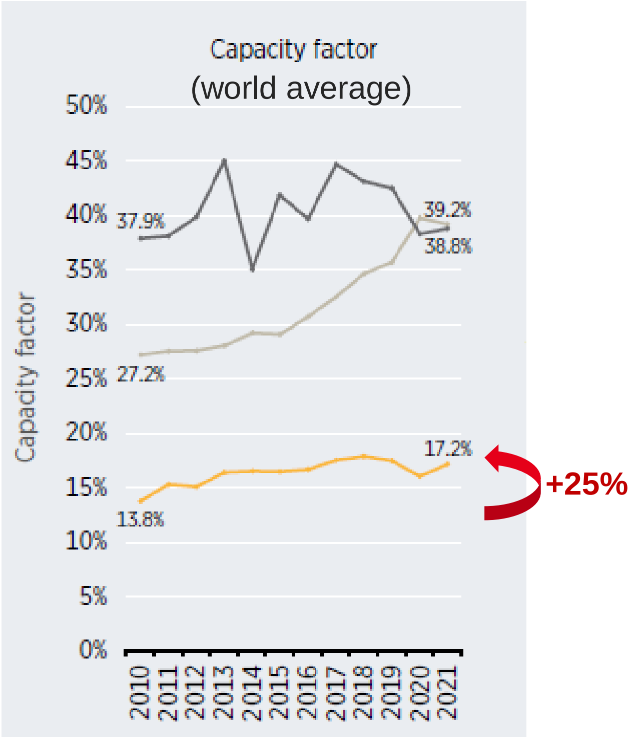


- ❑ **Large variation on installed cost induced by national policies**
- ❑ **Increase of cost from 2020 to 2021 caused by inflation rate and higher module prices**

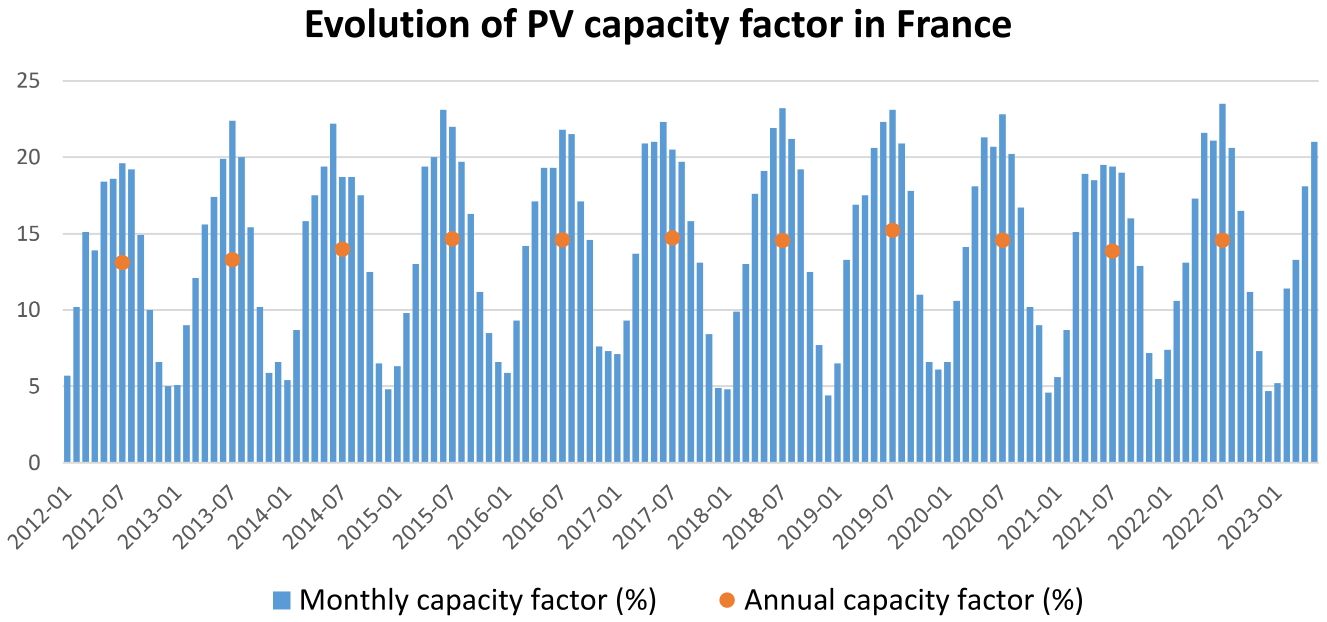
Capacity factor of PV

$$CF = \frac{Producible\ (kWh)}{Nameplate\ Power(kW) * Time\ (h)}$$

Ex: $Annual\ CF = \frac{Annual\ Producible\ (GWh)}{Nameplate\ Power(GW) * 24 * 365}$



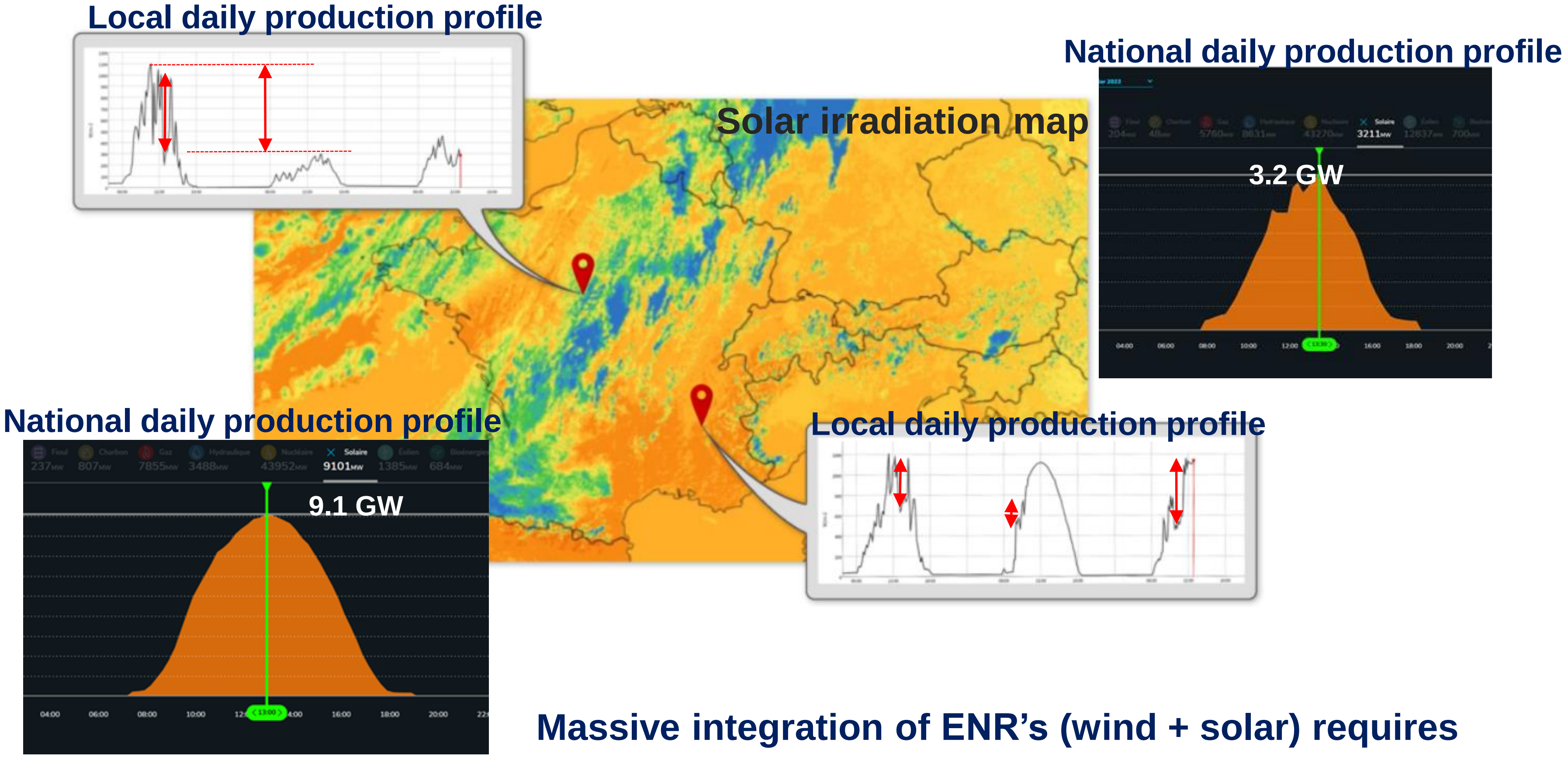
Source: IRENA – RENEWABLE POWER GENERATION COSTS IN 2021



- **Increase of CF contributes to the lowering of cost of PV electricity**
- **Capacity factor of PV is relatively low (pay attention on the difference between capacity and producible)**
- **Annual average values of CF ‘mask’ variability of the PV production (fct of geography)**

Intermittency and variability of PV

Intermittence = alternance day/night (on/off; fully predictable)
Variability = fluctuations of production intra-day and day-to-day (forecast accuracy < 100%)



Aggregation allows smoothing of otherwise discontinuated local productions

Transport & distribution networks are necessary to offset local imbalances demand/supply

The grid is a critical element of the energy transition

Massive integration of ENR's (wind + solar) requires

- **Accurate production forecasts to anticipate the activation of controllable productions**
- **Reinforcement of the grid to agregate local productions**
- **Flexibility means (storage, controllable productions, load curtailment) to equilibrate demand/supply**

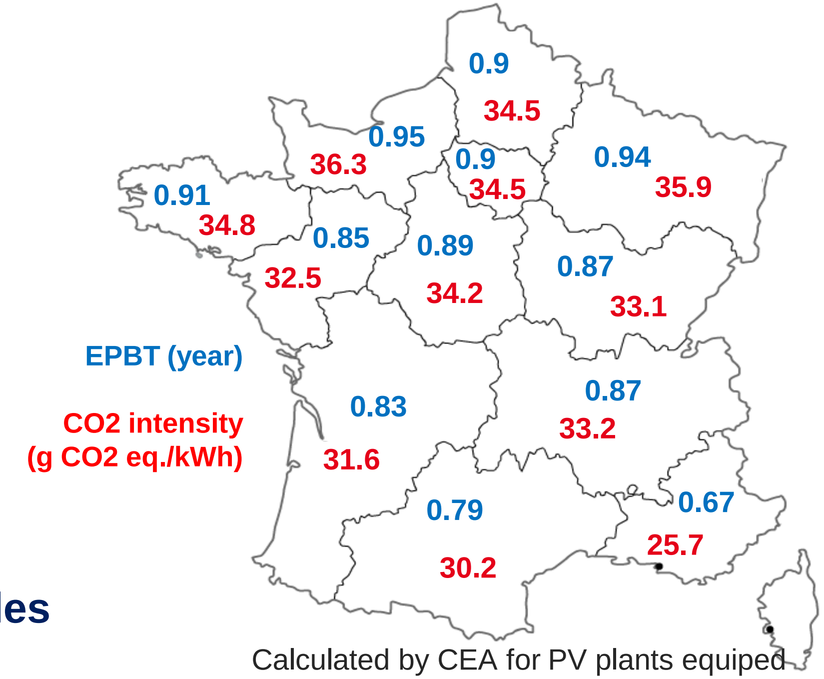
Carbon intensity and energy paybacktime of PV (ex of France)

Carbon intensity of electricity sources in France in 2021

	Wind onshore	Wind offshore	Photo-voltaic	Hydro	Geo-thermal	Nuclear	Coal	Oil	Gas
CO2 intensity (g eq/kWh)	**14.1**	**15.6**	**43**	**6**	**45**	**6**	**1060**	**730**	**418**

Values calculated by ADEME for 2021

Carbon intensity and EPBT of new PV plants (2023)



Calculated by CEA for PV plants equiped with premium modules produced in China

Mean EPBT : 0.86 year (10.3 months)
Mean CO2 intensity: 33 g CO2 eq./kWh

- ❑ **Lowest CO_2 emitting sources are hydro and nuclear**
- ❑ **Important decrease of CO_2 intensity of PV (-25%) with best-in-class modules (energy savings, reduced material consumption, higher producible)**
- ❑ **Further decrease possible with relocalisation of the value chain (low carbon electricity available in EU) → 17 g CO_2 eq./kWh**

Merci

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