Recent progress in PV technologies, and future reliability challenges

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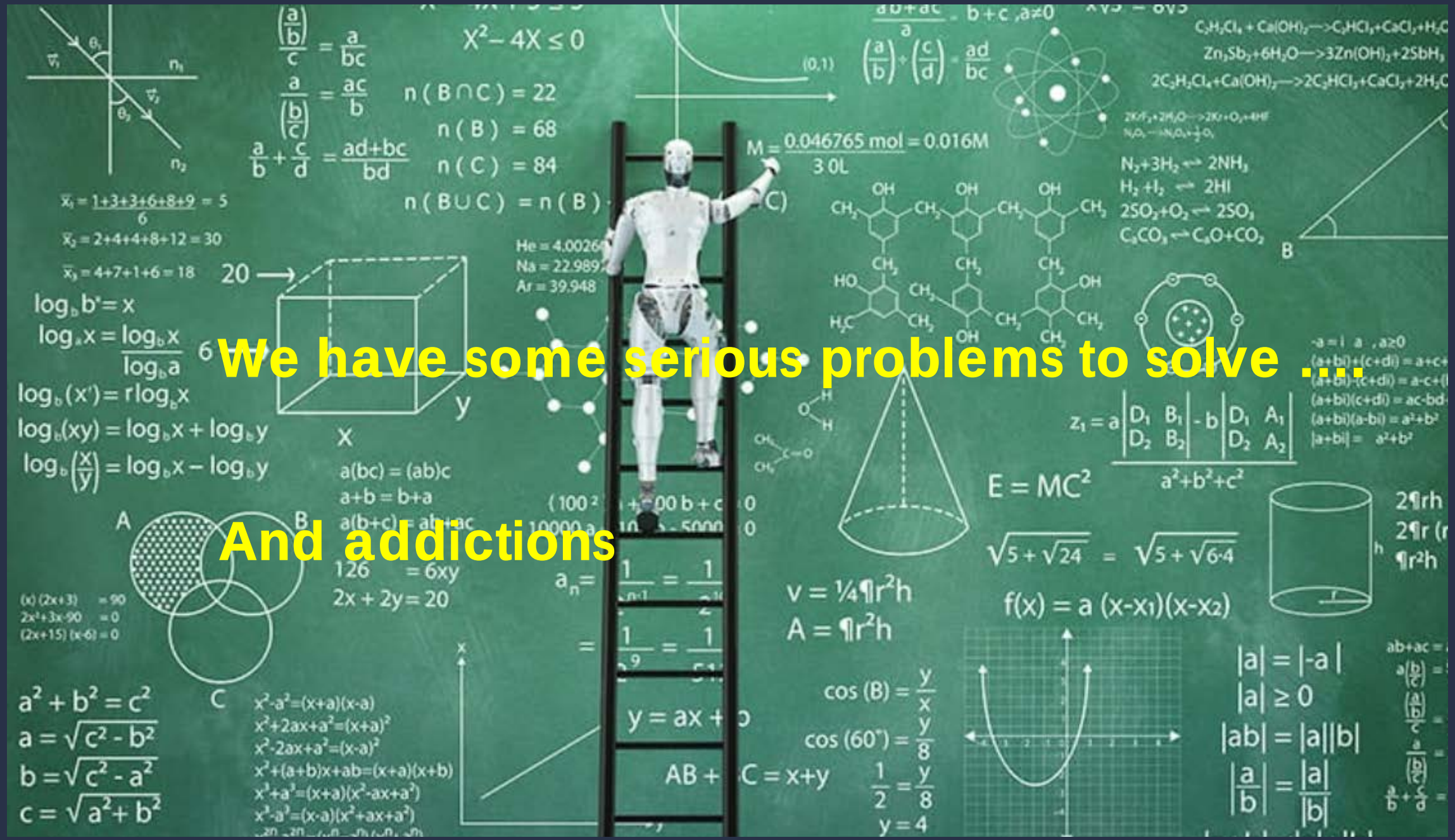
Neuchâtel
Suisse

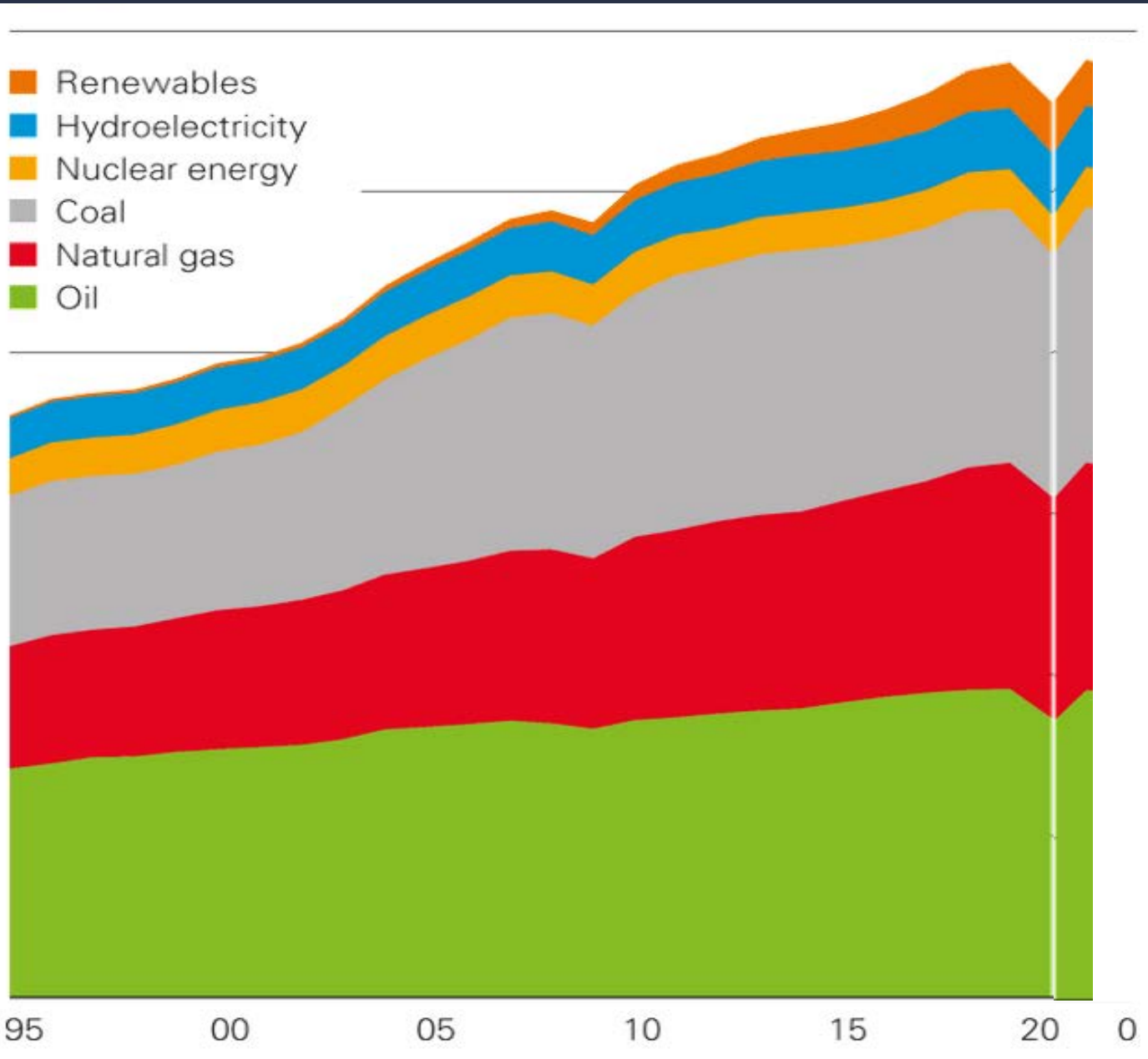
Sophia Reliability workshop, Neuchâtel, June 30th 2022


We have some serious problems to solve ....
And addictions


Fliegl
Fliegl
SAVARY TRANSPORT VESIN
avesco
MAKE DIESEL GREAT AGAIN


FR·3257779

Primary energy consumption



~ 166’000 TWh

Still 80% fossile fuel

Electricity + heating, transport, industrial processes

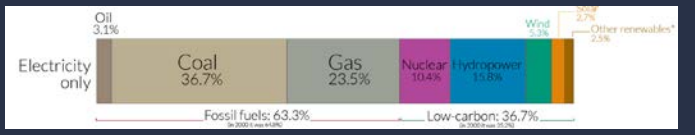
*Electricitiy of biomass, hydro, solar, nuclear wind taken with a factor 1/0.38 to be shown as primary energy source

*2021 data from IEA

Statistical Review of World Energy 2021

EA global energy review 2021

Quick rule of thumbs estimations for the world:



ourworldindata.org

- With a 2% growth in primary energy need → 250'000 TWh in 2050 (around 1000 x austria/ch today)
- Strong electrification of heating/mobility + power to gas (by 2030) with a gain of 2.5 + biomass

→100'000 TWh electrical production by 2050 (in 2020 hydro ~ 4300 TWh Nuclear 2600 TWh, wind 1500 TWh, Solar 700 TWh, Global around 25'000 TWh)

4 major options

Which can be combined

a) e.g. 40 TW of Solar and 15 TW of Wind (+ Hydro + Biomass)

b) 11'000 x 1 GW nuclear power plants (or 100'000 SNR)

c) Carbon sequestration

d) Don't care

Cheaper and greener: unbeatable price for solar and wind in large systems

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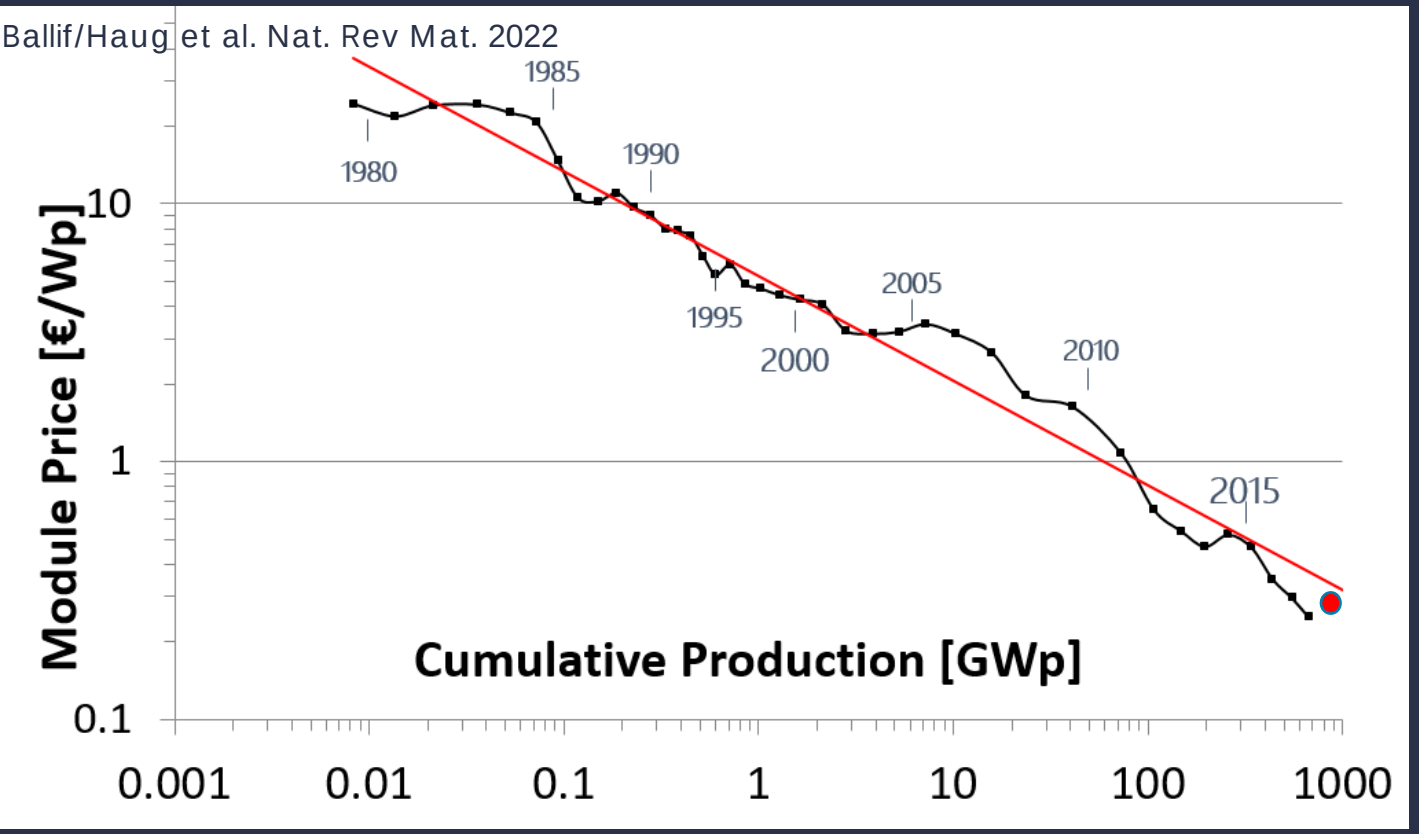
At the core of PV systems: learning curve of PV modules



- Current standard PV module price down to 22-30 cts/Wp ~ 40-60 CHF/m^2

Cumulative 1 TW (1000 GW installed) in march april 2022

- 2021: 1 m^2 of 20% module ~ 60 € → 6000-9000 kWh EU over 30 years
- PV modules better by a factor 15-20 in terms of energy import costs vs gasoline **

**1 W PV modules -> 1cts/kW, 1 liter oil imported (3kWh mechanical in combustion engine) 60 cts → 20 cts/kWh useful

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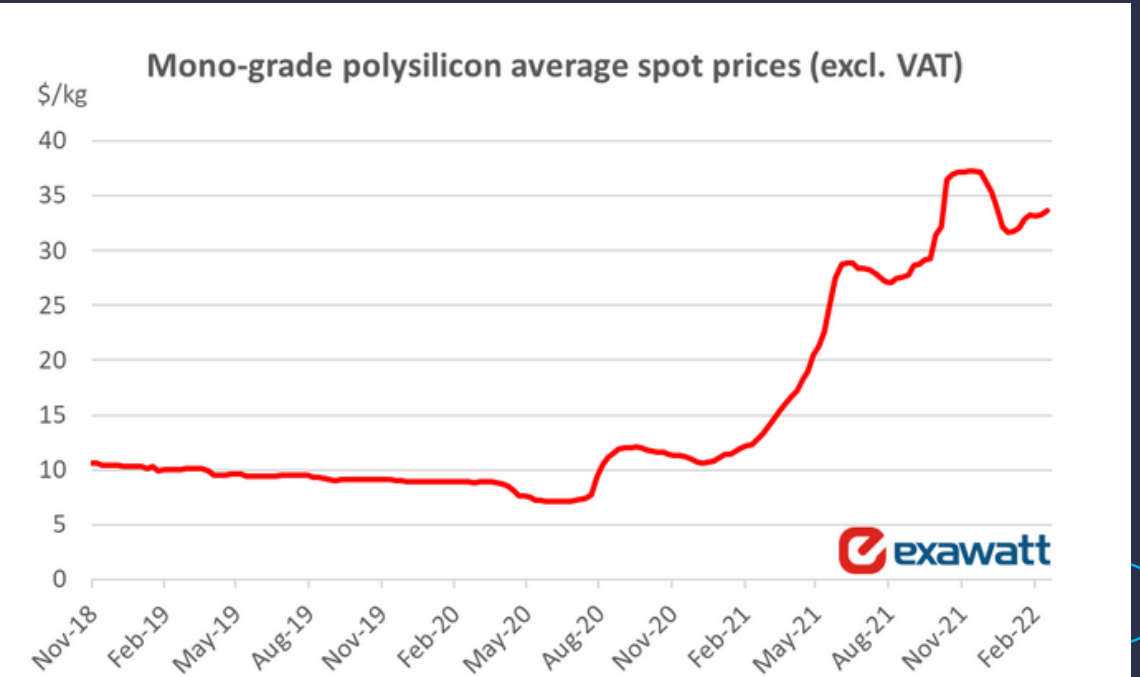
But

- Temporary price increase because of shortage (polysilicon, glass, silver) brings mainstream PV prices higher…. (from 20 to 30 cts in one year)
- World supply chain under stress
- Likely to stay for 1-2 years, because of strong demand… if demand stays strong → price remains high



Polysilicon prices started to increase considerably in February 2021.

Source: Exawatt analysis of spot price data from China Nonferrous Metals Industry Association, EnergyTrend, PV InfoLink and PVInsights

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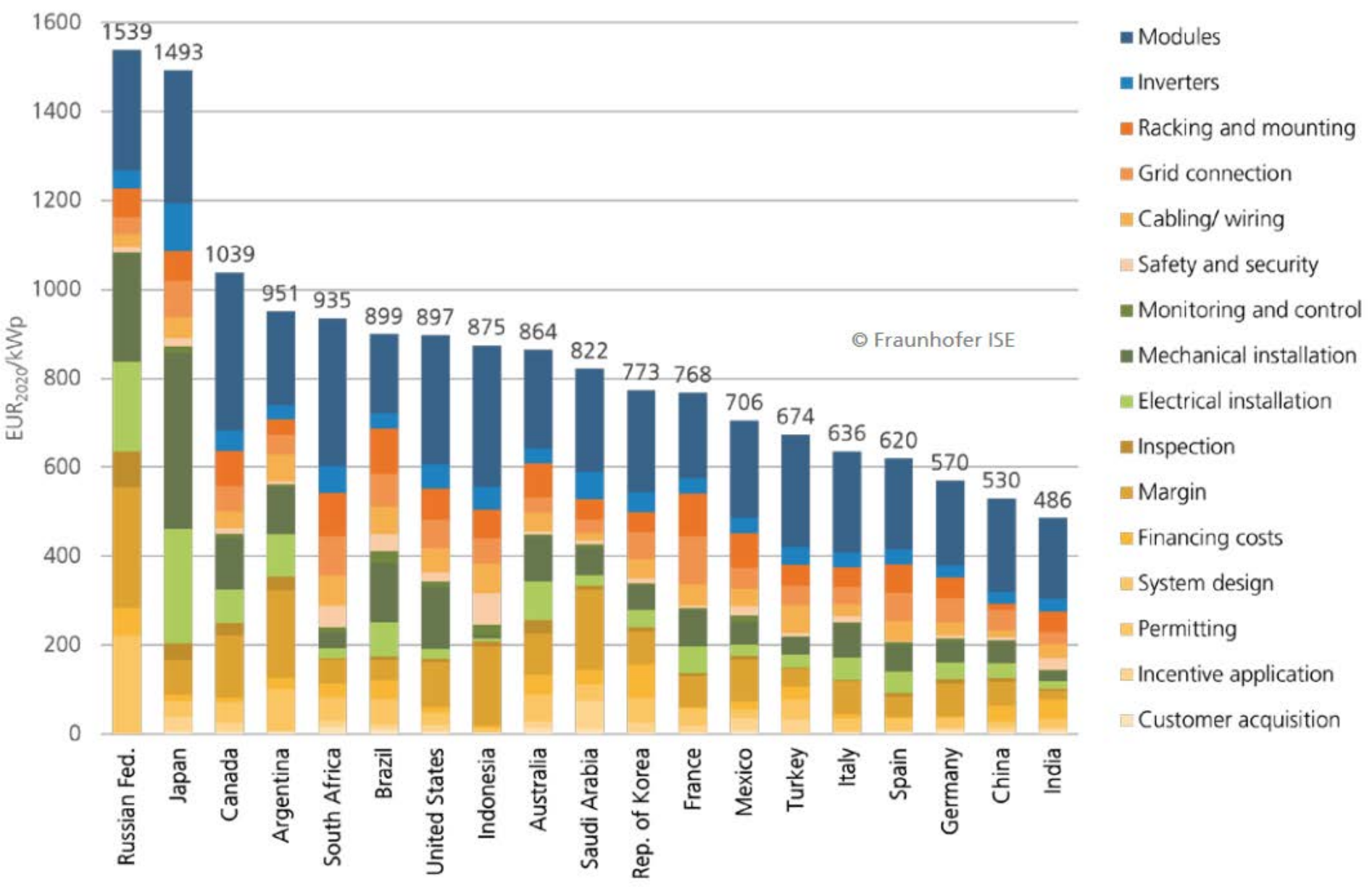
Utility-scale PV Total Installed Costs in 2020

Le photovoltaïque dans tous ces états



Investment
Country dependant
CAPEX: 0.5€ - 0.7 €/W
in many countries

Data: IRENA (2021), Renewable Power Generation Costs in 2020, International Renewable Energy Agency, Abu Dhabi. Currency converted from USD to EUR. Date of data: june 2021

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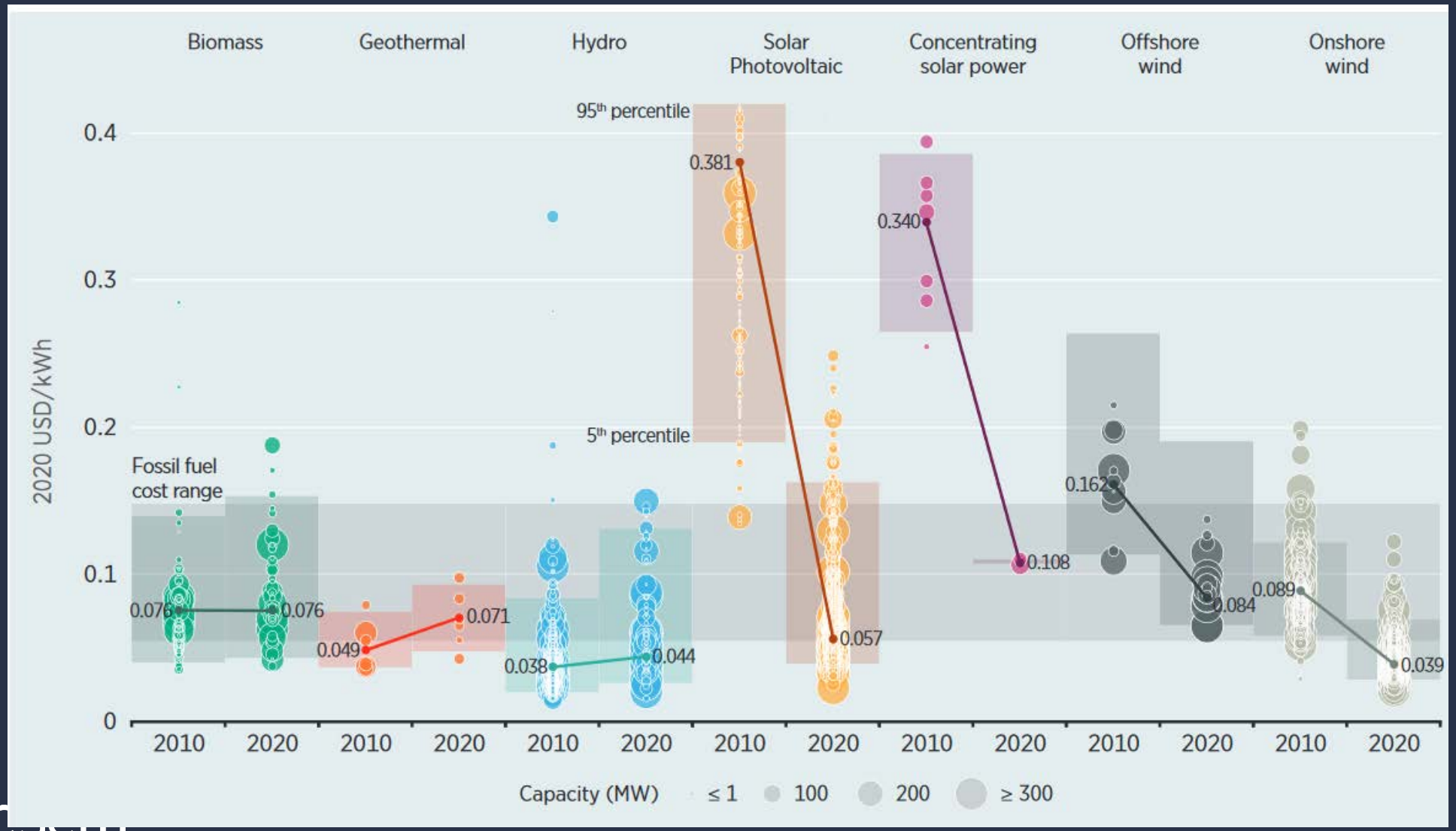
Electricity market

Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2020

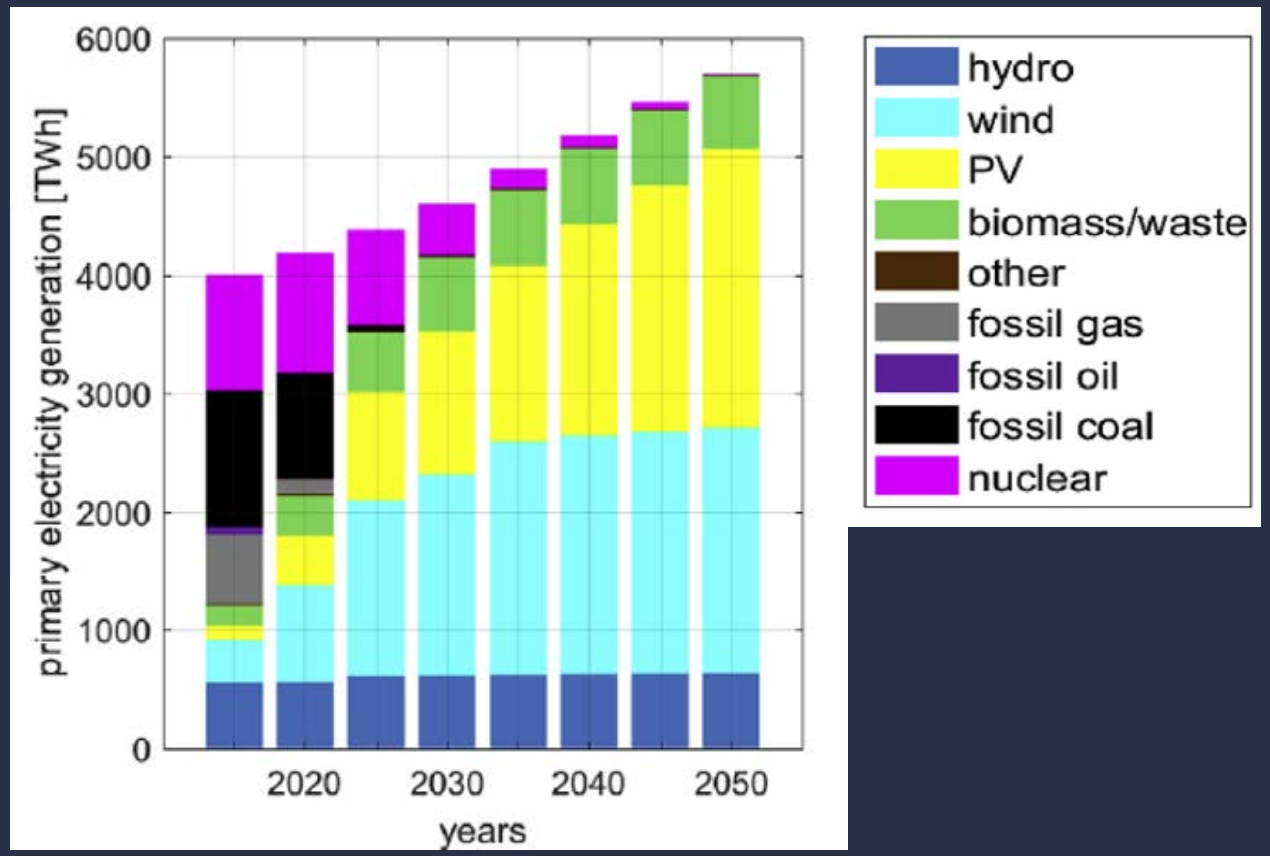
Drop in generation costs of renewables from 2010 to 2020

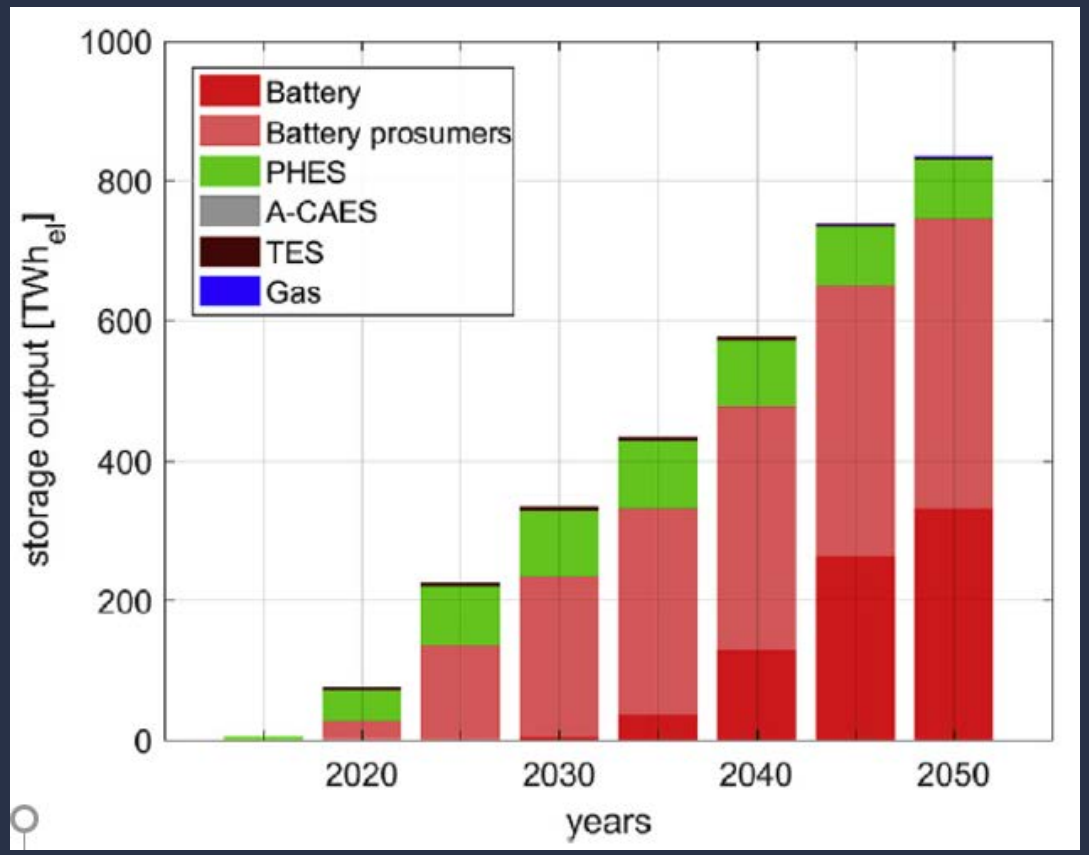


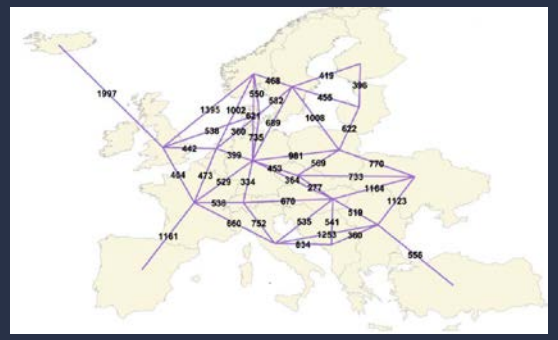
In ten years Wind and solar large parks well below LCOE of fossile fuels

Source: IRENA report «Renewable power generation costs in 2020"

A short look at Europe (in a area connected scenario) for clean power sector (with only moderate electrificiation) **







Michael Child, C. Breyer, et al. Renewable Energy 139 (2019) 80-101

Change possible but Battery storage and pumped hydro necessary to balance the grid on an hourly/weekly basis

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Sustainability

- Good practice required
- Enough silicon for PV panels
- Enough materials for batteries and electrolysers
- Possible temporary bottlenecks (→ a Marshall plan to prepare the supply)

But is PV really «sustainable» ?

(CO2 emission, energy pay-back time)

Durability of PV

1st major improvement

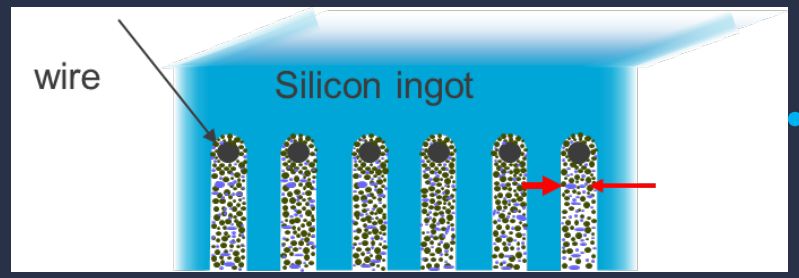
- Siemens silicon recrystallation process

200 kWh/kg of Si in 2000 !!!

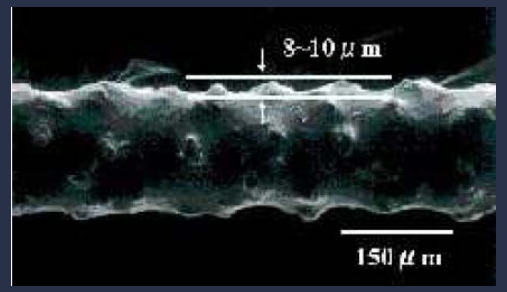
Today:
Can make 10 tons of silicon per run, tubular filaments, cold reflected coated walls.
Only 40-45 kWh/kg

Durability of PV

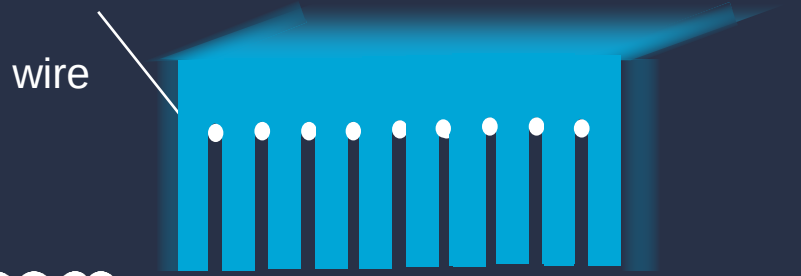
2nd major improvement: Wafer sawing



- Yesterday, multi-wire sawing, SiC particles loose 200 microns



Today, diamond wire for mono loose 60 microns
→ 60 % more wafers than 5 years ago !



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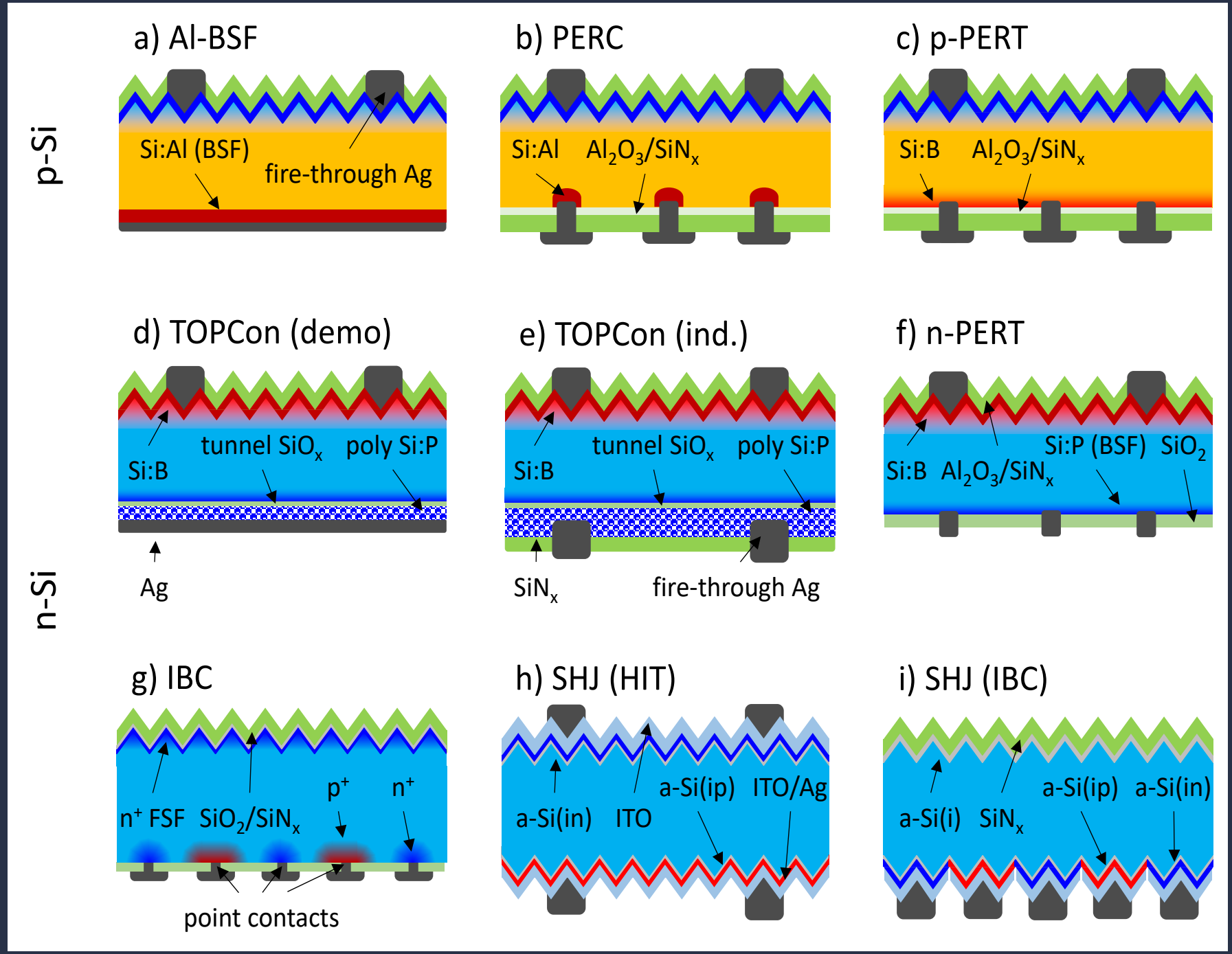
The various types of silicon technologies



Ballif/Haug et al.

Nat. Rev Materials 2022

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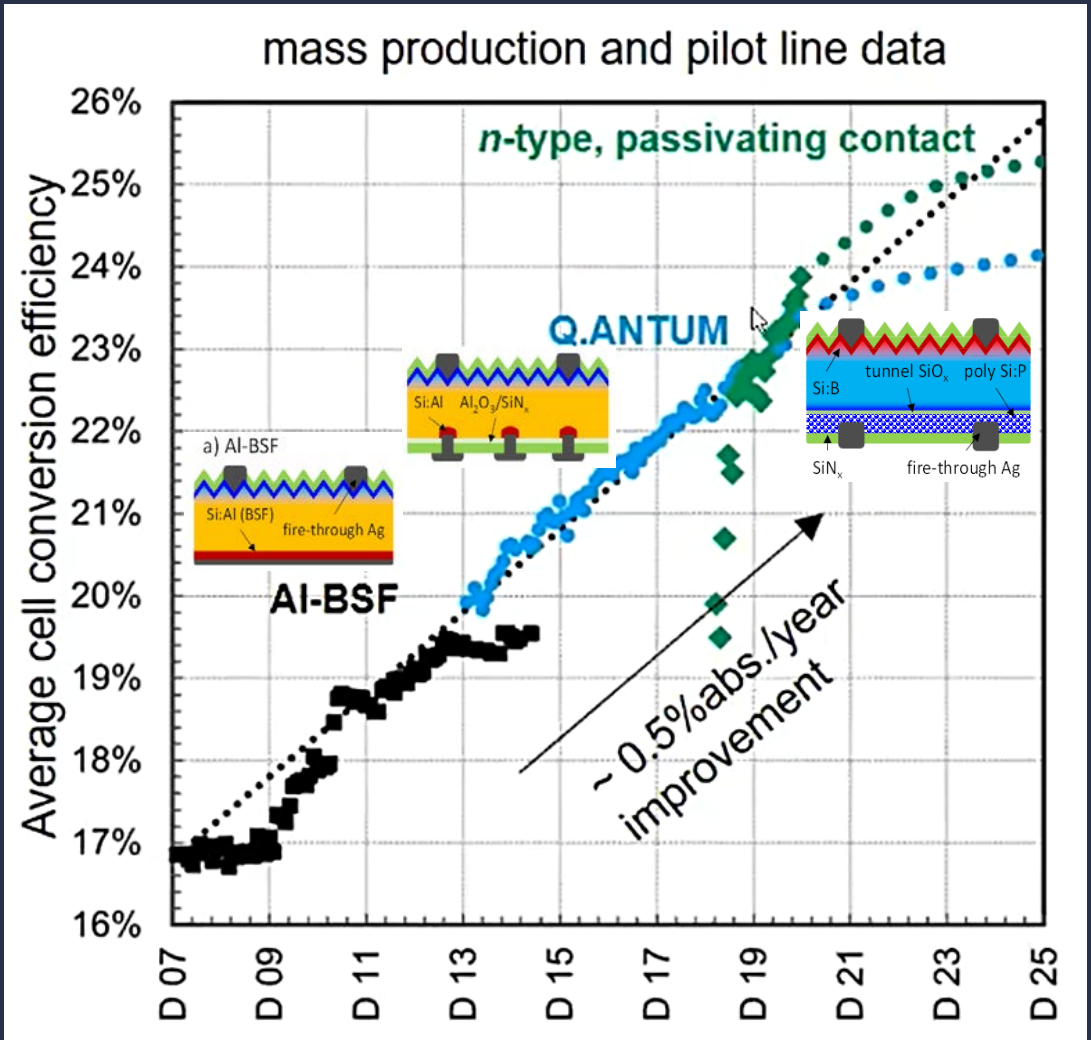
Efficiency increase

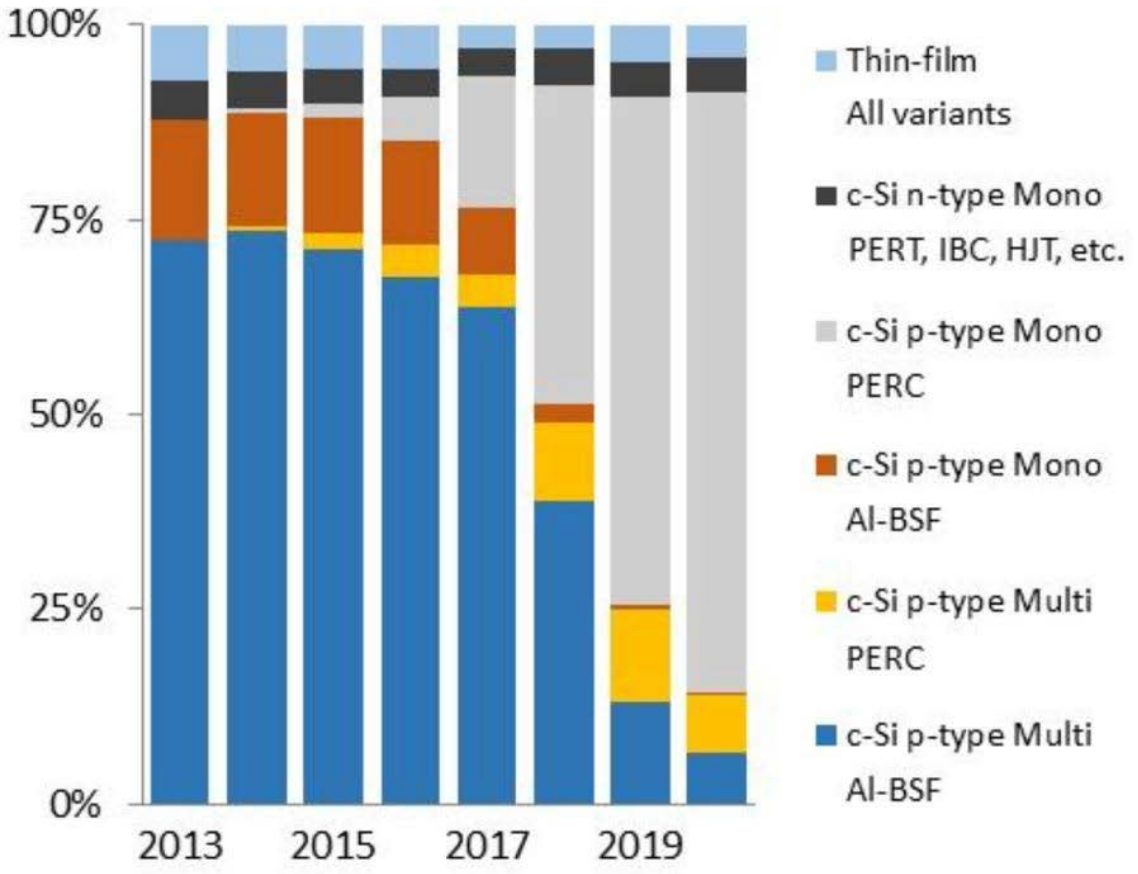
a)Technology continuous improvement and changes



Each technology evolves and then «saturates»

*J. Müller (Q-cells), pres. at the 11th SiliconPV/nPV workshop (2021)

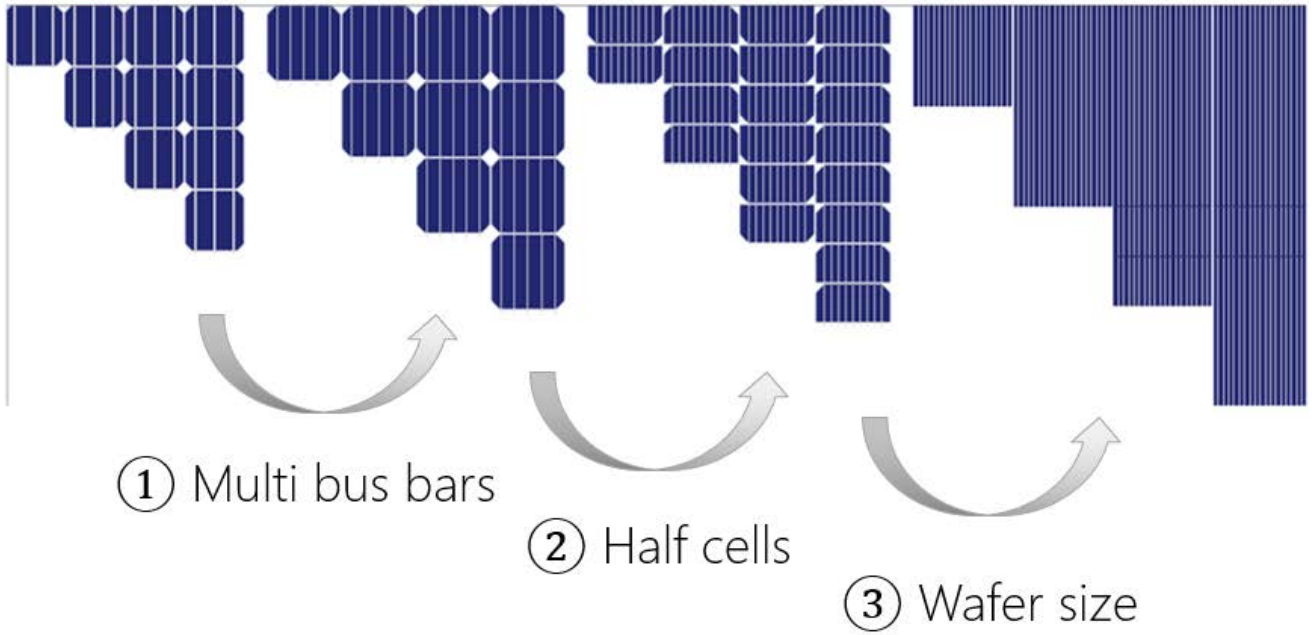
A drastic change in the PV industry lead by need for higher efficiency



Source : PV tech

- **PERC solar cells are taking >90%** of the c-Si market. Typical cells at 22-23% in production, module at 20-21.5%
- **TOPCON** and **Heterojunction** as high higher efficiency products pulling, with efficiency in the 23.5%-24.5% in production
  with record up to 26.3% on 6 inches wafers by Long for Heterojunction (and great results by Ines with p-type)
- **IBC** up to 25% in production (Sunpower)

Efficiency increase



Ballif/Haug/Boccard et al. Nat. Rev Materials 2022

b) Module design change

(0.5-1.5% absolute gain)

More bubars: reduce losses in siliver finger (gain 0.1-1% relative)

Half-cells: less losses in cupper ribbon interconnects (gain 2% relative)

Larger cells: less empty area, less edges per area (up to 21 x 21 cm2 solar cells) (0.5-1% relative)

Larger modules: less spacinga the edge (1-2% relative for 700 W modules)

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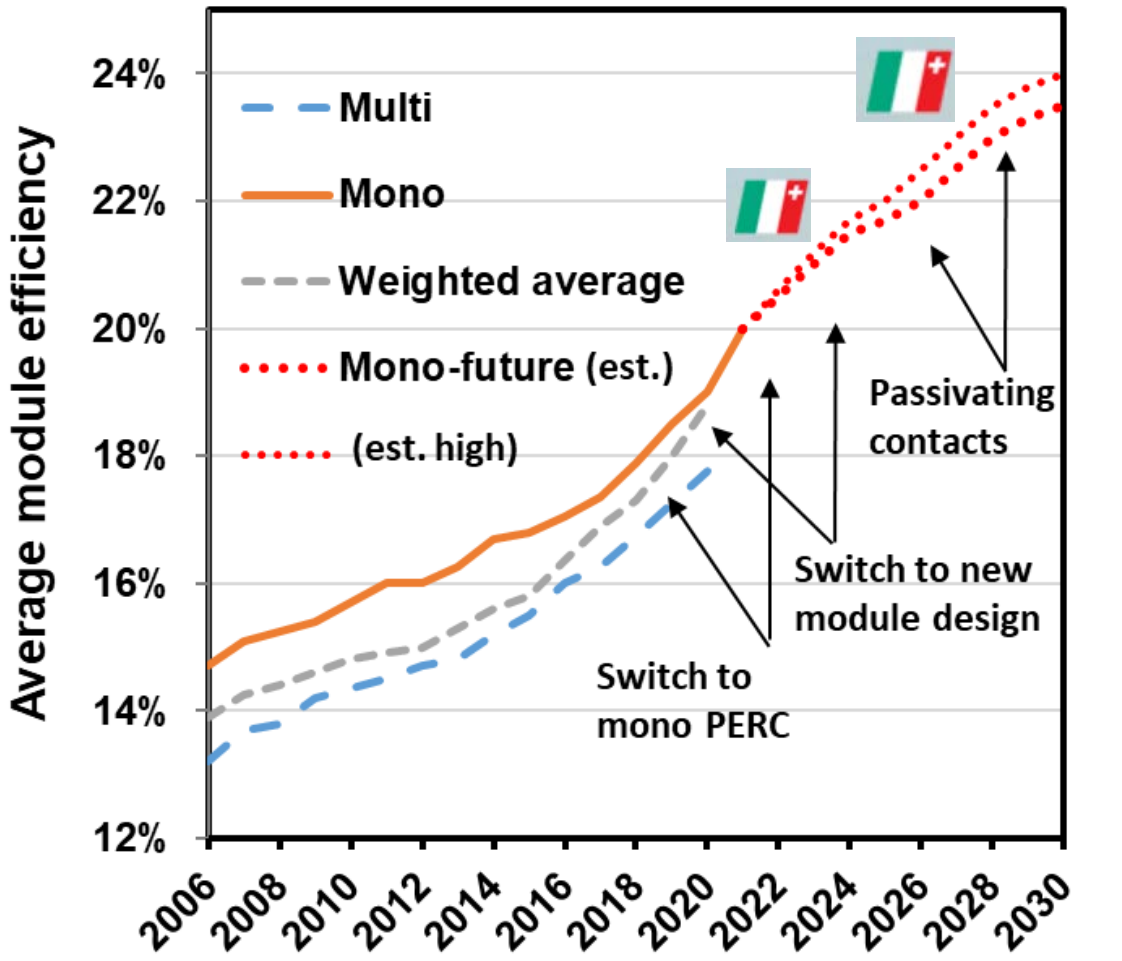
Beyond efficiency

Pricing for standard c-Si :
0.2$/W in 2020, rose to 0.27$ in 2022 (bottlenecks, transport).
40-60$/m2

Performance Warranty:
Most least 84% of nominal power after 25 years with linear degradation loss garanties (e.g. -0.4% year)
Some TIER one already offer 30 with more than 86%
Maxeon even offers 40 years and 88% nominal power warranty.



Haug, Ballif et all. Nat. Rev. Materials 2022

Permanent increase in the module efficiency

- 0.4-0.5% gain per year
- Efficiency of PV modules will further increase

(average 21.5-22.5% in 2025)

- Practical limit at 24-25% for silicon modules (PK next ??)

Reduces all other material costs/usage per W

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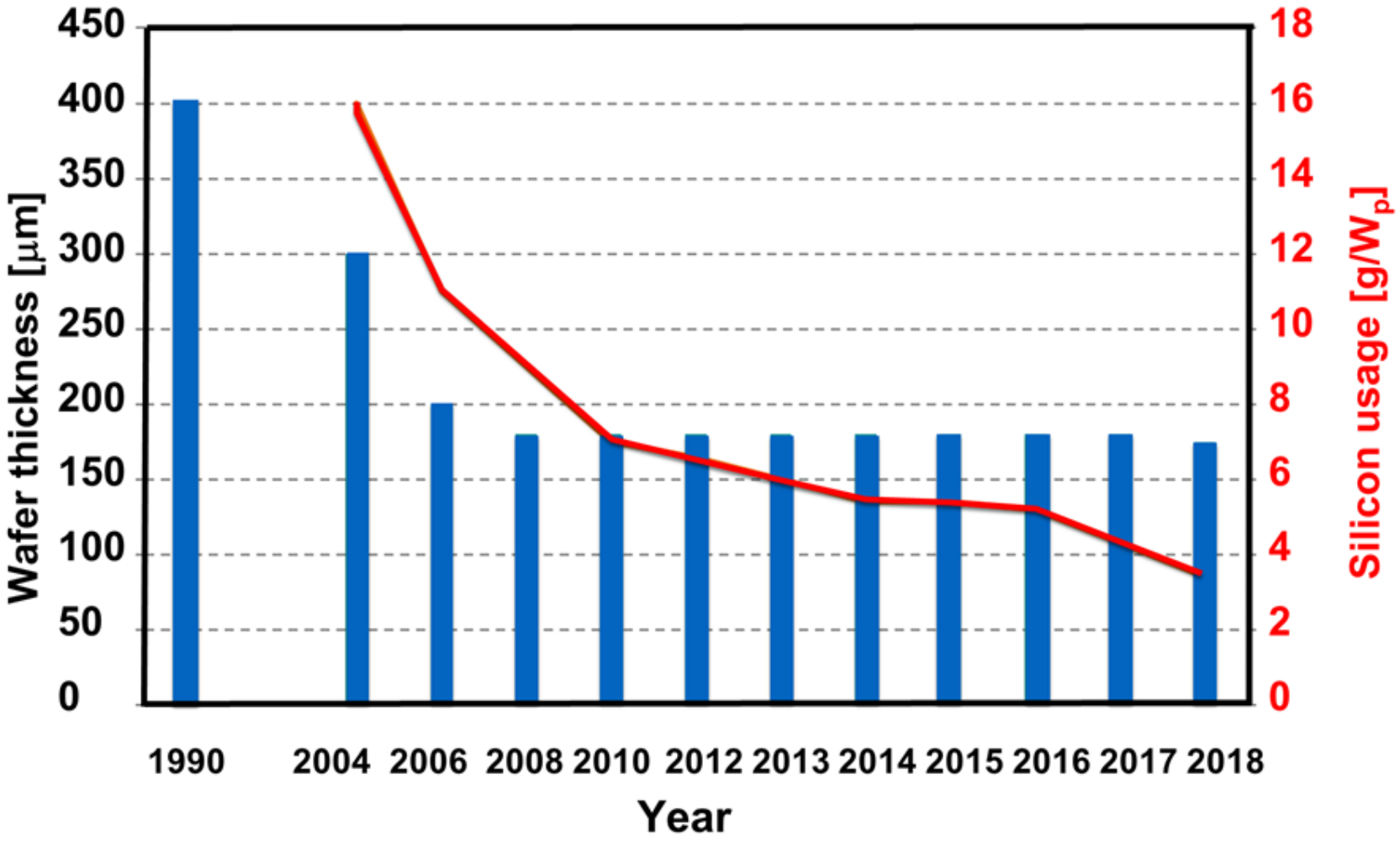
Purified silicon usage per watt



Haug, Ballif et all. Nat. Rev. Materials 2022, source Fraunhofer ISE, PSE)

- Improved processes (poly-si)
- Diamond sawing
- Efficiency increase

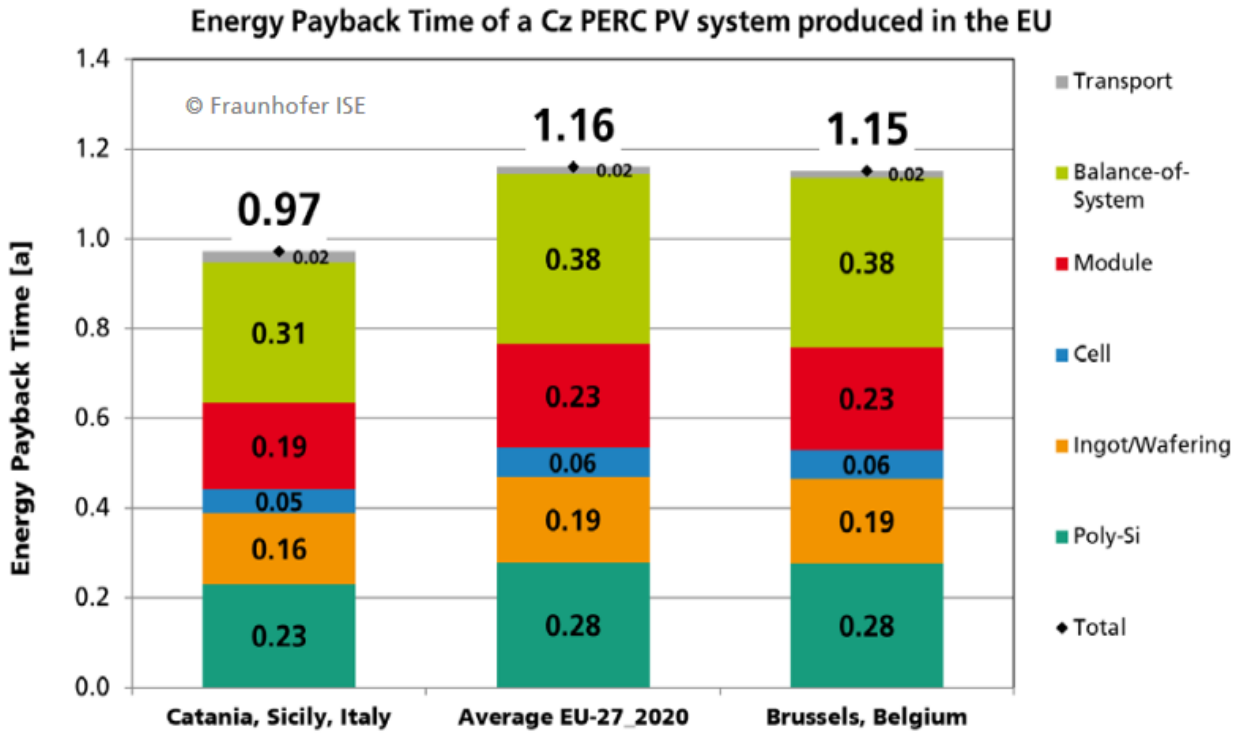
→From 17 to 3.5 g/W in 20 years,

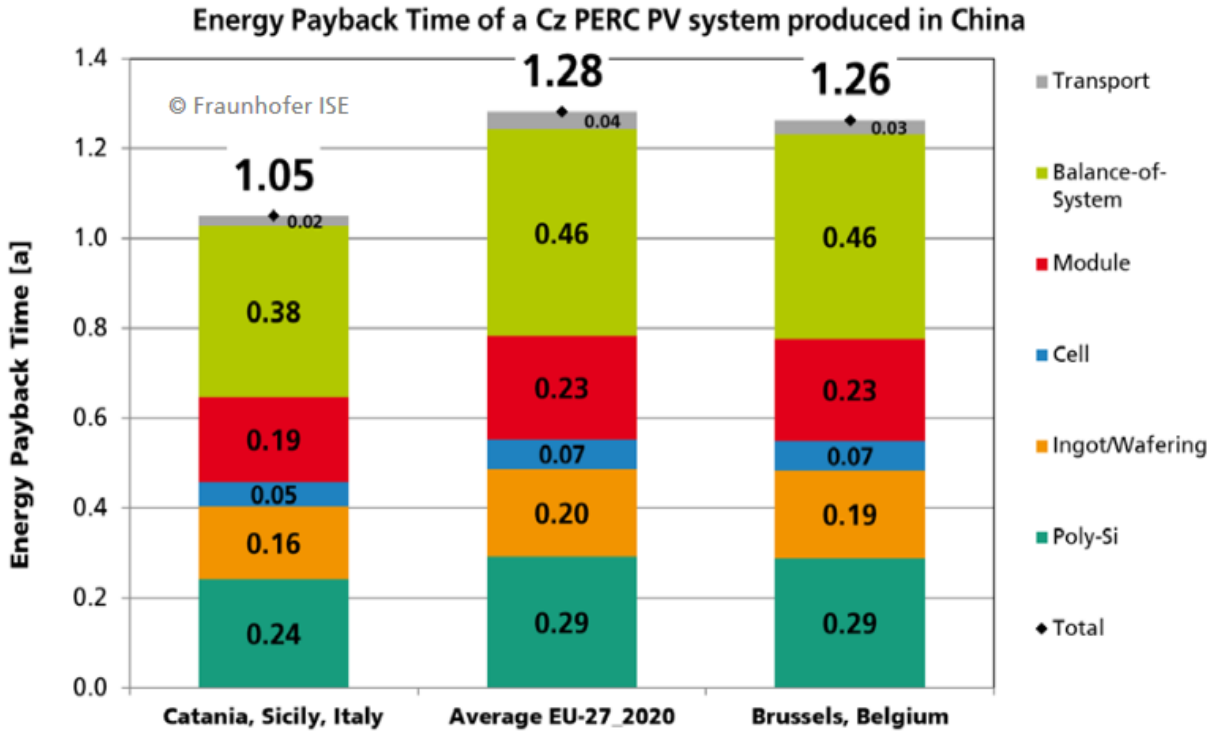
With low grey energy

System payback in

One year !

Energy Pay-Back Time (EPBT) of Silicon PV Rooftop Systems: strong improvments





A typical PV system will give back the energy required for fabrication in 1 year. Module around 60-65% of the total.

Source: Fraunhofer report 2021

Full module: currently around 0.5-0.6 kWh/W electricity required (5-6 cts/W at 10 cts/kWh local electricity)

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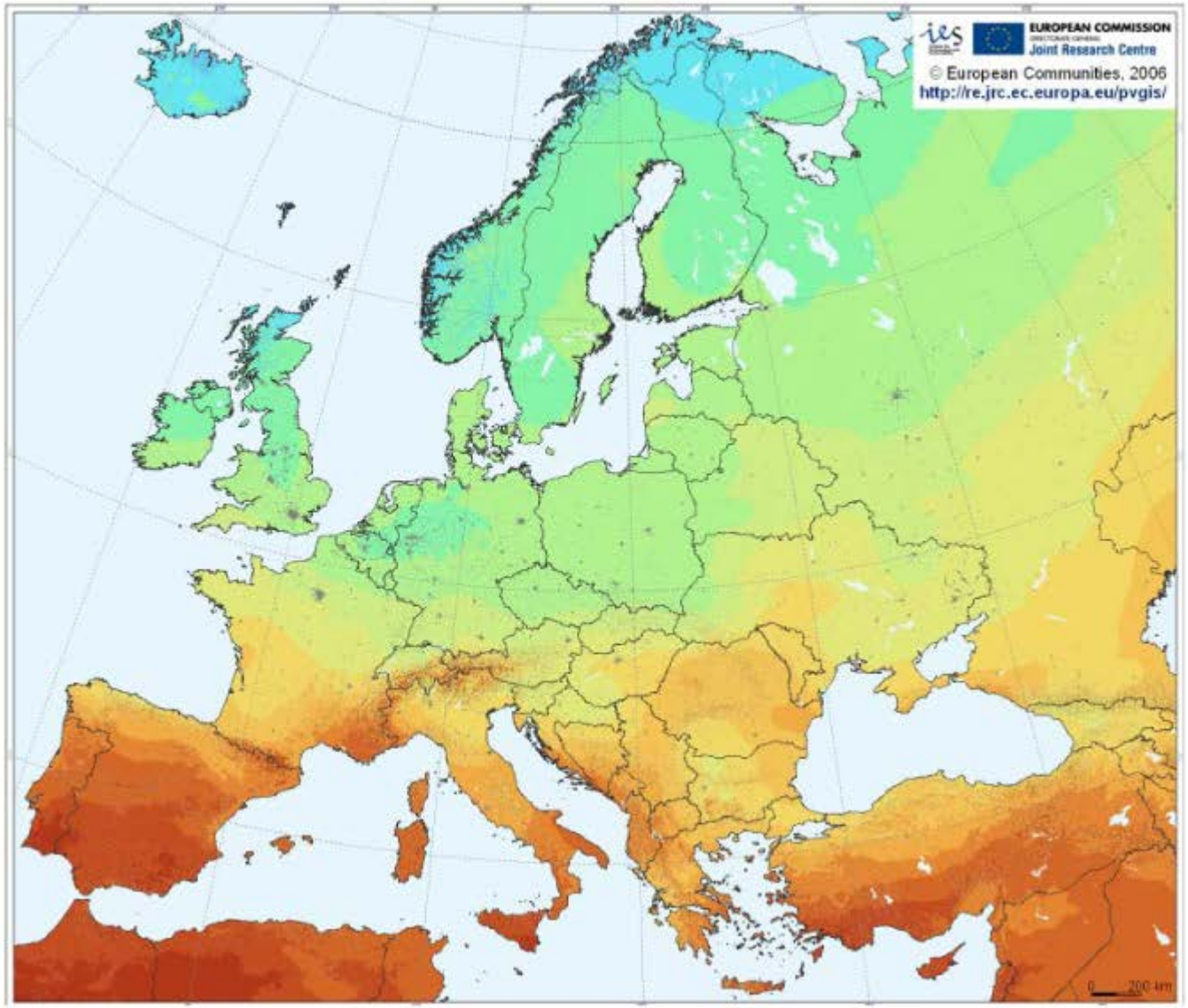
Energy Pay-Back Time of Silicon PV Rooftop Systems (2020)



Irradiation (GTI, kWh/m²/a) EPBT

<600
800
1000
1200 — 1.3 years
1400
1600
1800
2000 — 1.0 year
>2200

Source: Fraunhofer report 2021

Module CO_2 footprint

EU electricity: 430 gCO_2/W

china coal electricity: ~700 gCO_2 /W)
25 years of lifetime → 25 kWh

With the modern processes of module fabrication → 8-30 gCO_2/ kWh

In summary: even with mono c-Si modules,
system energy payback time ~ 1 year and CO_2 emission is acceptable (20 – 40g CO_2/kWh)

A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory – ScienceDirect 2021, Muller et al.

Comparison:

- Gas power plant 400g/kWh
- Coal power plant 900g/kWh

powered by Q.ANTUM DUO

Q CELLS modules earn further low-carbon certification for French tenders

Hanwha Q CELLS GmbH, the German subsidiary of one of the largest solar cell and module manufacturers in the world, Hanwha Q CELLS Co., Ltd, has received on March 14 a Certisolis carbon footprint (CFP) certification of 300 kgeq/CO²/kWc in France for its high-efficiency Q.PEAK DUO module series.

APRIL 1. 2019 Q CELLS

However, these projects must be built using components that are certified as low-carbon during their production. The official certification from CRE module series has a carbon footprint of 300 kg-eq/C0²/kWc, attained through a 25% recycled poly SI methodology.
Sustained and sustainable solar growth thanks to France continues to enjoy encouraging growth as the country aims to reach its government-mandated solar capacity target of between 18.2 GW and 20.2 GW by 2030. Currently, cumulative solar capacity in France stands at just above 8 GW

Favor the renewal of a large PV industry in Europe ??
Meyer Burger, Enel as leaders ?

Ready to pay more for a product with local content, less CO2 from polysilicon ?

No controversial human rights practice ?

Revive a European Industry ?

Reduce independancy to Asia ?

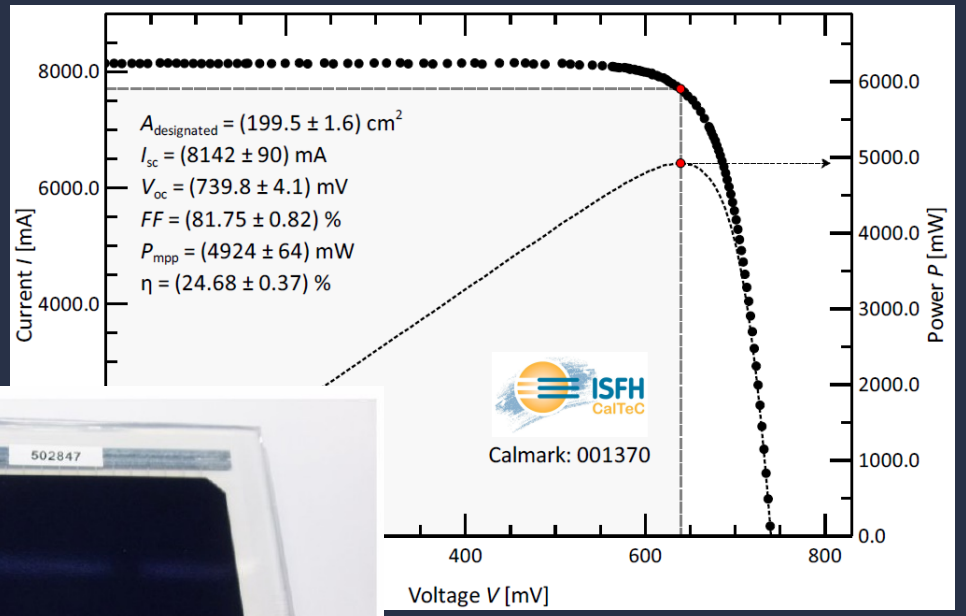
Invitation to all installers: promote EU products, with EU cells even if more expensive in the first years…

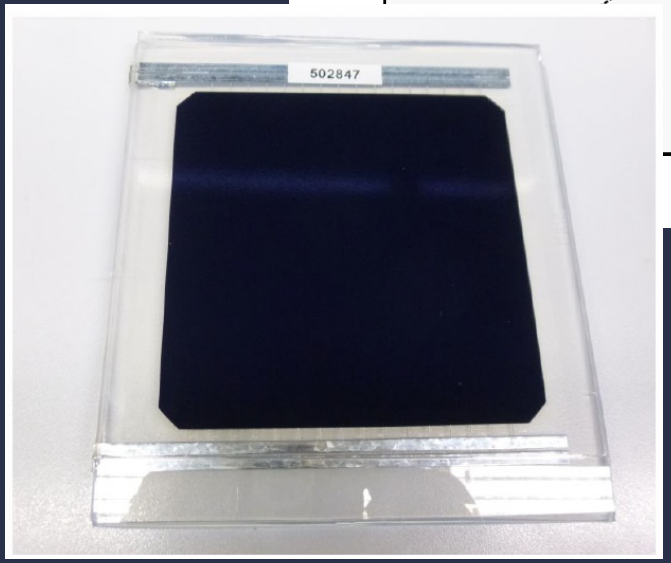
Some R&D activities in Neuchâtel

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office of Energy SFOE

- World record single-cell **laminate** with tunnel-IBC + SmartWires® :





✓ 24.7 % efficiency: world record for a laminate !

- First 60-cell tunnel-IBC module in glass/backsheet configuration:

32

MEYER BURGER

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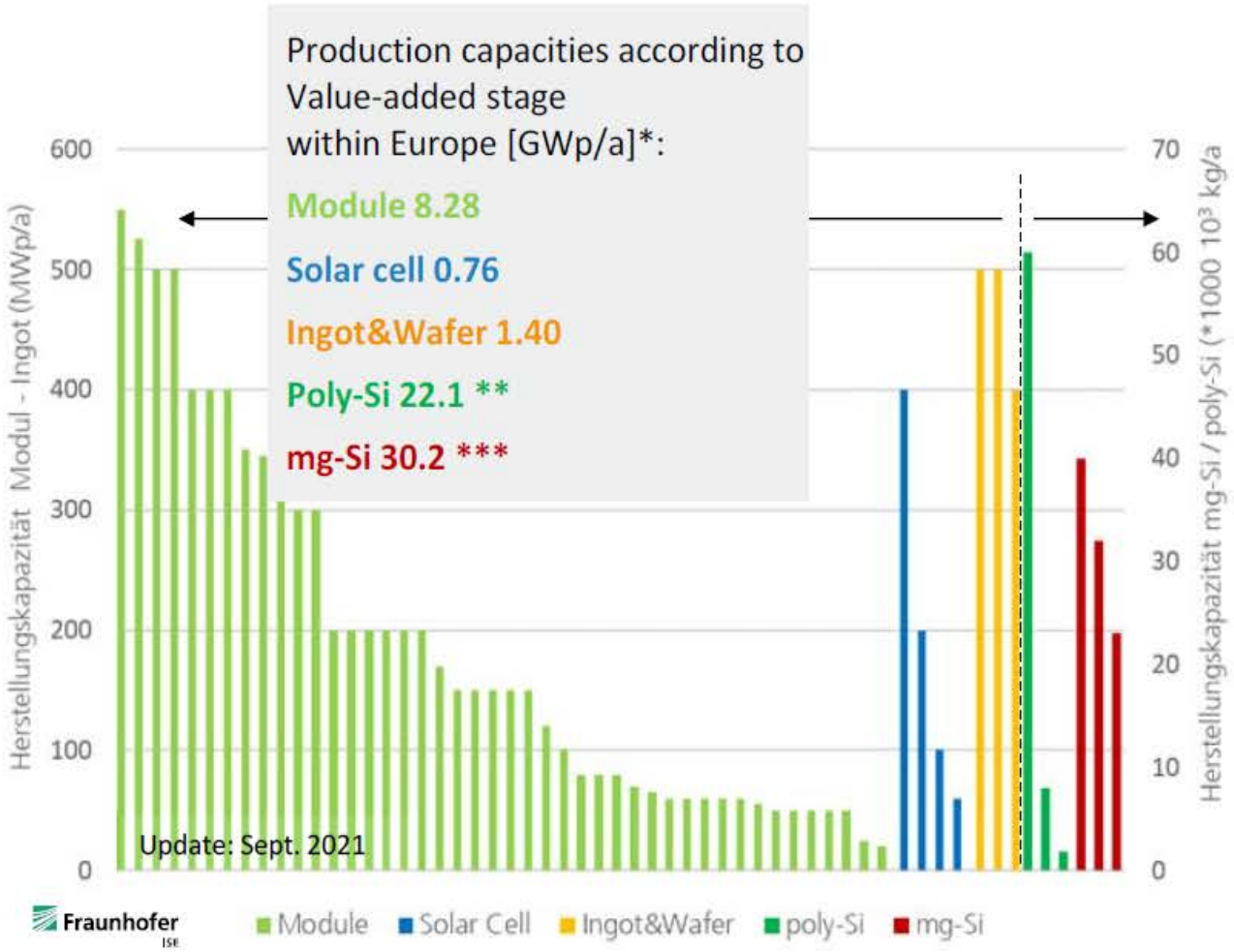
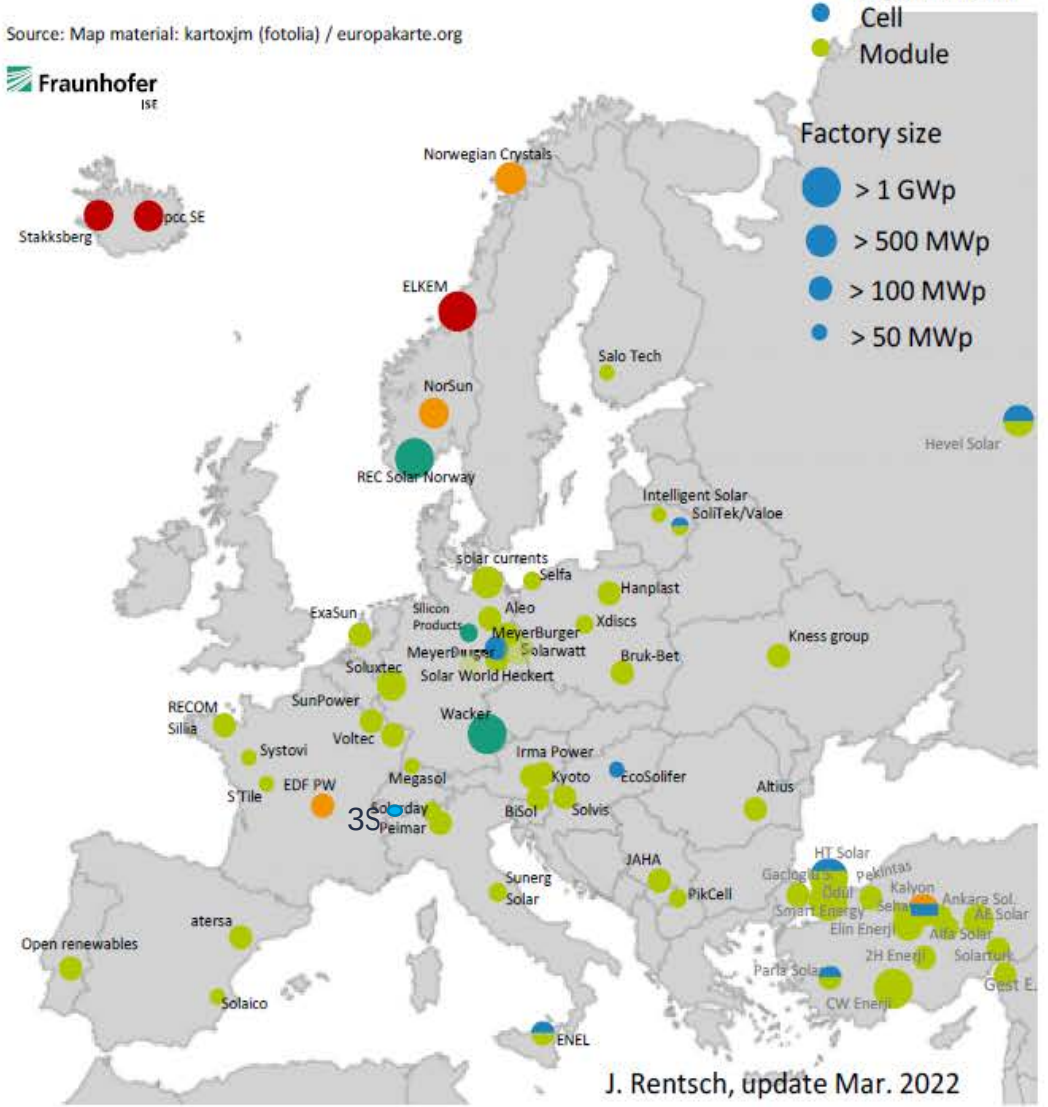
M. Despeisse, B. Paviet-Salomon, A. Faes, D. Lachenal et al.

These activities are supported by SFOE in the frame of the project “SIRIUS” (2021-2024E)

Current European c-Si PV Manufacturing Landscape

Status Quo of PV Production Along the Value Chain





* without Turkey and Russia

Source: A. bett, Fraunhofer ISE, Swiss PV conference 2022. Might be uncomplete

New Initiatives in Europe: Ingot & Wafer & Cell Manufacturing

Newly Announced Entrants and Capacity Expansions Until 2025

Ingot & Wafer

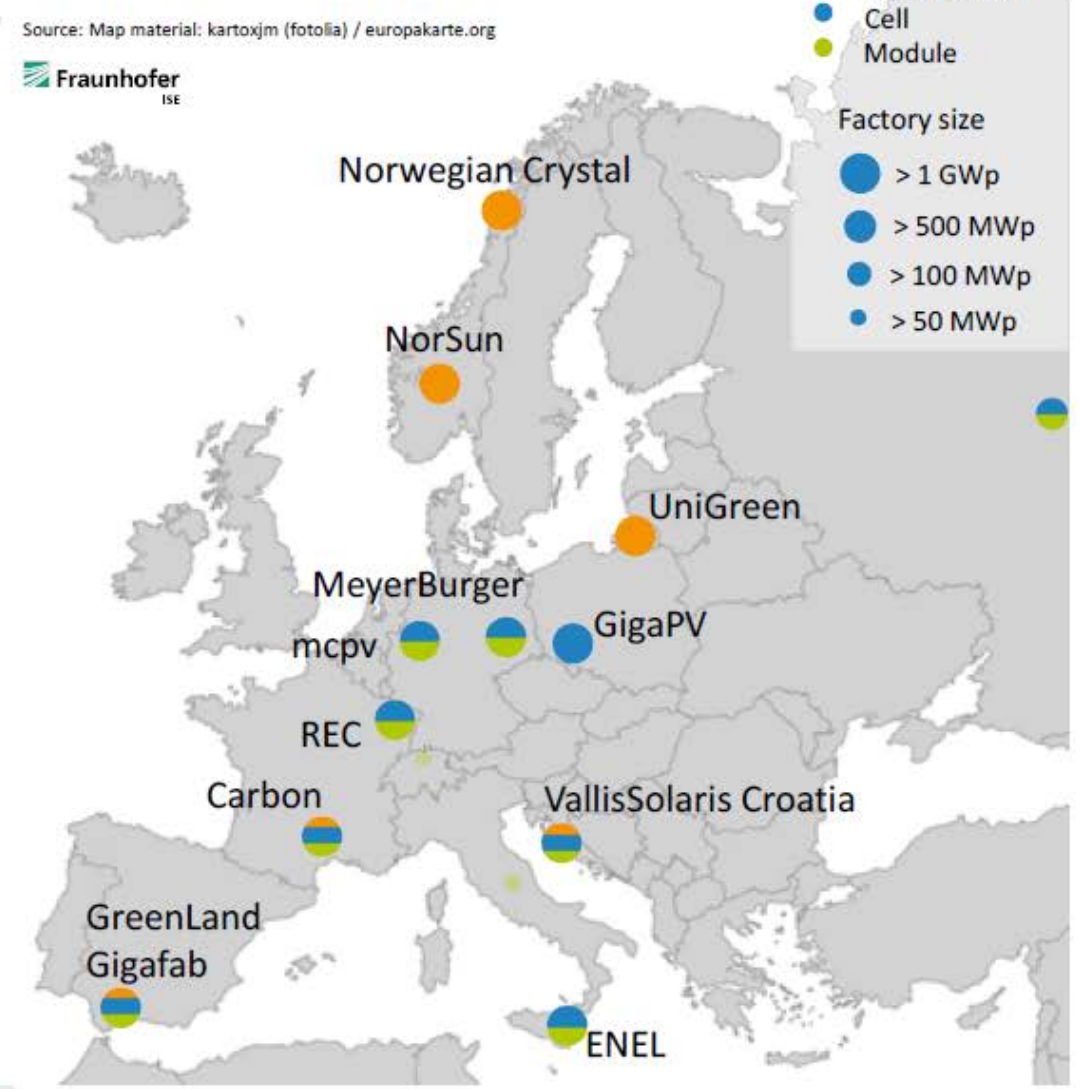
~22 GW

- Norwegian Crystal 5 GW
- NorSun 5 GW
- Greenland 5 GW
- VallisSolaris 1 GW
- UniGreen 1.2 GW
- Carbon 5 GW

Cell

~30 GW

- MeyerBurger (HJT) 7 GW
- mcpv (HJT) > 5 GW
- UniGreen (HHJ) 1 GW
- Greenland (PERC/TOPCon) 5 GW
- VallisSolaris (PERC/TOPCon) 1 GW
- Giga PV (TOPCon) 1 GW
- ENEL (HJT) 3 GW
- REC (HJT) 2 GW
- Carbon (TOPCon) 5 GW
- Oxford PV (Tandem) 0.25 GW



The grand reliability challenges !

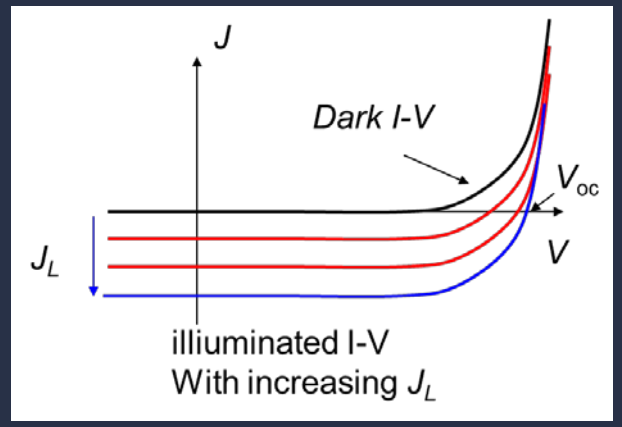
The solar cell diode equation

$$J = -J_L + J_{01}\left[\exp\left(\frac{qV - JR_s}{n_1 kT}\right) - 1\right] + J_{02}\left[\exp\left(\frac{qV - JR_s}{n_2 kT}\right) - 1\right] + \frac{V - JR_s}{R_p}$$

Various resistances

Shunts

Defect in space charge region



$$J_{01} = J_{0n} + J_{0p}$$

$$J_{0n} = \frac{eD_p n_i^2}{N_D L_p} G_{F(n)}$$

Depends on lifetime in the emitter and on

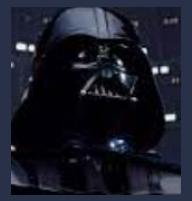
Surface passivation

$$J_{0p} = \frac{eD_n n_i^2}{N_A L_n} G_{F(p)}$$

Depends on lifetime in the bulk and on

Back surface passivation

Jo's add up..... A bad one can destroy all



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Major new reliability challenges with cell efficiency gains

Cells becomes much more sensititive, to bulk lifetime changes, surface passivation changes, or introduction of extrinsinc impurities (at surfaces, in the space charge region,.....

→ More sensitive tu intrinsinsic bulk lifetime variation (e.g. B-O complex or Fe). Solving partly possible (e.g. B doping → Ga doping. Better gettering)

Still many unknown defects, and high sensitivity to external impurities which can come at surfaces or in the bulk by diffusion (e.g. PID and Na, or Cu diffusion at RT)

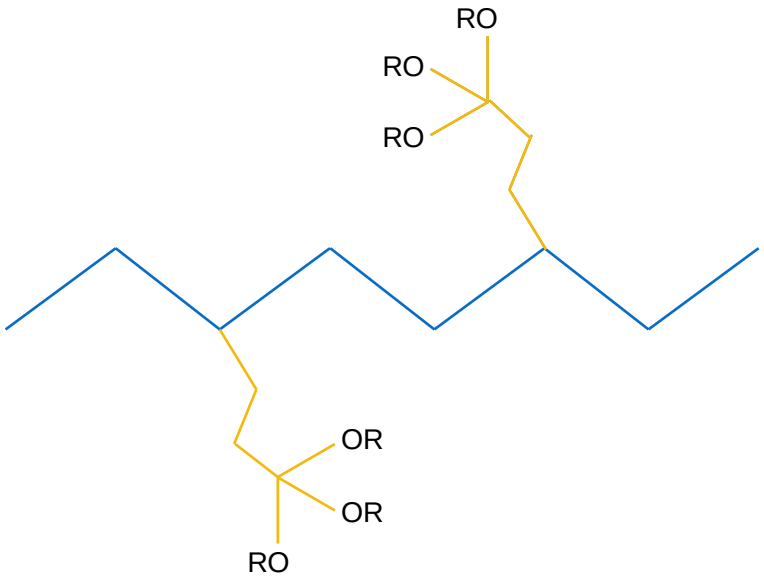
Exemple: a 14% cell would loose only 1% efficiency if 10^{11} Fe/cm^3.

A 24.5% cell would loose 7% efficiency if 10^{11} Fe/cm^3

Conclusion

- It was much easier (but also less understood) to offer a good warranty 35 years ago than today !!
- Needs for enhanced testing, combined testing and understanding
- Inevitably many challenges and issues sill likely to have !

Exemple of dveloppement by Padanaplast and CSEM
Encapsulant film formulation and production



Polidiemme® Solar

SPO compound

\+ (antioxidants, UV filter,…)

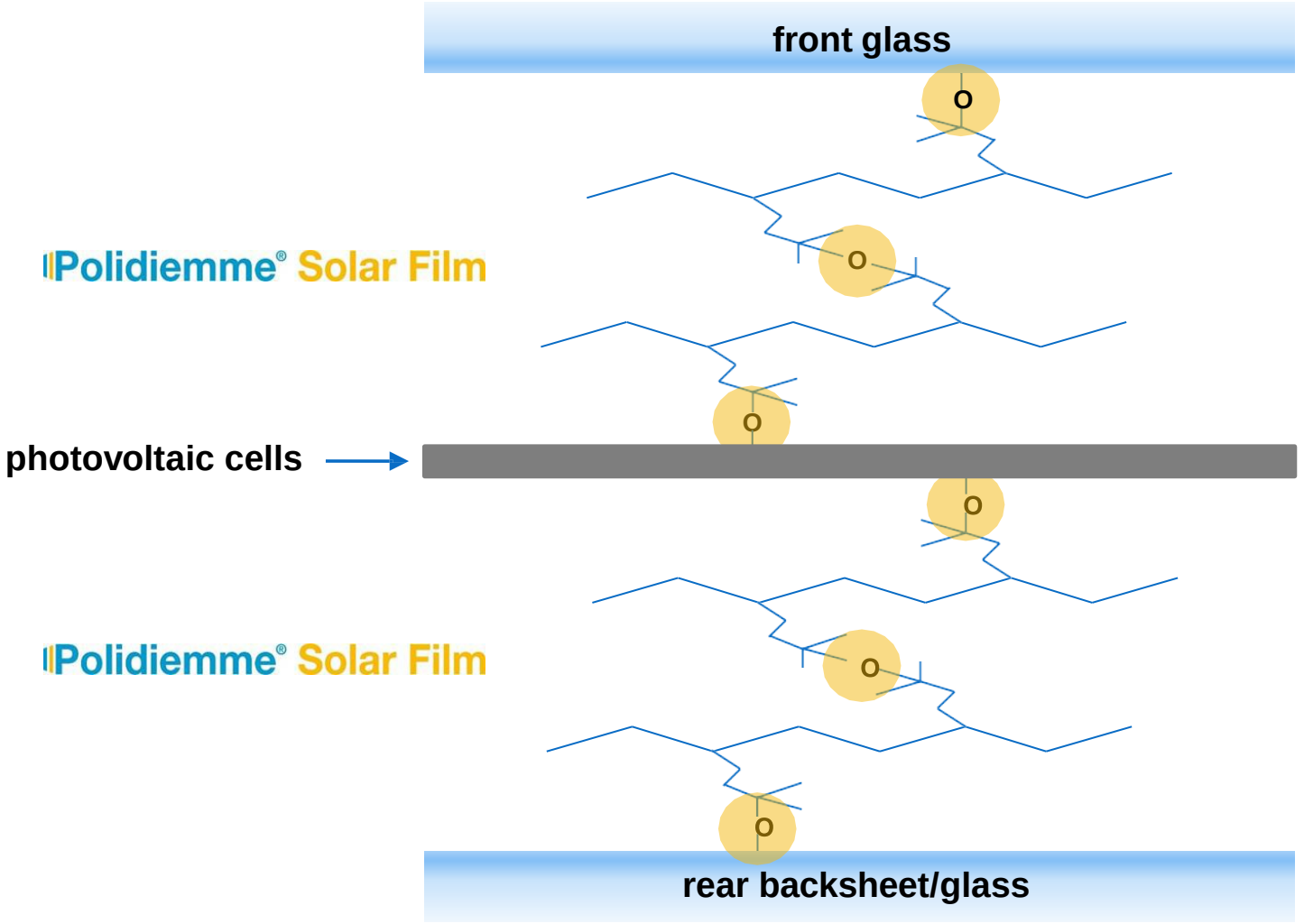
Masterbatch PV

Polidiemme® Solar Film

- processability as easy as a thermoplastic film
- facile customization through Masterbatch PV formulation
- low density (-8% vs EVA 28% VA)
- very low Water Vapor Transmission Rate (WVTR)
- very low water intake
- high volume resistivity

padanaplast®
EXCELLENCE IN COMPOUNDING

Encapsulant film lamination



- high adhesion to front/back-sheet and cells: strong chemical bonding with silane alkoxy groups
- very low creep: tridimensional bonding network in the bulk encapsulant layer
- low melting point and no chemical reactions to be activated: lamination at moderate temperature and reduced time
- minor risk of insufficient lamination (no residual materials)

Conclusions:

Polidiemme® Solar Film

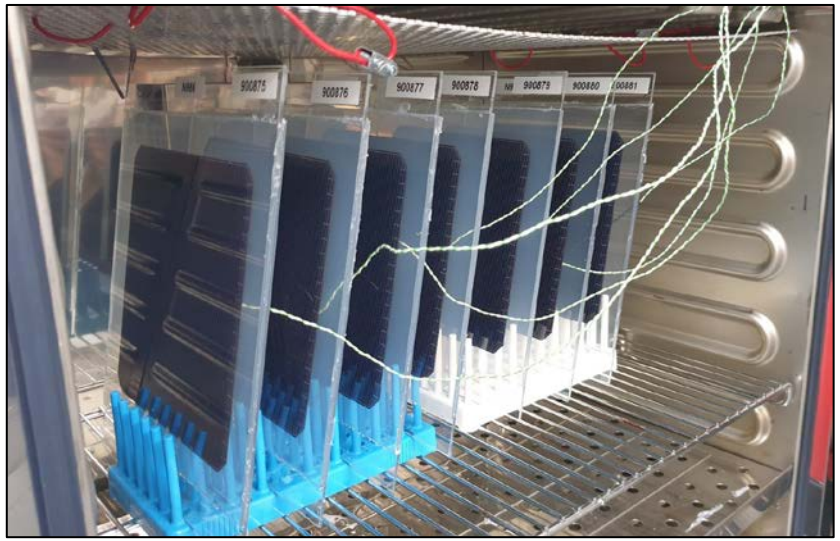
- Made with SPO (Silane Poly Olefin), a POE modified with silane-grafting technology
- designed for very competitive LCOE PV modules
- no peroxide reaction to be activated
- time and energy saving
- high and stable adhesion on silica substrates
- no acidity evolved along PV module lifetime
- very low content of impurities
- high stability to weathering and low water absorption and transmission
- effective barrier against PID-d
- suitable for temperature sensitive photovoltaic cells

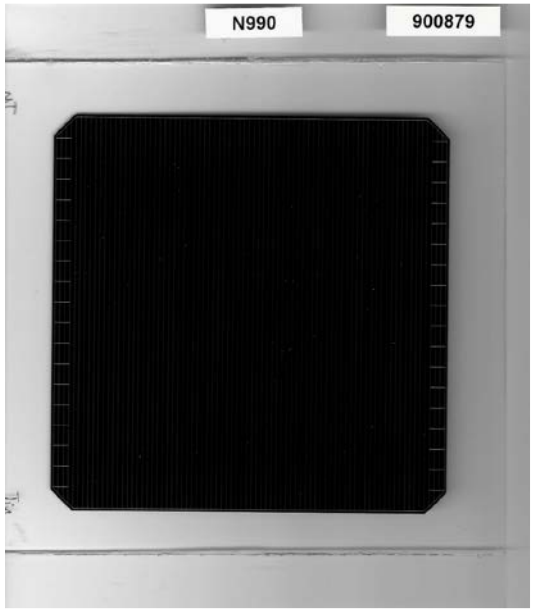
T2.3: New colored foil development

Padanaplast clear encapsulant optimization for SX colored layer

Polidiemme® Solar Film

Creep test (IEC 61730-2) : 105°C ± 5°C in a dry oven for 200h



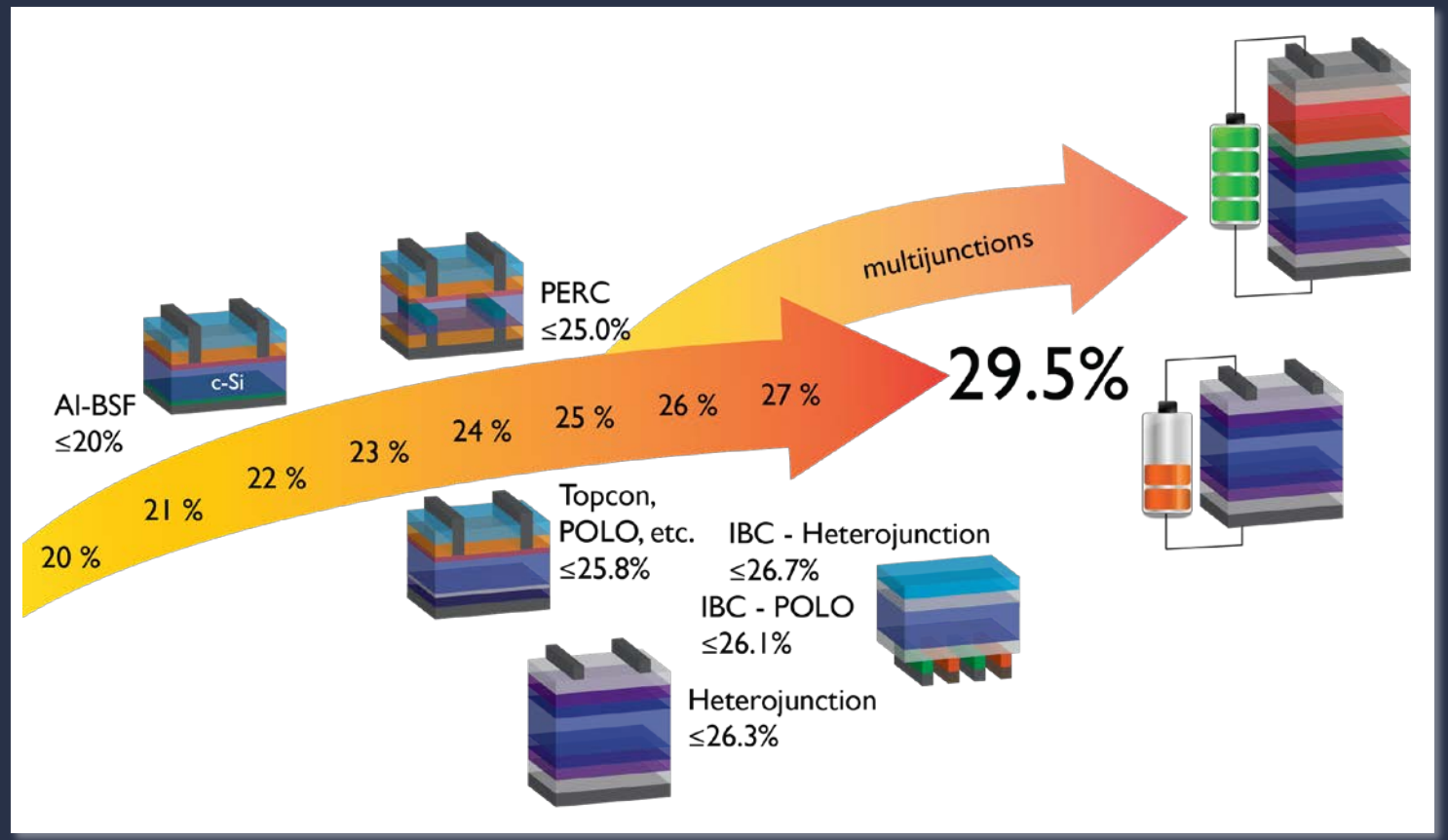


No creep after test

The Be-Smart project has received funding from The European Union's Horizon 2020 research and innovation programme under grant agreement No 818009.

Efficiency-driven technological upgrade

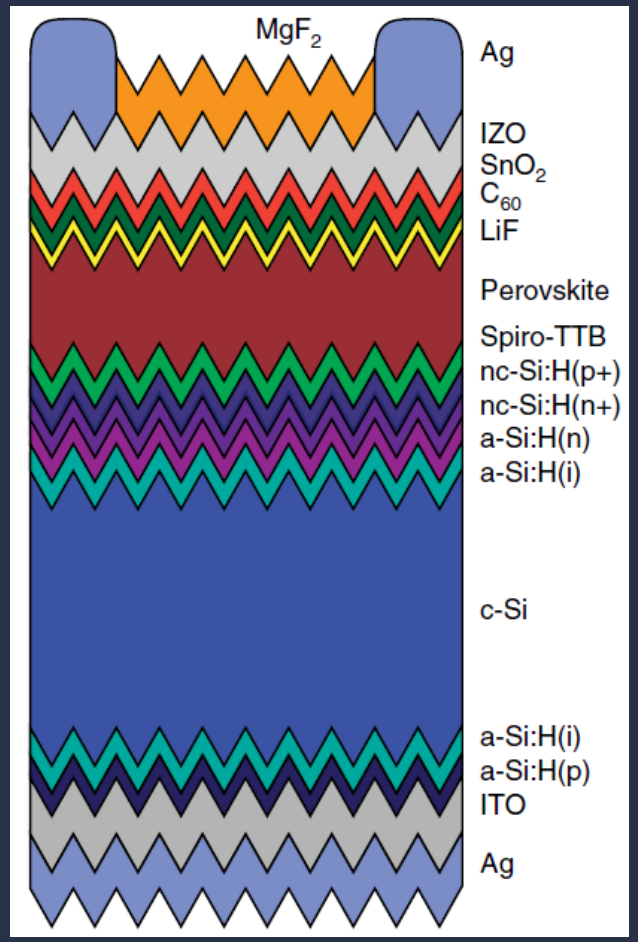
- Quick technological update to more efficient silicon technologies
- Theoretical limit of silicon solar cells at 29.5%, practically at 27%



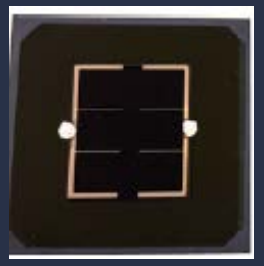
Among tandems, currently Tandems PK/Si are the best approach to extend the learning curve of Si PV (and currently the only potentially cost effective approach)

csem EPFL

Cells above 29% Perovskite/silicon tandem solar cell



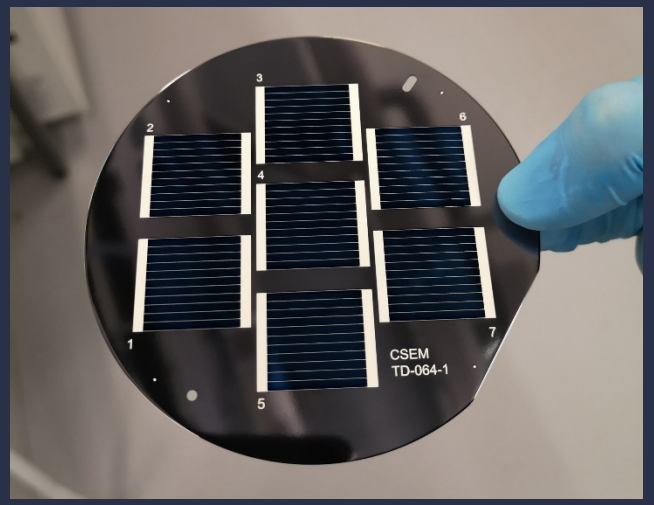
Sahli et al. Nature materials 2018



EPFL PV-lab:

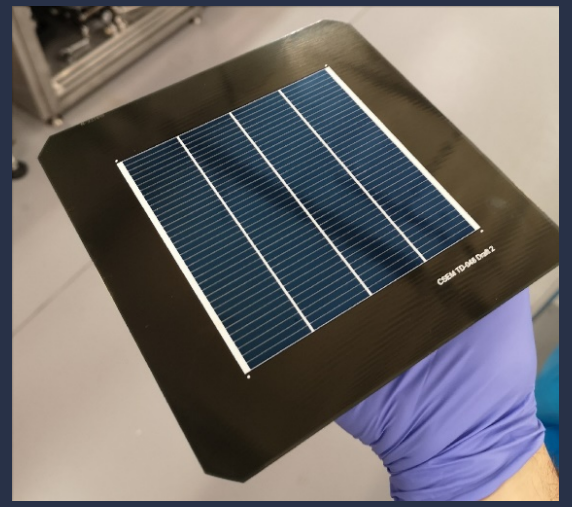
Certified > **29%***

More to come!



CSEM : **28.25%** on 4 cm2

Upscaling ongoing



csem

Xin Yu Chin, Quentin Jeangros, Christian Wolf, A. Walter, B. Kamino et al.

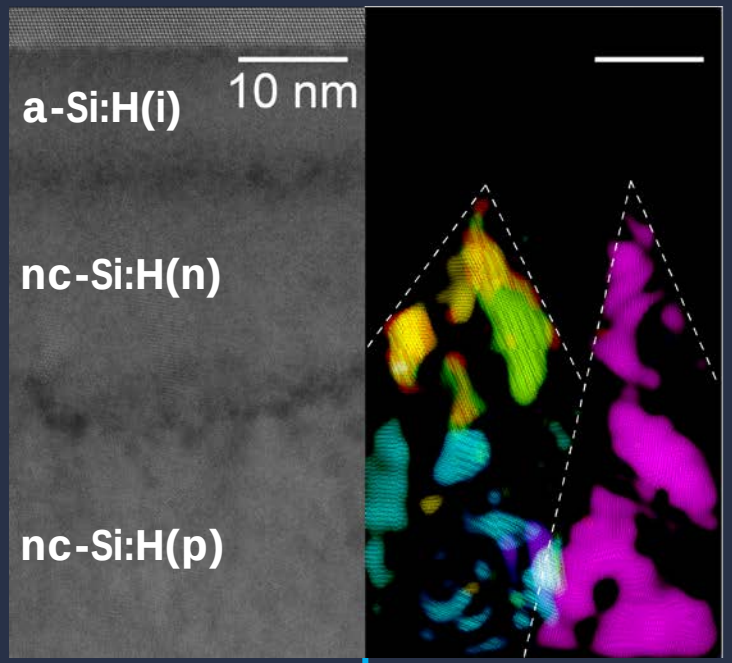
EPFL

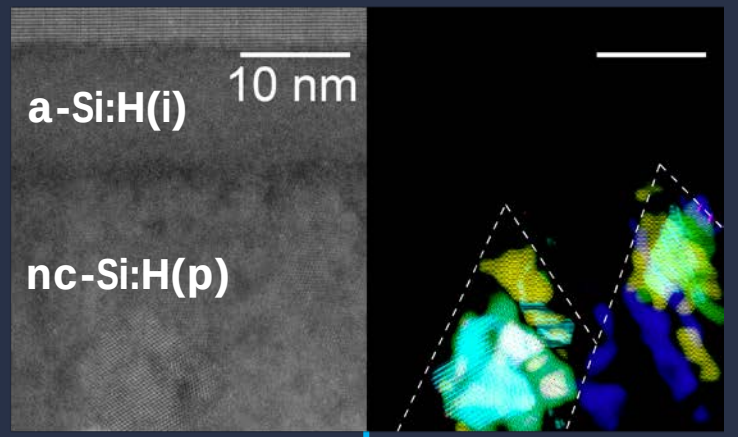
24.4-cm² 3-terminal perovskite/IBC tandems

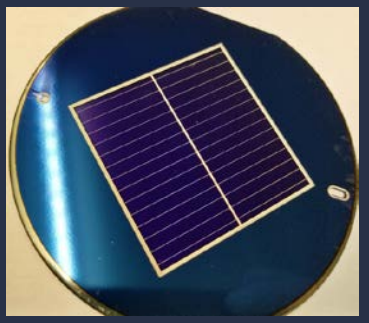
Interdigitated back contact bottom cell to remove current mismatch losses

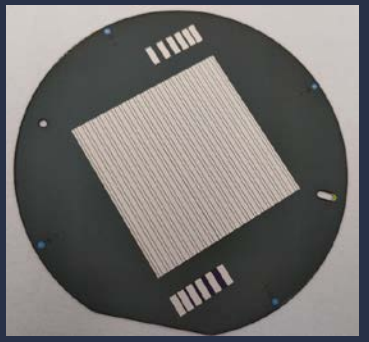
Photolithography-free process to pattern IBC rear side

Epitaxy between between nc-Si:H(n) & nc-Si:H(p) layers









10.1038/nenergy.2017.62

csem EPFL MEYER BURGER EPFL

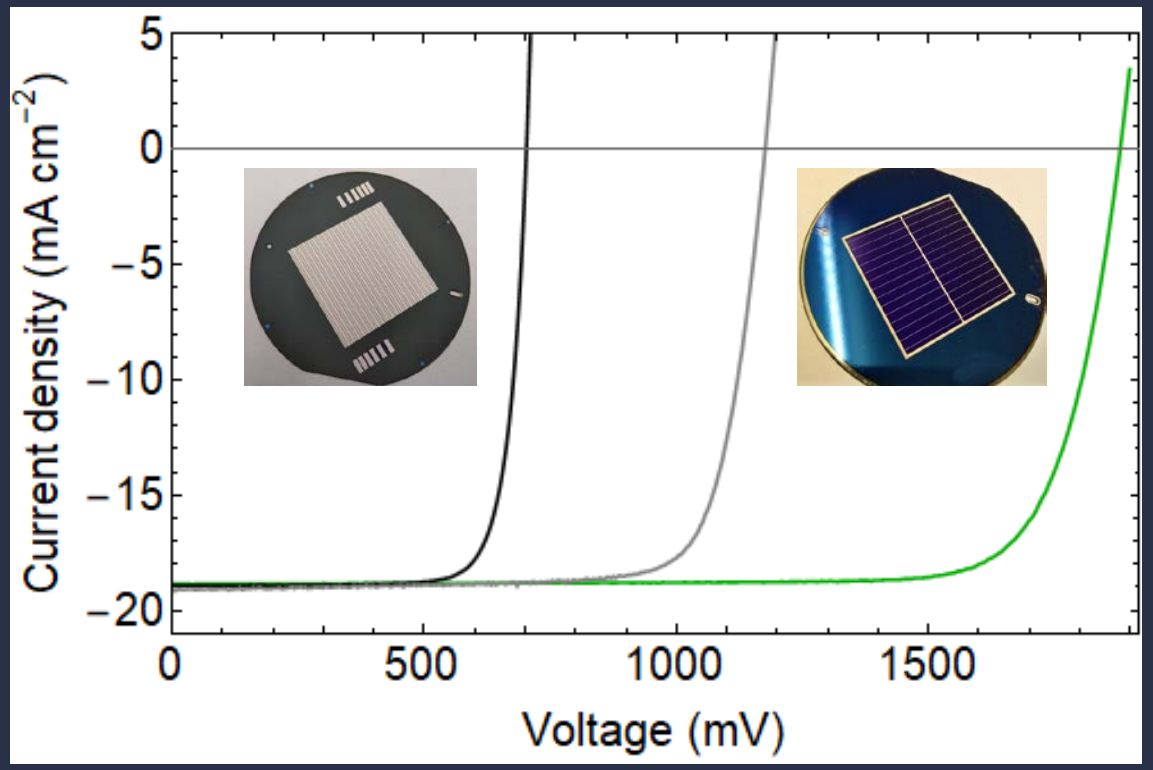
29%-efficient 3-terminal tandem on 24.4 cm²

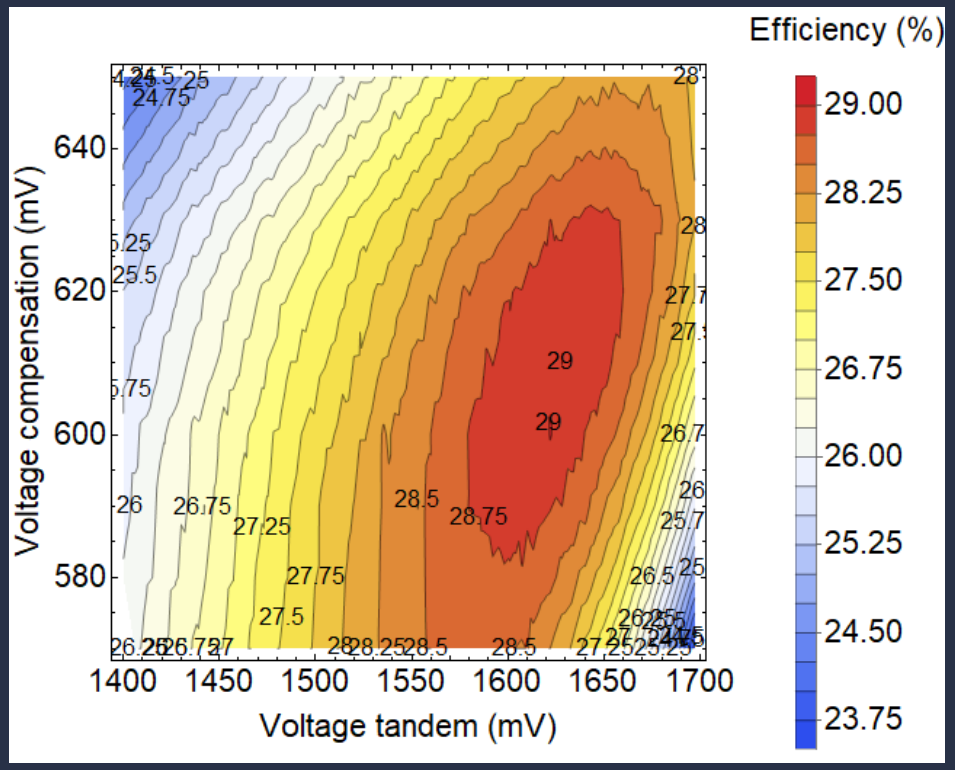
		V_{oc} mV	J_{sc} mA cm^{-2}	*FF* (%)	η (%)
IBC	R	702	18.93	80.3	10.7
PK	R	1176	19.11	79.0	17.8
2T PK/IBC	R	1881	18.87	81.3	28.9

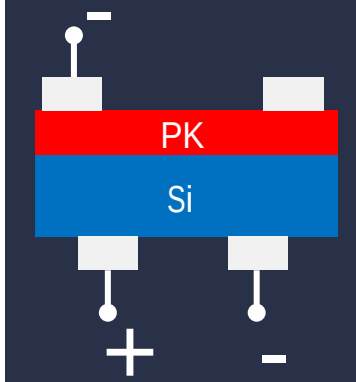
Measurement of individual sub-cells

Slight gain with 3rd terminal to reach 29%

- Top cell optimized for 2-terminal design







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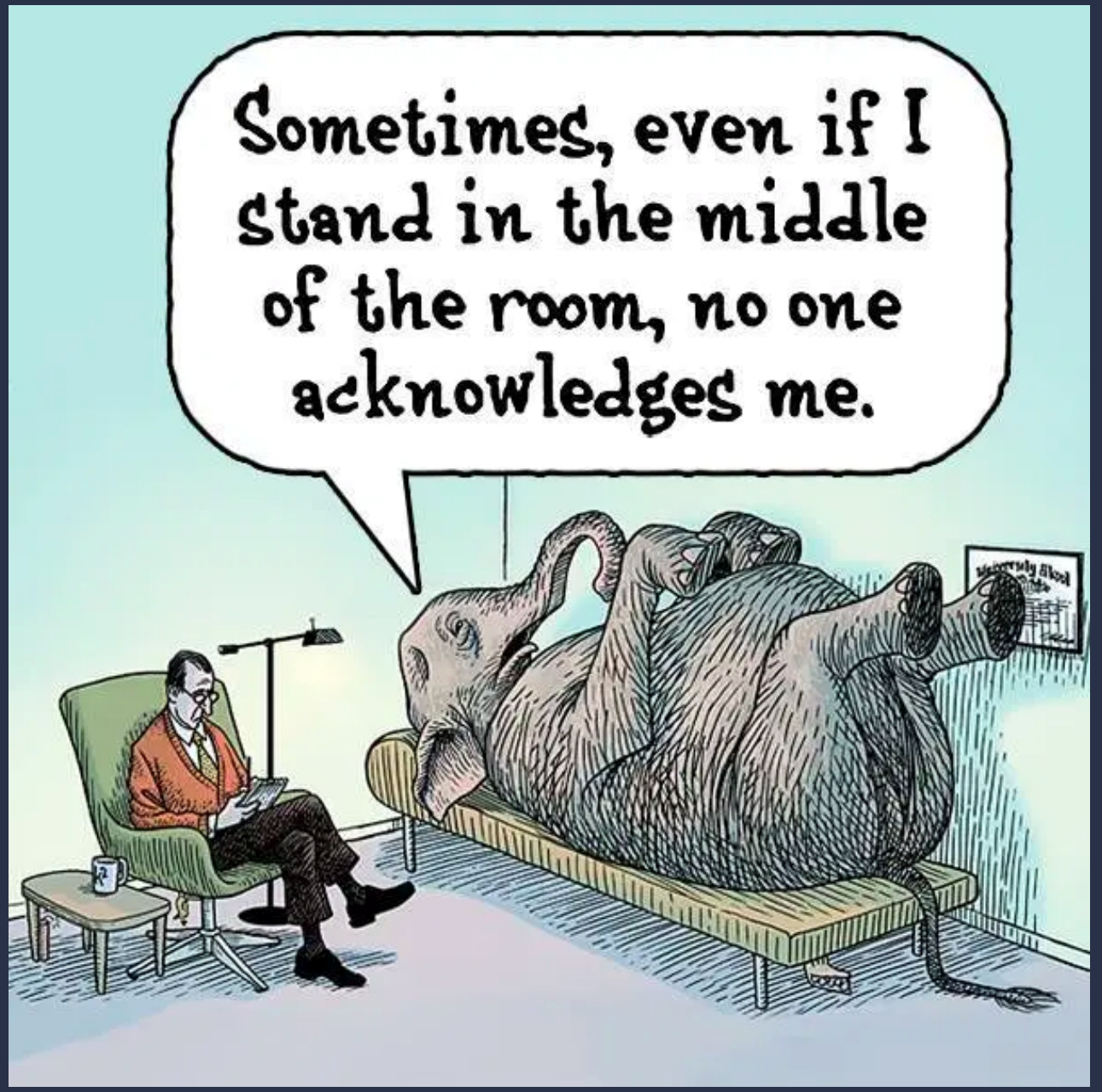
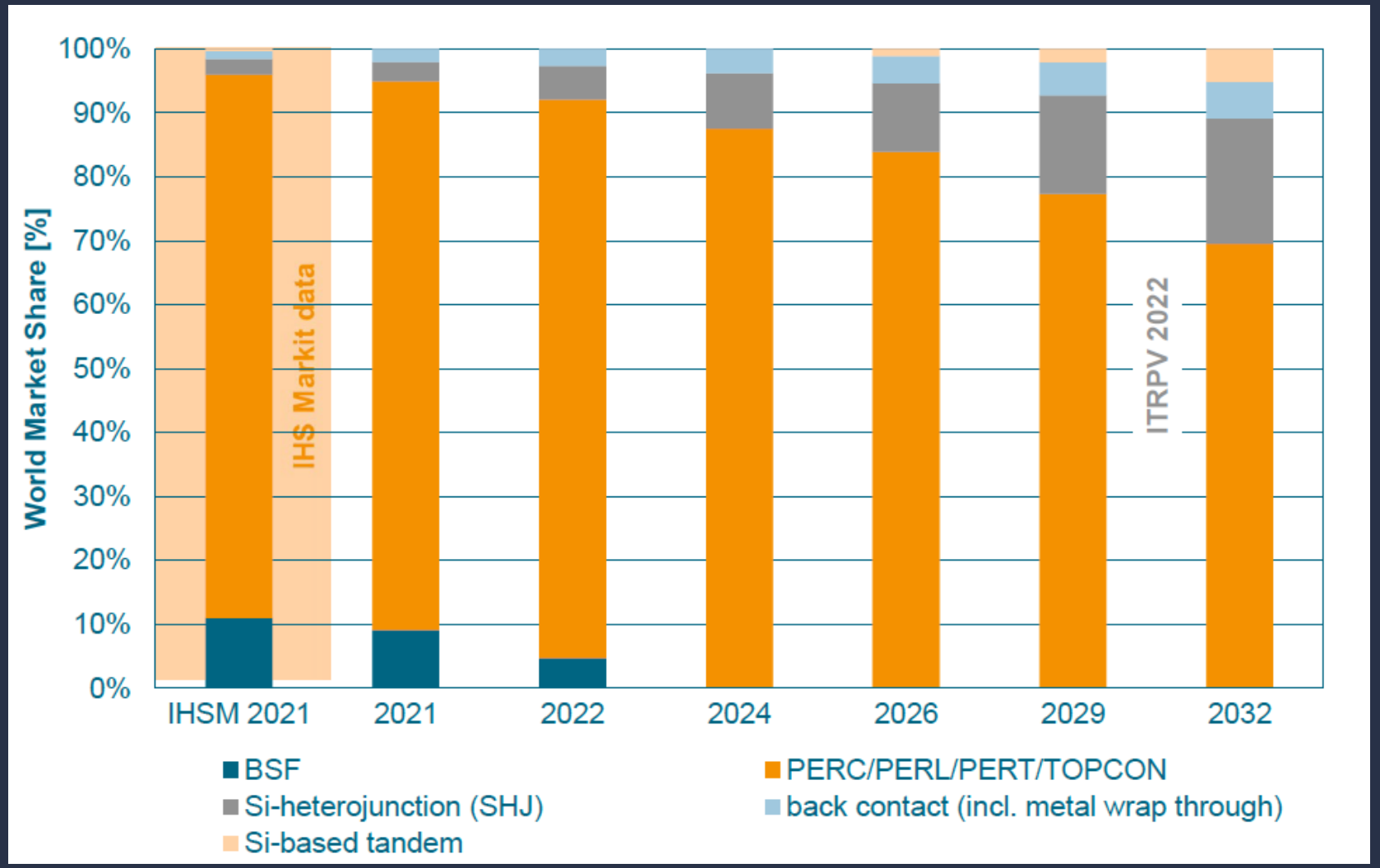
Stability



Cartoon by Dan Piraro

When could/should mass penetration of tandem device take place ?



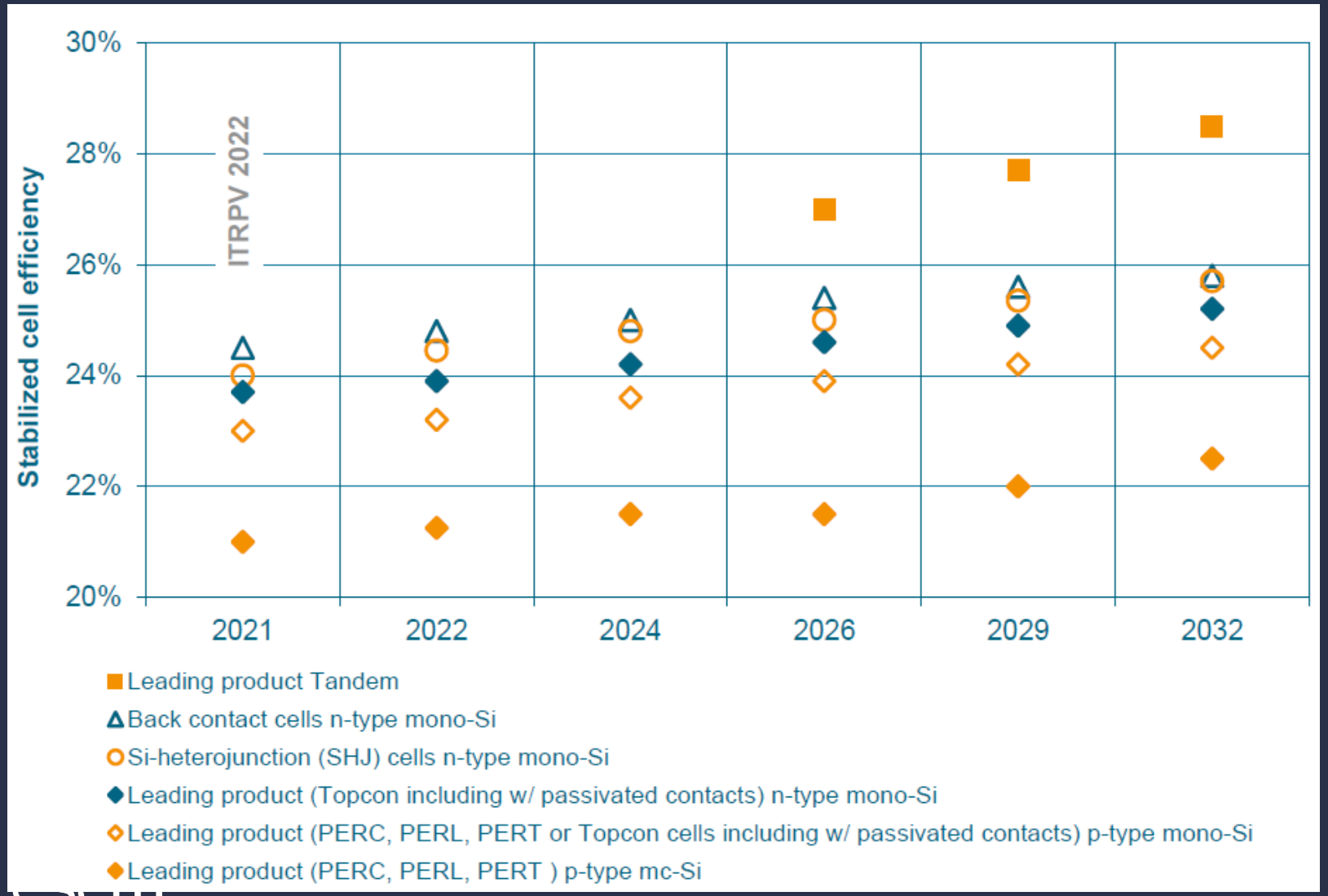
The current view of industry ITRPV survey

Up to 5% in 2032

(of 600 to 1000 GW annual ?)

Source ITRPV 2022, released March 2022

Average stabilized efficiency values for Si solar cells in mass production according to ITRPV 2022



Large solar values expected

At 28.5% by 2032

Source ITRPV 2022, released March 2022


There is so much you can
do with solar ....

Niche Swiss products:

Thin film solar dials and OS by CSEM
in the new Tissot T-Touch solar connect (By Swatch group)
Full autonomy and solar esthetics

The case for Switzerland by 2050

- 34 TWh by PV (or more) in Swiss Federal office scenario (50 GW → 50 TWh in Nordman's)

- «easily» doable on existing surface. 50 TWh on roofs, 17 kWh on facades potential
- Upside potentional with unconventional surfaces

idea

DHP (CH)

Horizon

- Deployable PV systems
- Over streets, parking, water,....
- Charging EV station

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Agrivoltaics on the move

Voltiris

Insolight: Special greenhouse modules

insolight

ROMANDE ENERGIE

csem

hiperion MAX SOLAR POWER

EPFL

CSEM Light weight ultra-reliable modules: all around the world

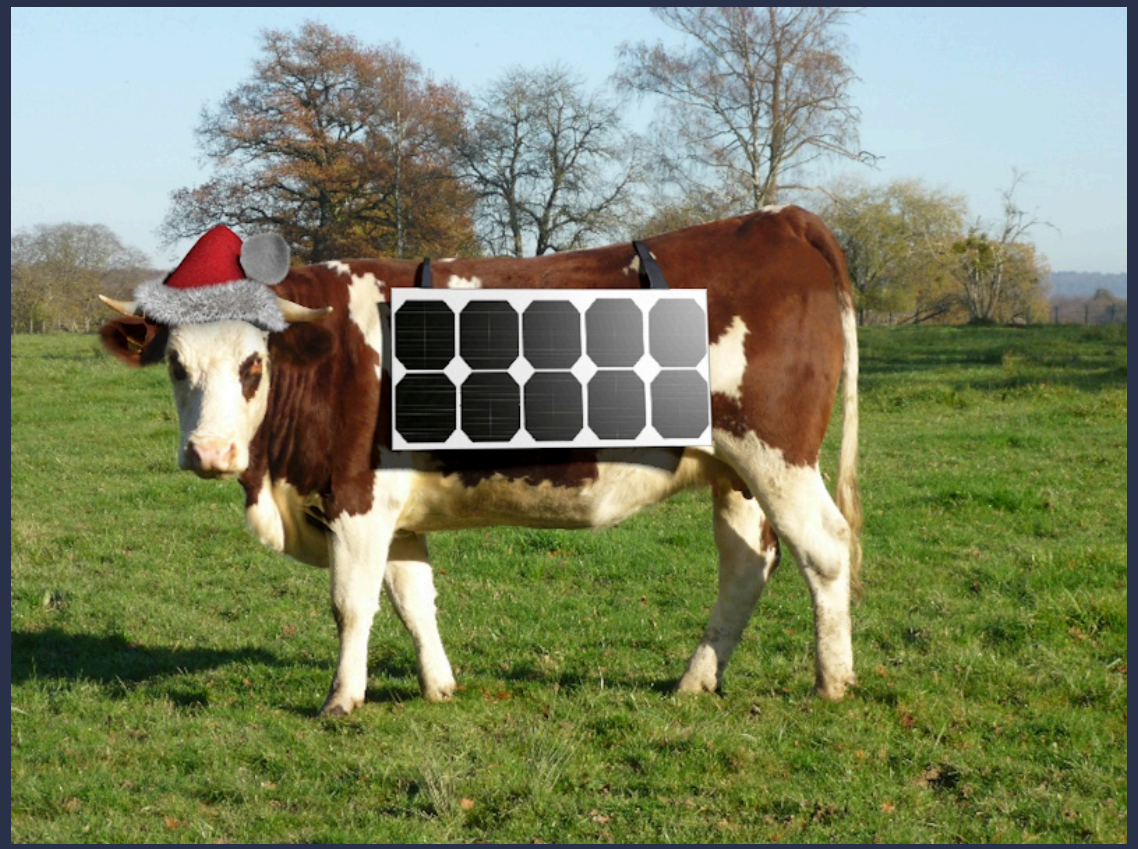
Whatever scenarios, we need to cover a large part of the bulidings with PV in mayn countries

Massive solarisation of building

And not one out of 5 roof or 20% of a single roofs (at least in Switzerland)

Switzerland (and Austria ?), sensitive to acceptance in Rural and Urban Environment

Sensitive to aesthetics… increase acceptance and potential

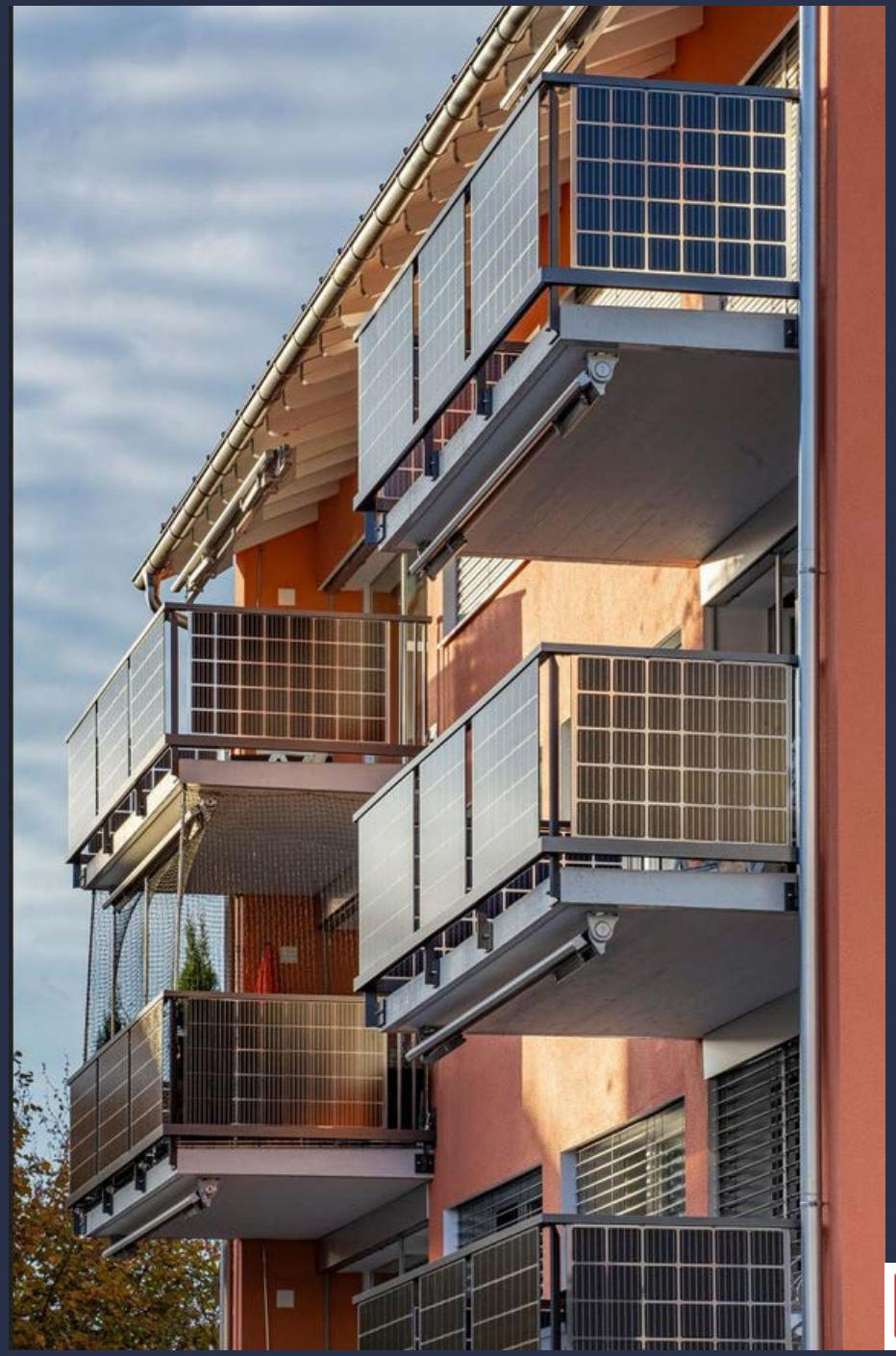


Some examples of Switzerland, a pioneer in transformative PV technologies

- **Neuchâtel, maison des associations, Swiss Solar Award 2015 «renovation category»**
- **Over 12’000 “megaslates” systems installed**

Prix solaire

Suisse 2015



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3S Solar Plus

EPFL

Elegance and architecture

Transforming building and cities

- CSEM as pioneer of transformative technologies for PV panes

Based on low cost c-Si modules, ...

White PV panels, together with Solaxess


RESTRICTED
AREA
DO NOT


SOLAXESS
white solar technology

SOLAXESS
white solar technology


SOLAXESS
WHITE & COLOR SOLAR TECHNOLOGY

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Elegance and architecture

Transforming building and cities, renovating houses

Prix solaire

Suisse 2018

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Ecuvillens

- 27 kWp
- 28’000 kWh during 1st year of operation
- One of the Terra-cotta tones


Prix solaire
Suisse 2019
With support of
ne.ch
RÉPUBLIQUE ET CANTON DE NEUCHÂTEL

SOLAXESS
white solar technology

3S Solar Plus

csem

SOLAXESS
white solar technology

3S Solar Plus

csem

EPFL


FREE SUNS
SOLAR ENERGY


FREE SUNS
SOLAR ENERGY


FREE SUNS
SOLAR ENERGY

Private house Neuchâtel

Courtesy L.E. Perret-Aebi

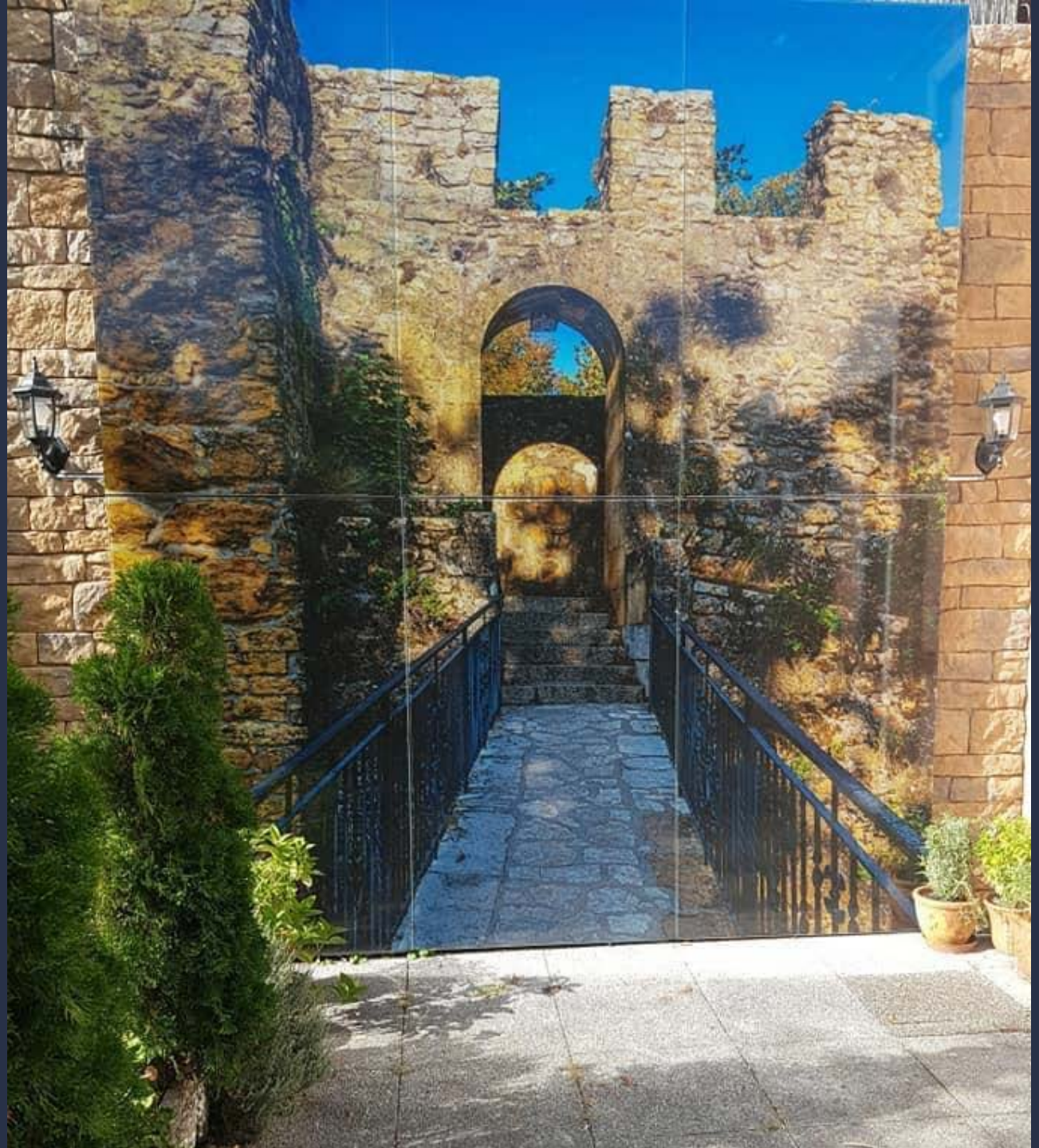
Make people love Photovoltaics !

And install for fun…

Everywhere !

csem

Private garden Neuchâtel



compáz

Courtesy L.E. Perret-Aebi

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EPFL

- **Conclusions**

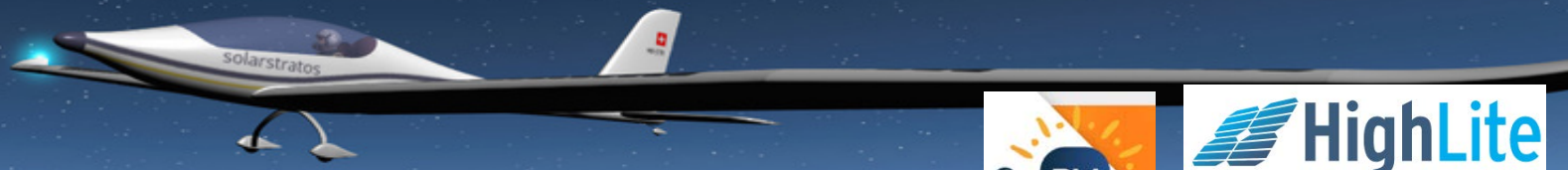
- Huge improvements in PV: greener, cheaper, verstatilty for construction.
- Don’t be afraid to have too much PV, there is never enough…
- Foresee long term «curtailement» possibility to avoid grid overload. Brings much more smartness in system (flexilibity)
- New products with higher efficiency will come with their enhanced newer issues. We need people to work on understanding reliability issues more than ever, and to create trust in new products
- Local manufacturing in Europe, important… try and develop a local economy with special products, work with local manufacturers…

Transforming the world, building and cities

“We need many more E. Becquerel’s Children”
Unknown source

Thanks for your attention

Solarstratos



For a large overview over c-Si:

Check the extensive review

Review Article | Published: 07 March 2022

Status and perspectives of crystalline silicon photovoltaics in research and industry

Christophe Ballif, Franz-Josef Haug, Mathieu Boccard, Pierre J. Verlinden & Giso Hahn

Nature Reviews Materials (2022) | Cite this article

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Swiss National Science Foundation

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Contact **christophe.ballif@epfl.ch**

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