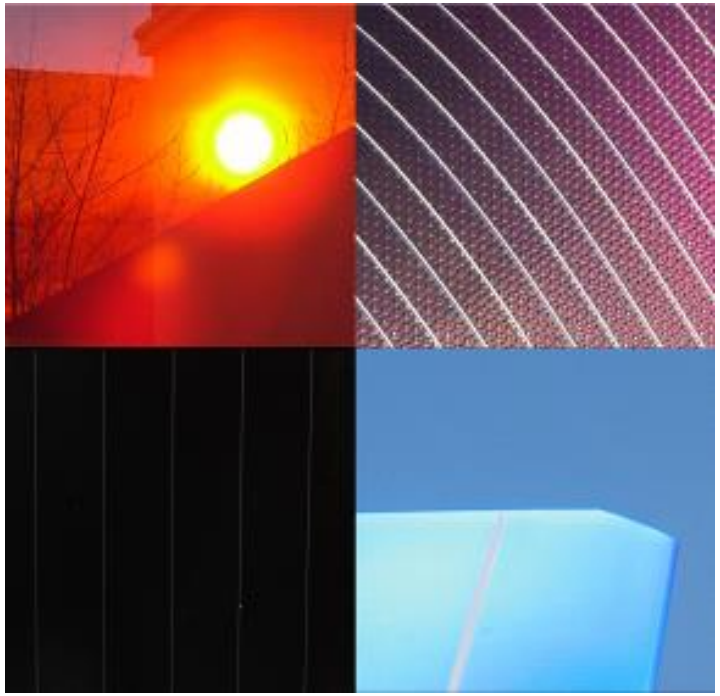
Fundamentals and processes for photovoltaic devices

PV-lab
IMT NEUCHATEL

Chapter II. Technology, market and scenarios

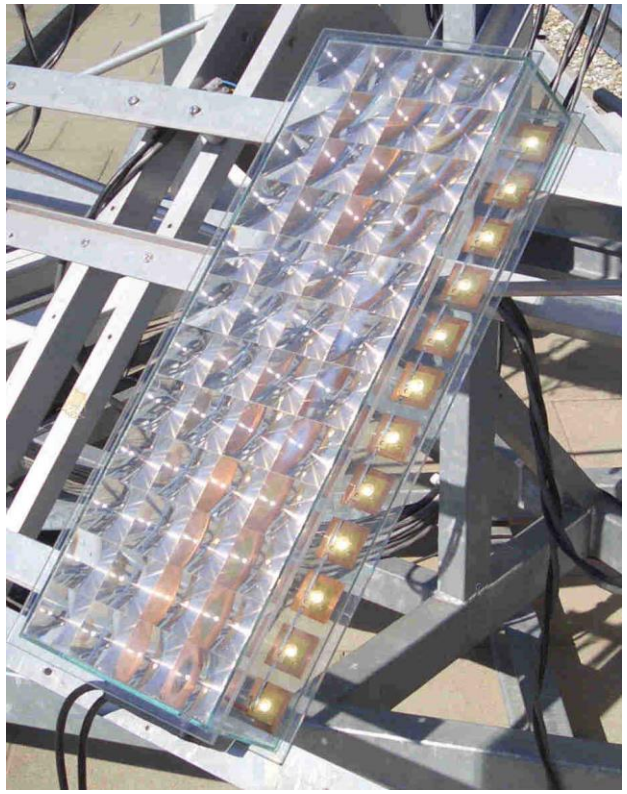
Basic principles, potential & market



Lecture Outline

1. A first technology insight
2. PV Market
3. Cost of solar electricity
4. Electricity Market, integration and scenarios

1. A first technology insight into PV modules



Crystalline Si

Multi-Mono

Commercial modules 20-24%

Potential 22-25%

Thin film

CIGS a-Si / µc-Si CdTe

6 (a-Si) -19.3 % (CdTe)

13-21%

III-V and Concentration

III-V based

25-35%

35-50%

Annual PV module production/all technologies

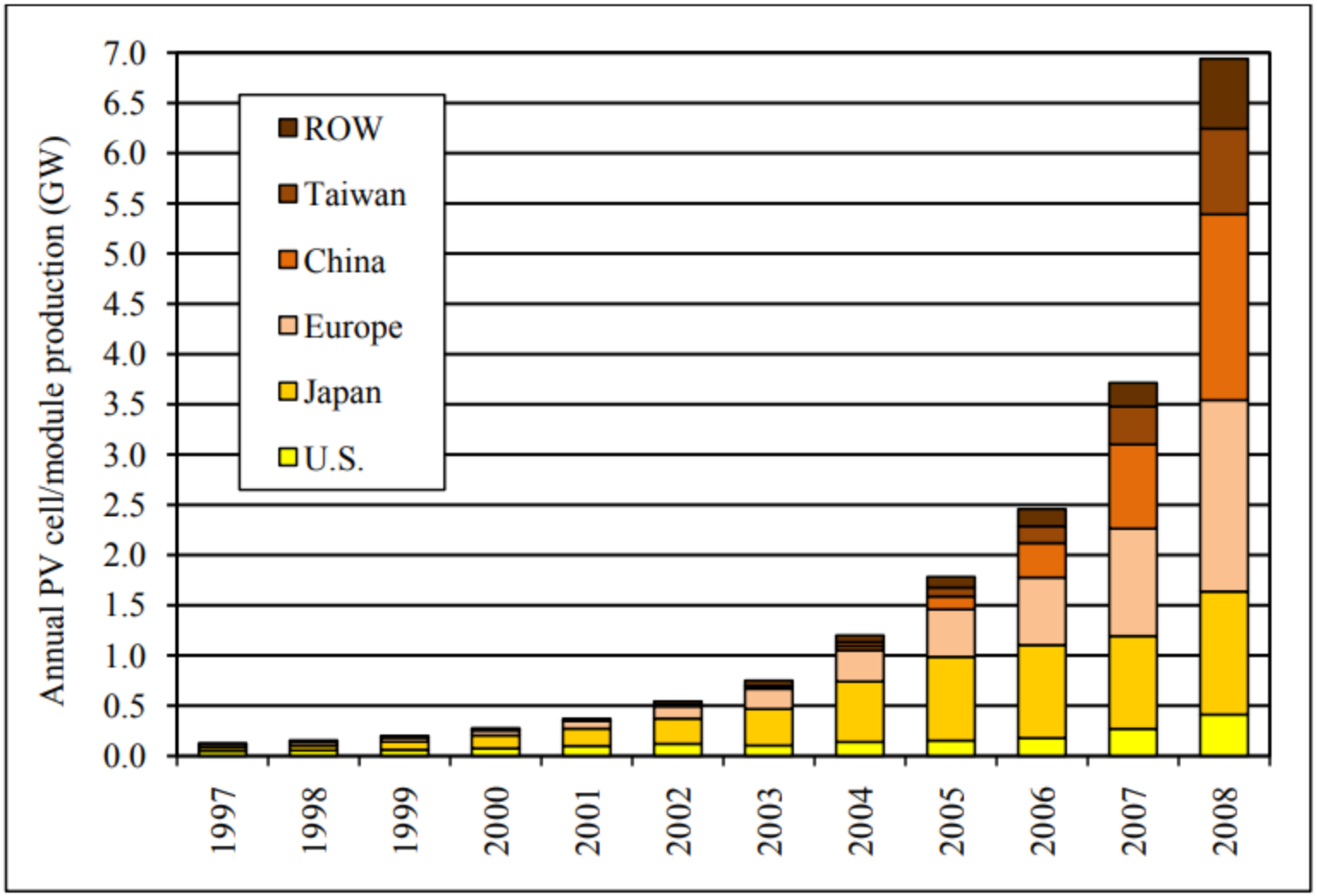


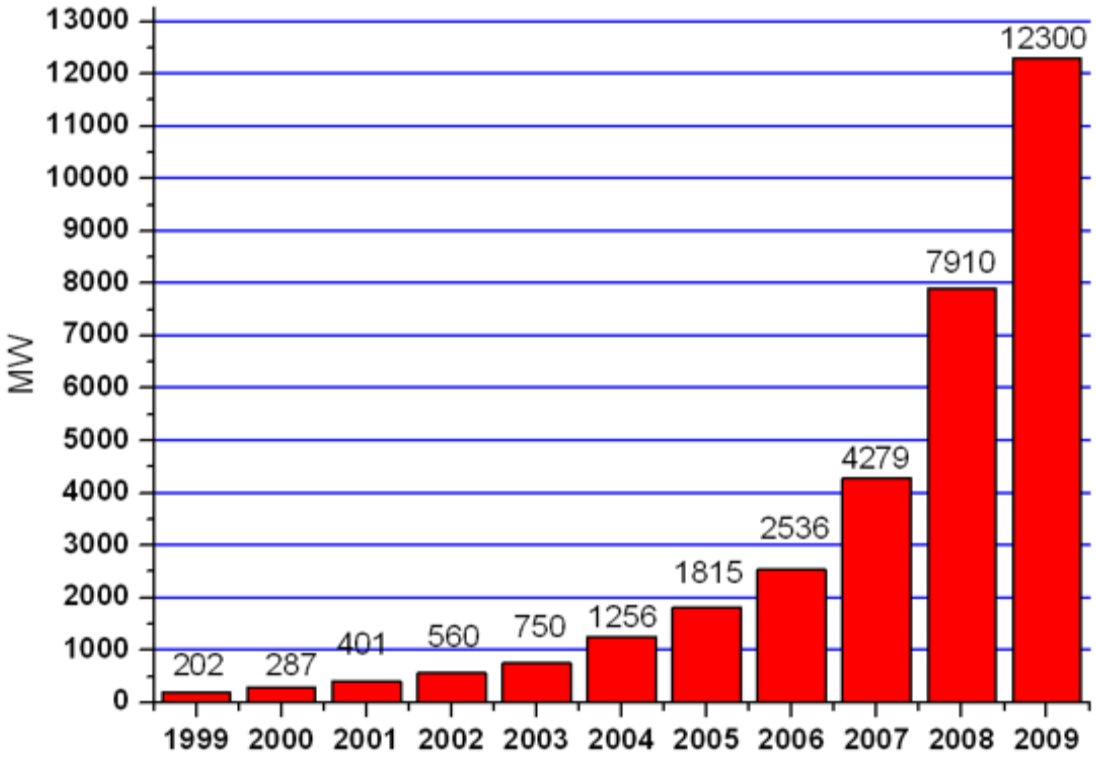
Figure 2.1. Global annual PV cell/module production by region
(Maycock 2002, Bradford et al. 2006, Bradford et al. 2008a, Bradford et al. 2009)

Until 2007, Europe and Japan leading in manfacturing

Europe: EEG (2000) in Germany stimulated the market

[2008 Solar Technologies Market Report]

8. PV markets



Cell and thin film module manufacture

Source
Solar Buzz/Photon Magazine

Note: there can be a delay Between production of cells and installation of modules !

Strong market growth >40% **thanks to policy** programs: **Germany**, Spain (07-08)
Japon, Italy, France, US,…

12 GWp new modules in 2009 !

(18 to 20 in 2010 !)

Vintage slide of 2011 lecture…. Incredible 20 GW in 2010 !!

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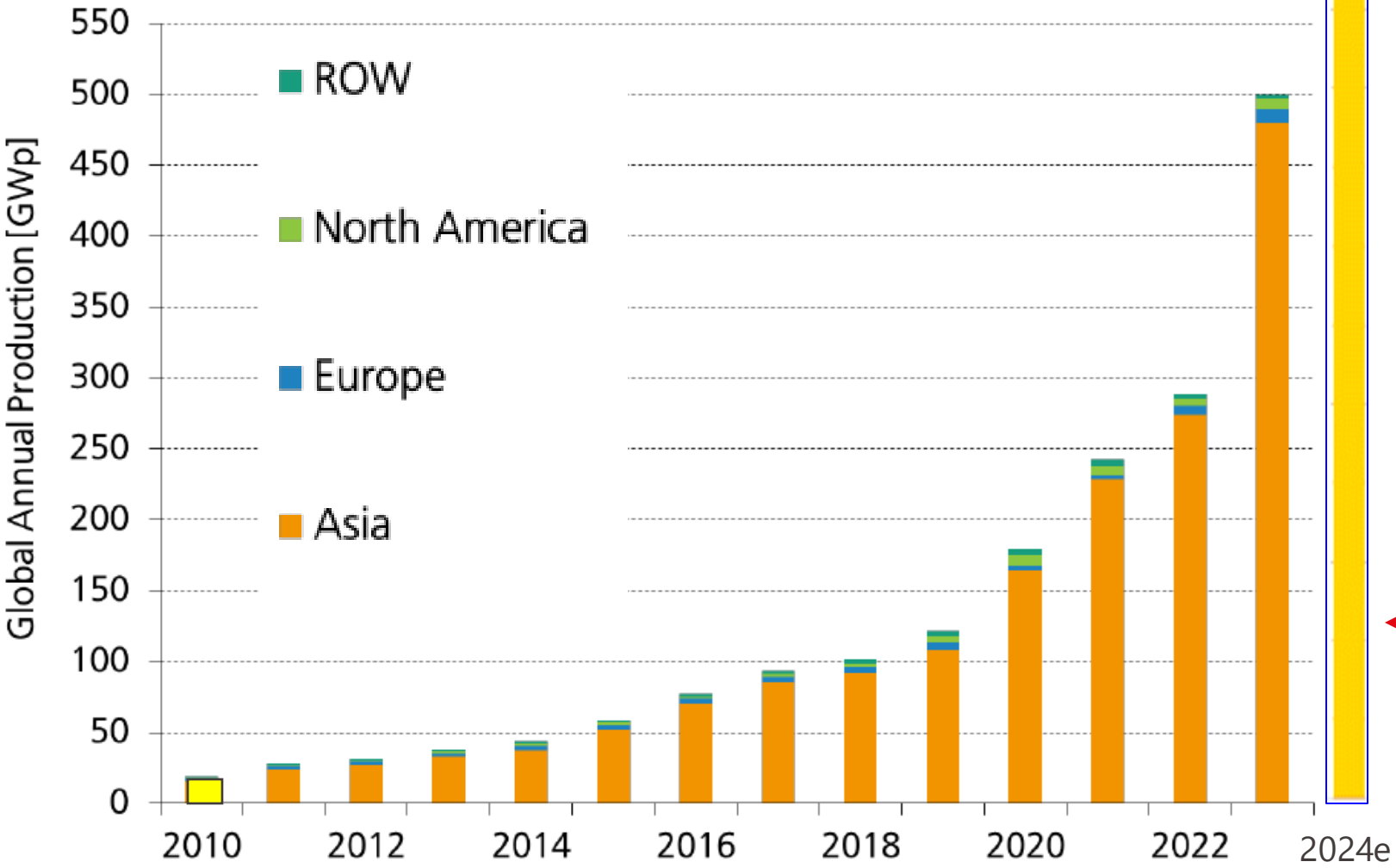
Annual module production



A strong volume growth thanks to policy:
Germany (2000, EEG), Spain, Japan, Italy, France, USA… then China,….

Module production:
250 MW in 2000

~ 500 GW in 2023
(> 80% produced in China

X 2'000

Est: **600-650 GW** in 2024

1 GW= peak power of
A large power plant

Source: PV-Report, Fraunhofer ISE (2024), PV-tech estimagtes 2024 Estimates CBA

Note: there is a delay between production and installation
Typically 6 months

Market share thin film vs crystalline Silicon

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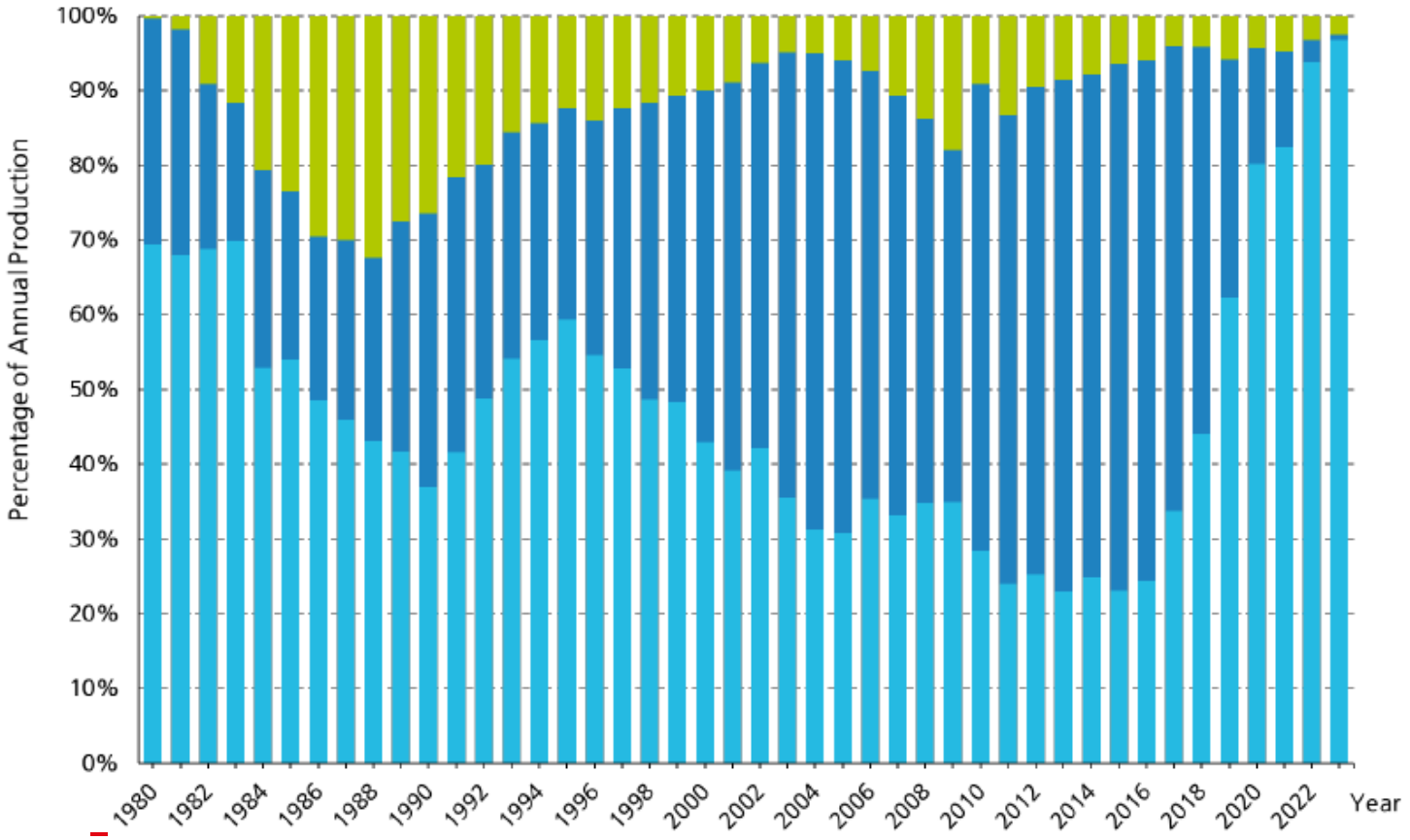
Production 2023
500 GW

Thin film	13 GW
Multi-Si	4 GW
Mono-Si	485 GW

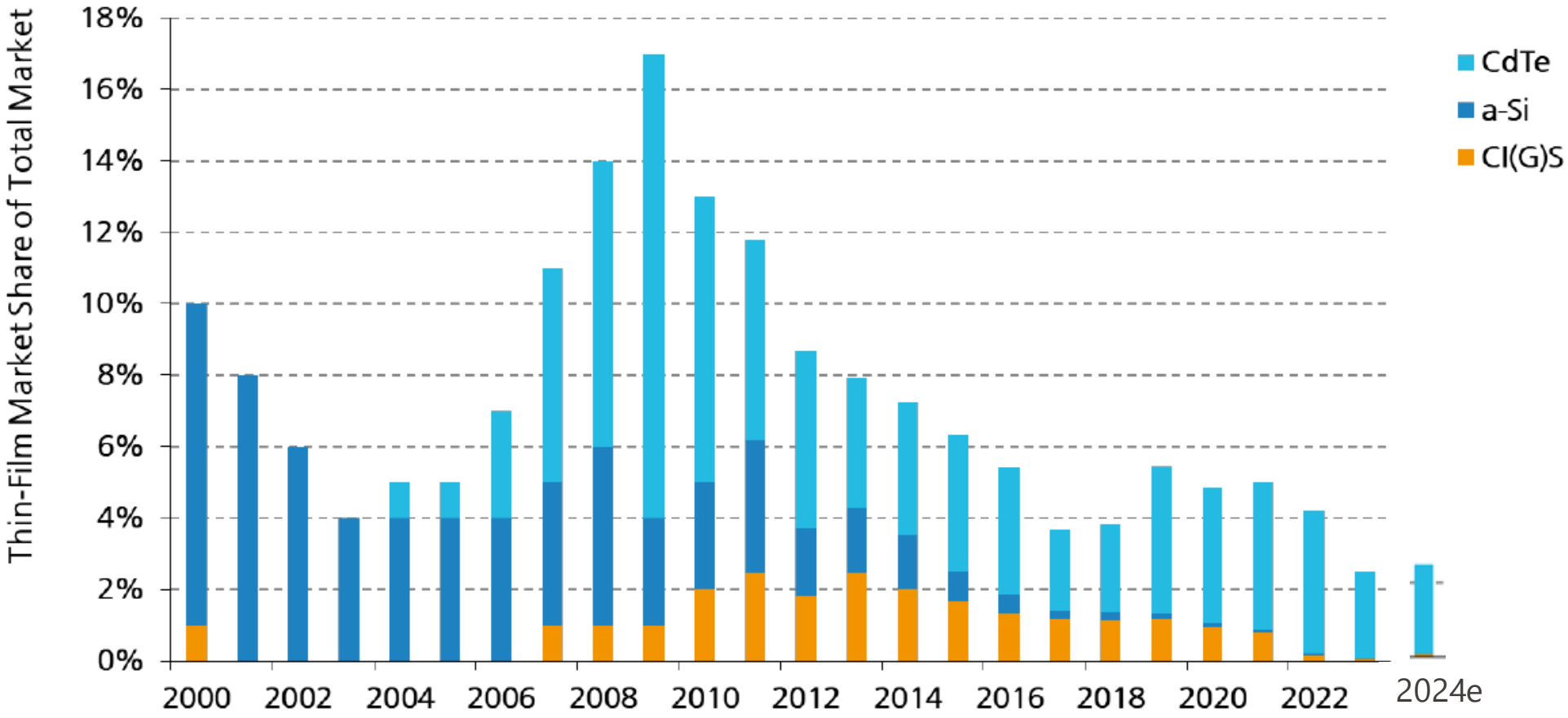
- Most new panels are mono crystalline silicon
- 2.5 percent thin films
- Many older modules are multycristalline



Data: from 2000 to 2009: Navigant; from 2010 to 2021 IHS Markit; from 2022 estimates based on IEA and other sources **PV Production by Technology** PercentageofGlobalAnnualProduction, Data: from2000 to 2009:Navigant; from2010 to 2021 IHS Markit;from2022 estimatesbased on IEA and othersources. Graph:PSEProjectsGmbH2024 . Dateofdata: 04/2024

Thin film market

Difficult to challenge crystalline silicon !



Production 2021 (GW)

CdTe	8.5
a-Si	0.15
CI(G)S	1.5

Source: PV-Report, Fraunhofer ISE (2024), PV-tech estimagtes 2024 Estimates CBA

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Thin film: directly from glass to module, and in theory low possible manufacturing costs

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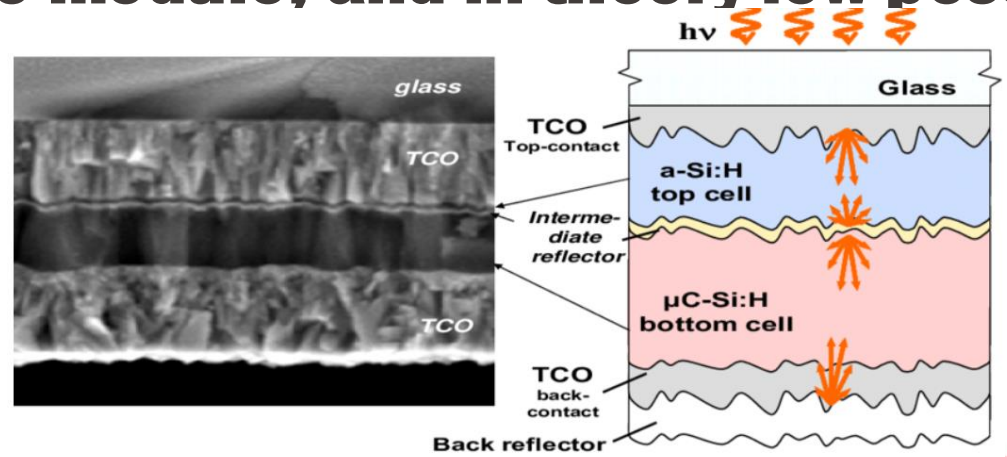
Example: Thin film silicon « micromorph » process (invented in Neuchâtel) tandem solar cells: Amorphous silicion/nanocrystalline silicon (or microcrystalline Si…)

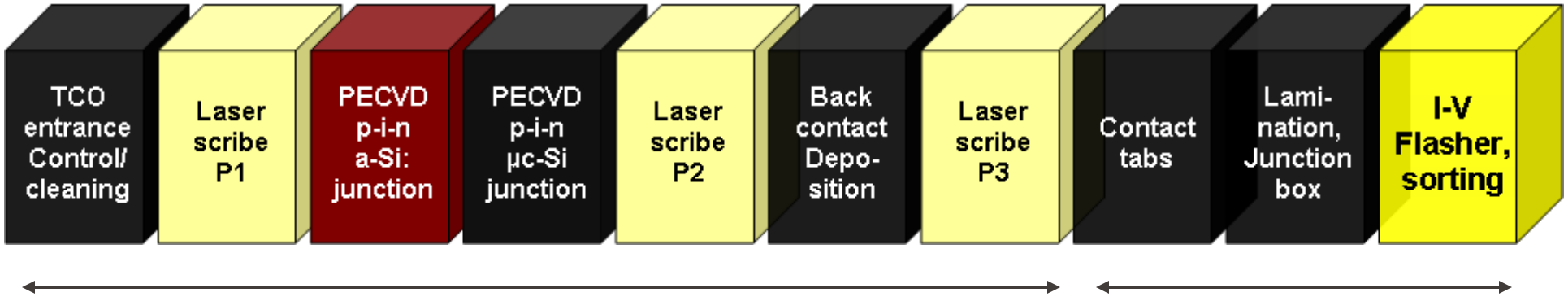


Amorphous silicon (a-Si) brown modules

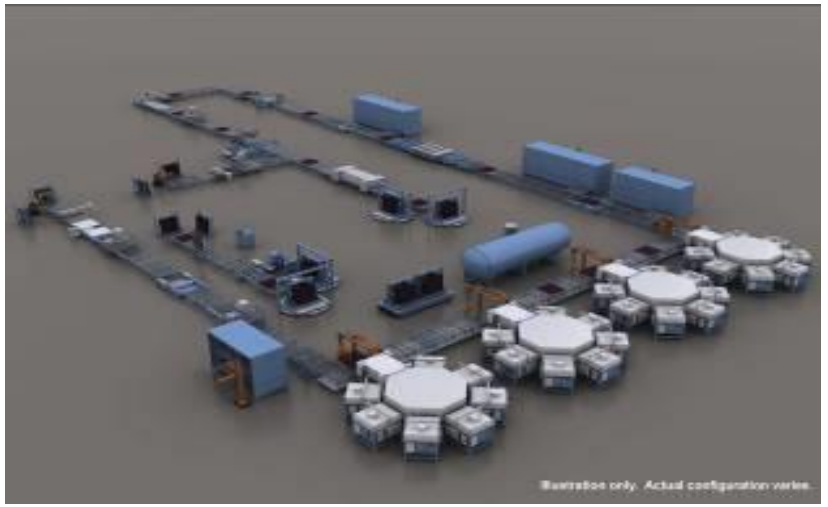
Tandem a-Si/nc-Si modules black modules

Thin film: directly from glass to module, and in theory low possible manufacturing costs

Example: Thin film silicon tandem « micromorph » process



Oerlikon line view



AMAT Sunfab sketch

Fewer process steps than full c-Si chain

Based on plasma deposition processes and tools of the flat panel display industry

- **Swiss group Oerlikon → 12% 1.4 m² modules in 2012. Good but not sufficient!**
- **Still used in many watches and energy scavenging applications with amorphous silicon !**

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(Only) Leader in thin film production: First Solar (US) with CdTe absorber

Leader in Thin film (and only mass producer) : **First Solar** sold 16-17 GW of CdTe modules in 2024 ! Focus on GEN7 modules up to 550 W modules, 19-19.7 % efficient, 25 years of development and smart-line copy. Likely direct production costs in the range of 0.16-0.20 cts/W manufacturing costs. Targets 25 GW by 2026. **Sales pipeline of 75 GW …. Unique positionning in USA to benefit from the USA inflation reduction act IRA !**

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Challenges for new thin film companies to follow First Solar (e.g. perovskites)

- Requires time (3-10 years) and money (> 100 M$) if technology needs to be developed
- Requires capacity for economy of scale (>> 100 MW)
  → large investment (>> 100 M$) with a risk

Next First Solar :

Perovskite based ?
Revolutionary concepts ?

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Ultra-high efficiency and concentrators

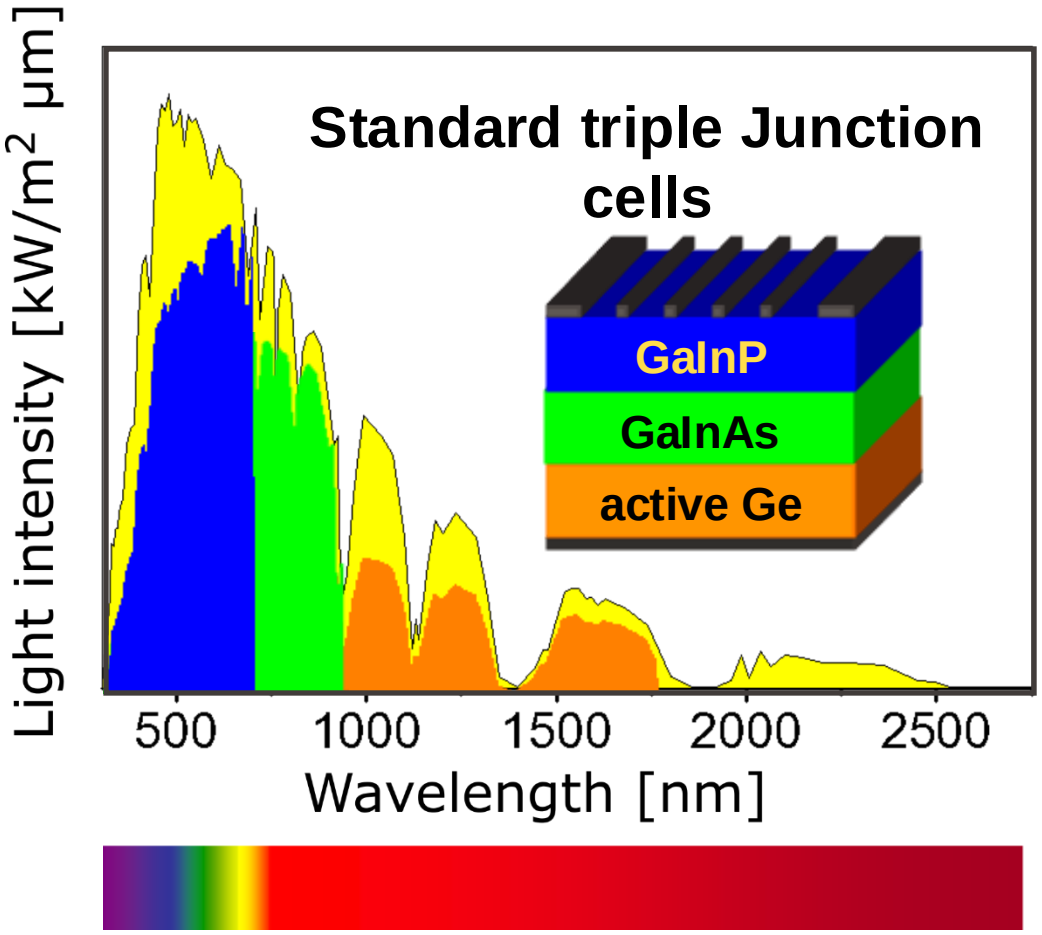
Multi-junction cells with III-V semiconductor compounds obtained by epitaxial growth (perfectly ordered atoms)

1 Sun single junction

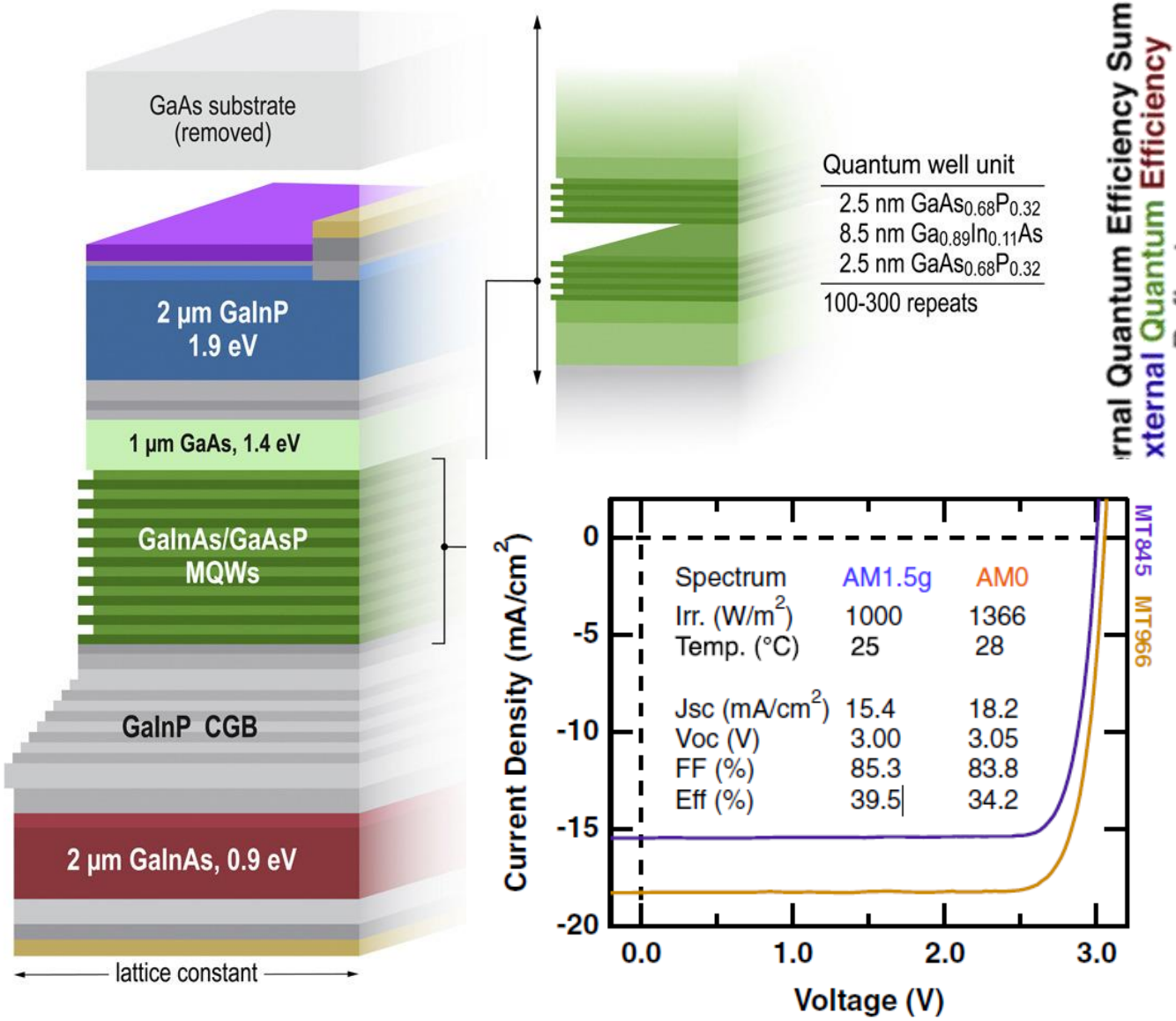
- *29.1% GaAs (2018 Alta device)*
- *39.5% (NREL, 3 junctions, 0.42 cm²)*

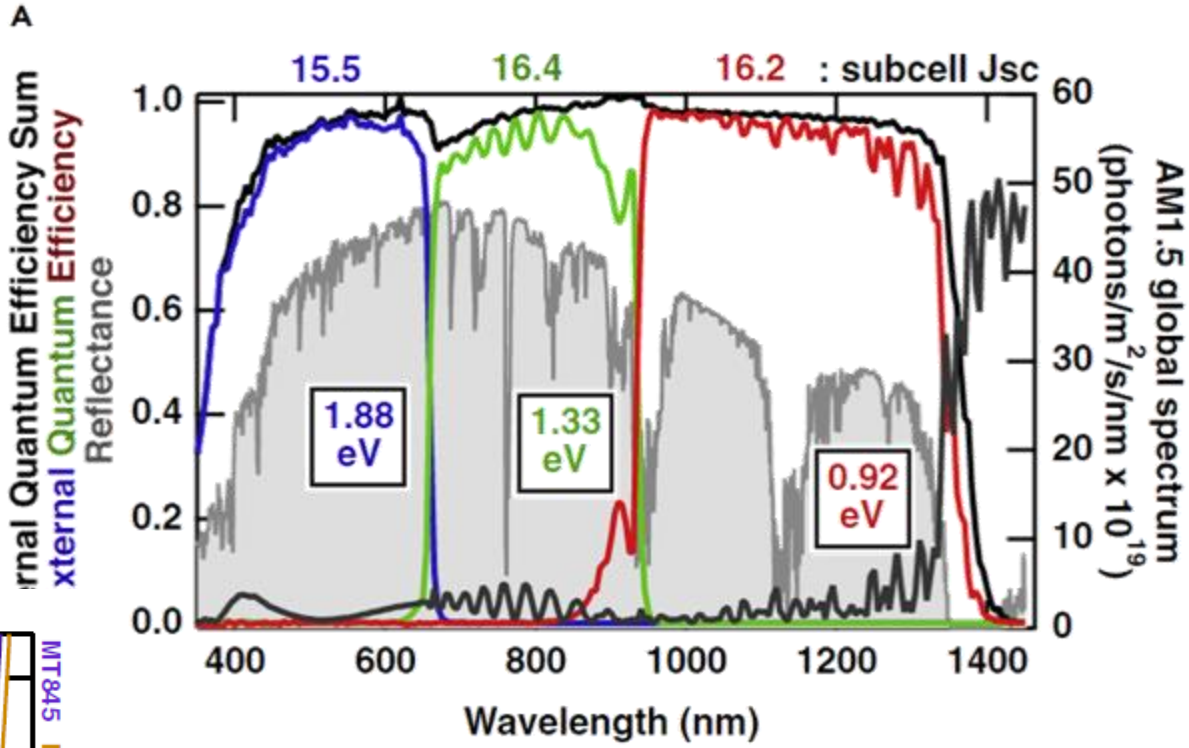
Under concentration:

- *2012:* **44.0 %**, triple junction GaInP/GaAs/GaInNAs (Solar junction) 942 suns)
- 2022: **47.6**% 4 junctions (Fraunhofer, 665 suns)



World record 1 sun, three-junction cell: 39.5%

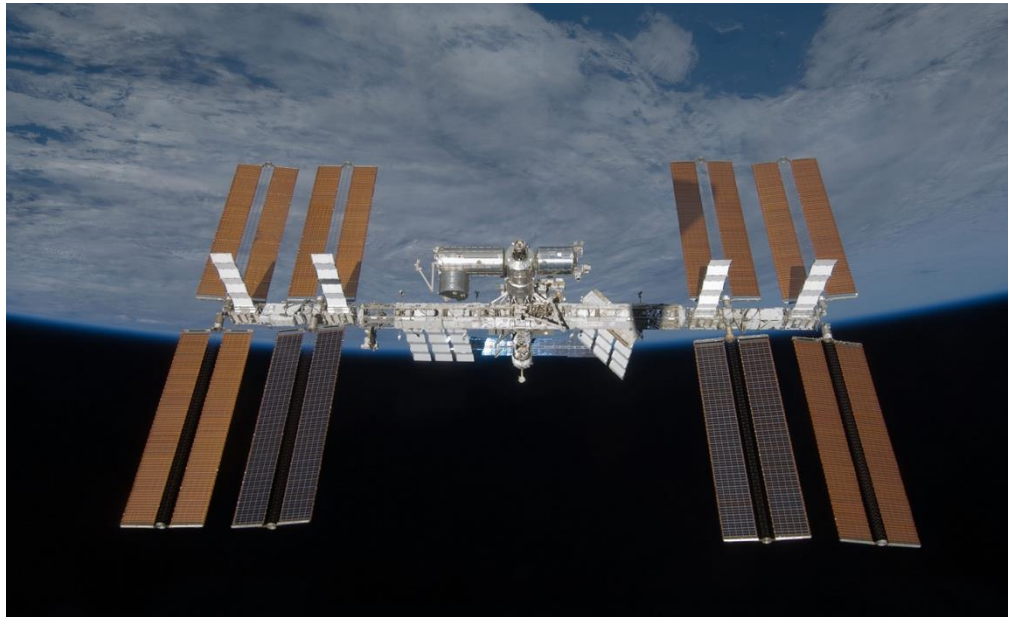




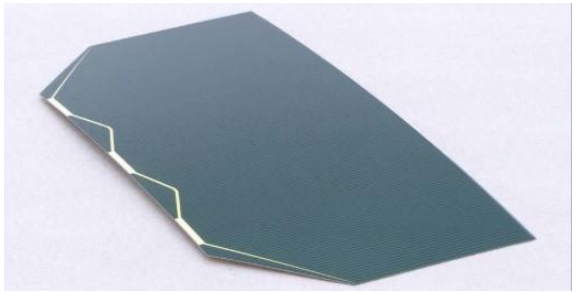
3 solar cells in series
With J_{sc} = of 15.4 mA/cm2
V_{oc} = 3 V, FF, 85.3%

R. M. France et al Joule
Volume 6, Issue 5, 18 May 2022, Pages 1121-1135

III-V solar cells for space



- Market of ~ 1 MW per year, growing with more and more satellite constellations
- Mostly triple junction (Ge/GaAs/GaInP) with 30% AM0 BOL (**B**eginning **O**f **L**ife)
- High cell cost: ~ 200$/W, i.e. 1000x more than terrestrial product
- Small volume, complex growth process, expensive substrates (GaAs, Ge wafers)



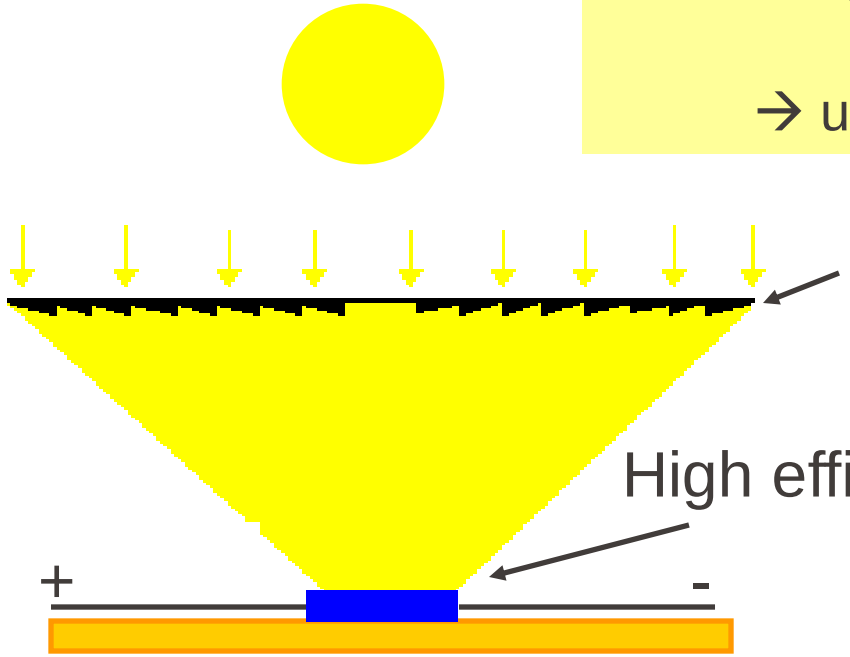
Azur space (EU) new **4 junction** space product with BOL 31% and EOL (End of Life) of 28.7% (after **10^{15} cm^{-2} 1 MeV electrons)**

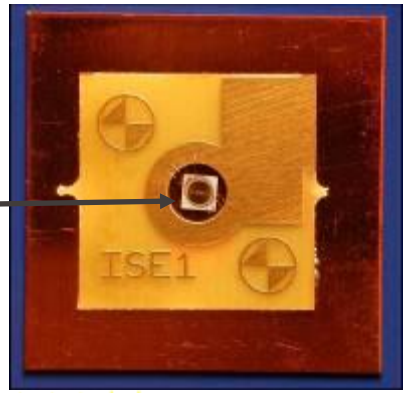
- For low lifetime constellation, new usage of lower cost c-Si.
- Datasheets on moodle

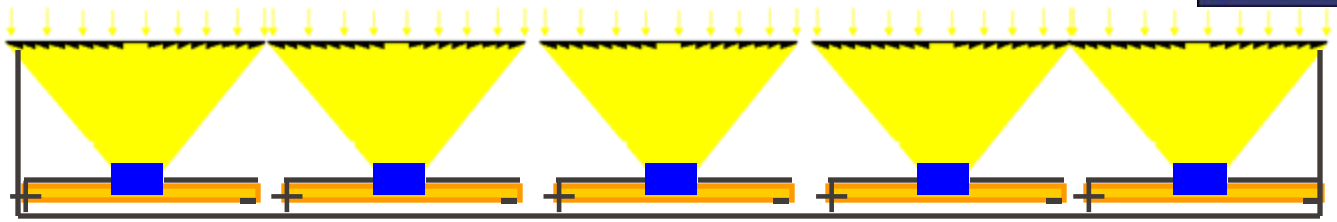
10.1051/e3sconf/20171603005

Concentration light system

Concentrated light (100-1000x)
with simple optical compound!
→ utilization of smaller active cell area







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Concentration photovoltaics

- High efficiency III-V multijunctions are expensive, but…
- If no (limited) series resistance is present in a solar cell, the V_{oc} and FF increase upon concentration (see diode equation) eq 1.8 → efficiency increase !

In first approximation FF increases as

$$V_{oc} \approx \frac{kT}{q} \ln\left\{\frac{I_L}{I_0}\right\}$$

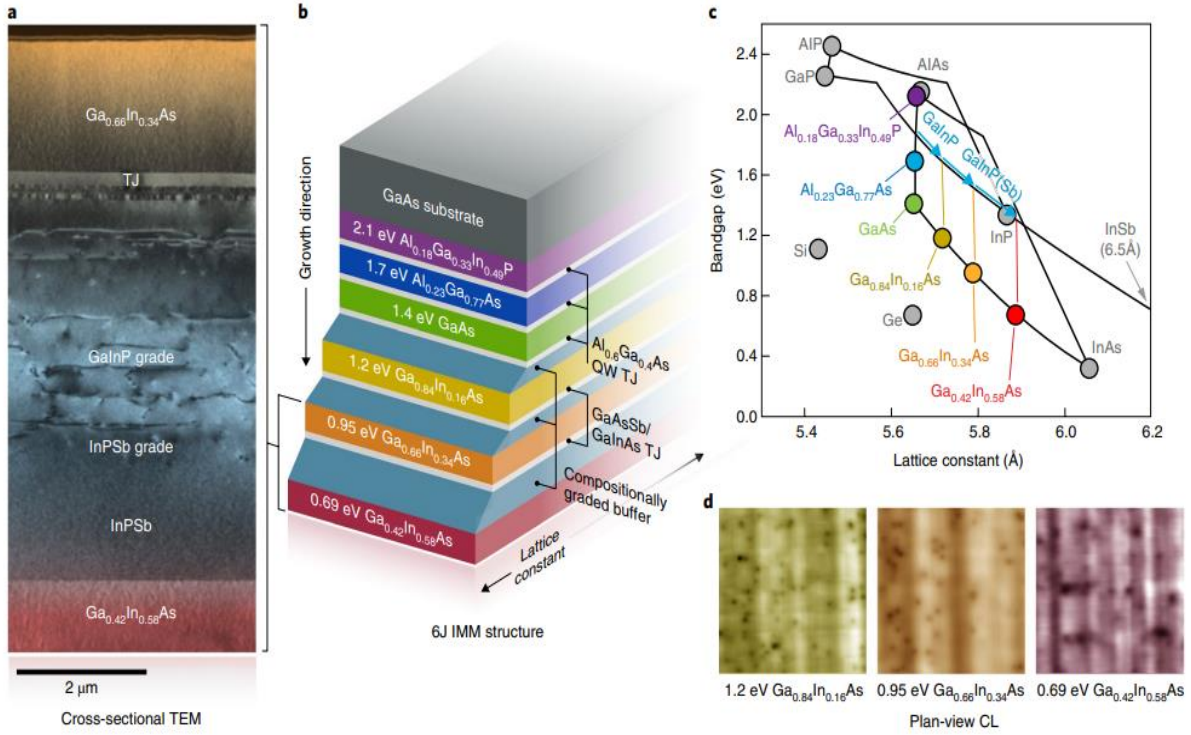
$$FF = \frac{v_{oc} - ln(v_{oc} + 0.72)}{v_{oc} + 1} \quad \text{with} \quad v_{oc} = \frac{V_{oc}}{k_b T/q} \qquad \textbf{(1.12)}$$

- Expensive solar cells can be reduced in size and light can be concentrated at
- Good heat management required (because Pmax decreases with T!)
- Maximum concentration of 45,000x (limited by the sun's size). Practically 100 to 1000 x concentration is used.
- !!! The more you concentrate, the lower the acceptance angle**

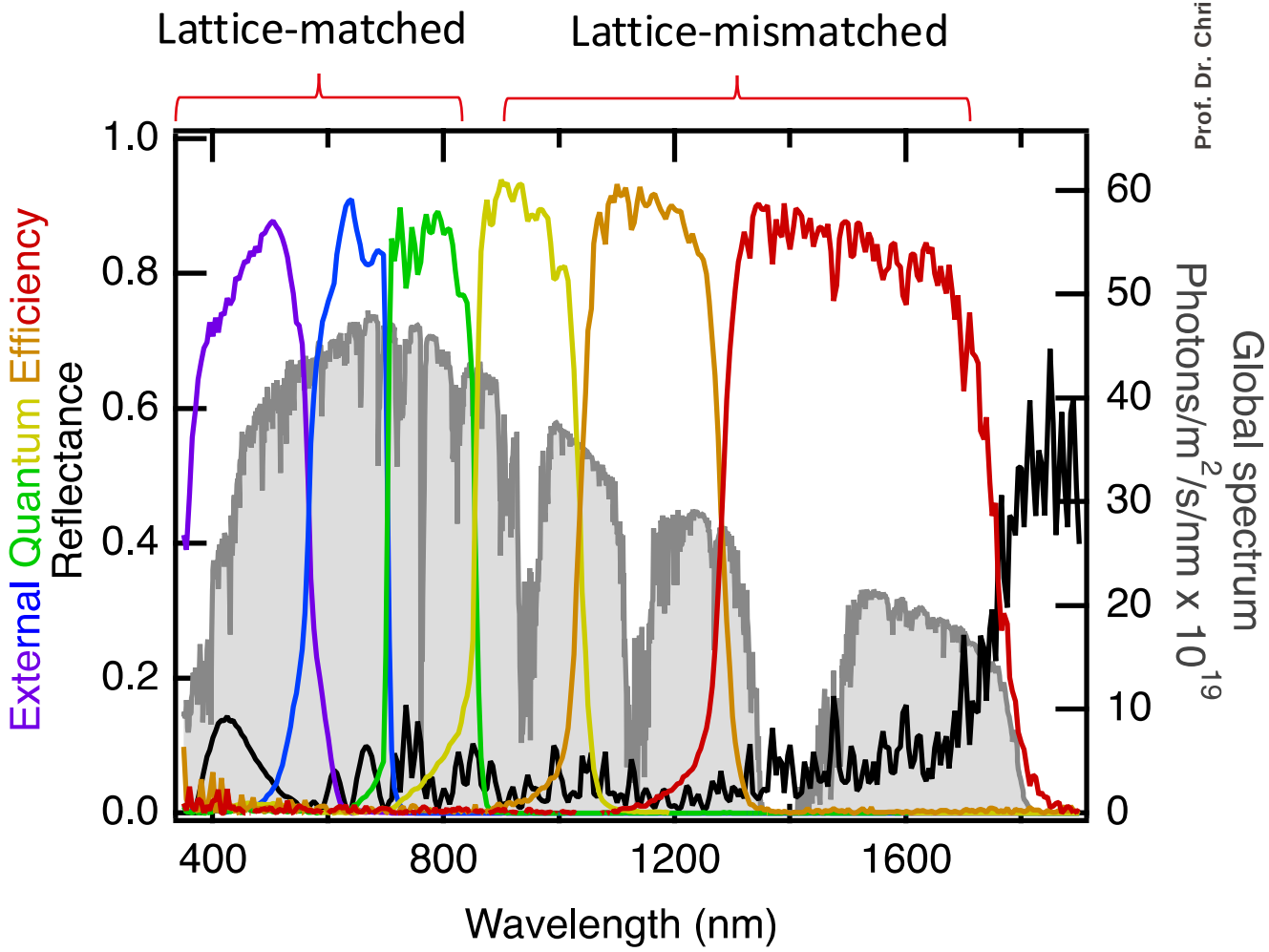
** for 3D concentration, the maximum concentration possible is given by $C_{max} = n^2/Sin^2(\theta)$ where n is the refractive index of the medium (air) and θ the acceptance angle.

Example of ultra-high efficiency devices

6 - junction inverted metamorphic reaching 47.1% at 143 Suns



J. Geisz et al., Nat. Energy., **5**, 326 (2020)
Lattice mismatched refers to growth of materials with different lattice constant. Buffer layers allow to relax part of the strain !



- 3 subcells lattice-matched to GaAs
- 3 independently mismatched GaInAs subcells

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Concentrator modules

Module Flatcon ISE/ Concentrix/Soitech. Demonstrated efficiency of > 30% at AC level (AM1.5d , 10% lost light!)

++ Potential for high efficiency (> 35%) and low (?) cost for sunny regions

++ better cells → system improvements (if 60% cells → high interest)

Amonix concentration modules

- Mechanical aspects/ tracking complicated
- High concentration → more accurate tracking required
- Sensitive to dust/soiling
- Cost of electricity higher than for c-Si

➢ **Despite higher efficiency, concentrating PV does not succeed in taking a market share**

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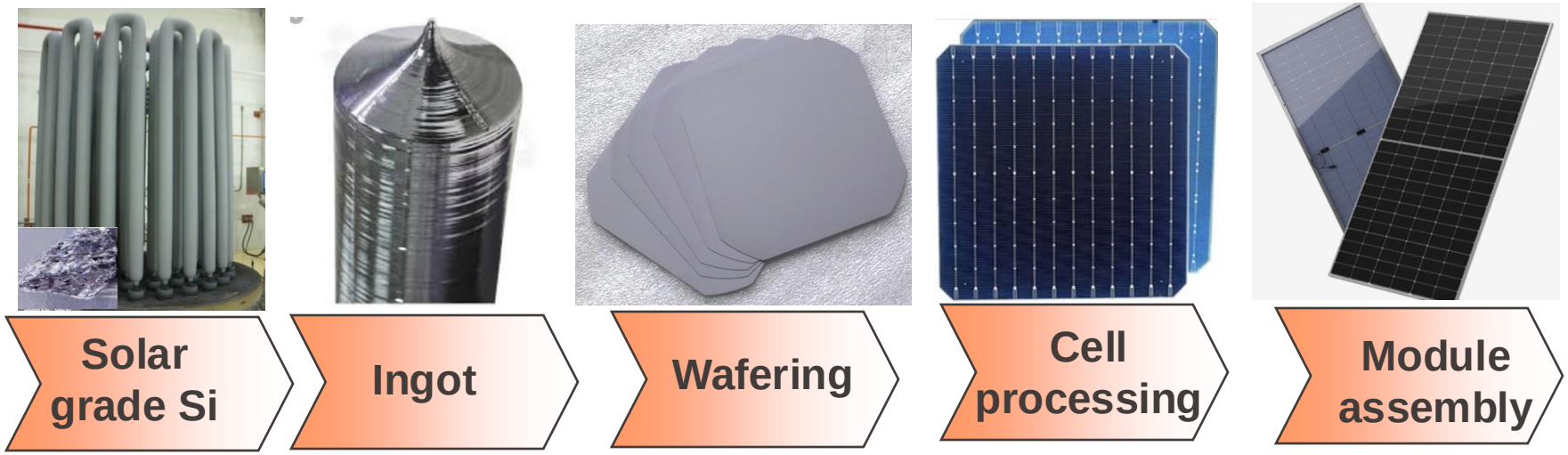
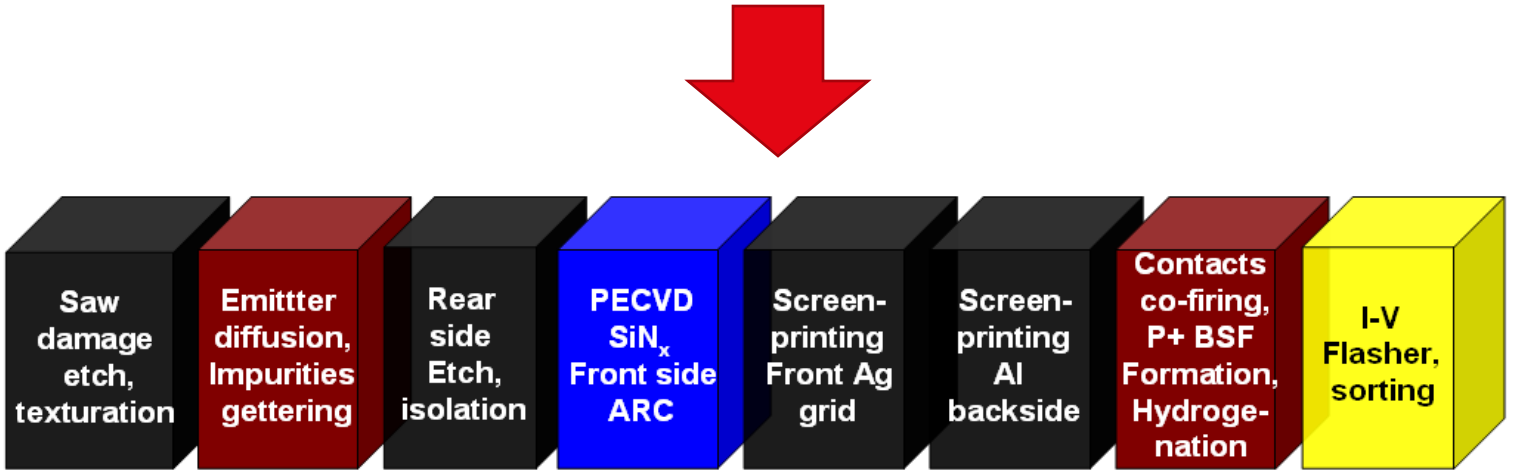
Crystalline silicon: a chain split in over 50 steps





This is the most simple solar process: **the Al-BSF process**

The initial disadvantage of crystalline silicon (many steps) turns to an advantage (splits of the steps, specialise, disgard easily out of spec wafers or cells)

Moncrystalline vs multicrystalline silicon

Large multicrystalline block

Monocrystalline ingot (single crystal)

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The various types of crystalline technologies

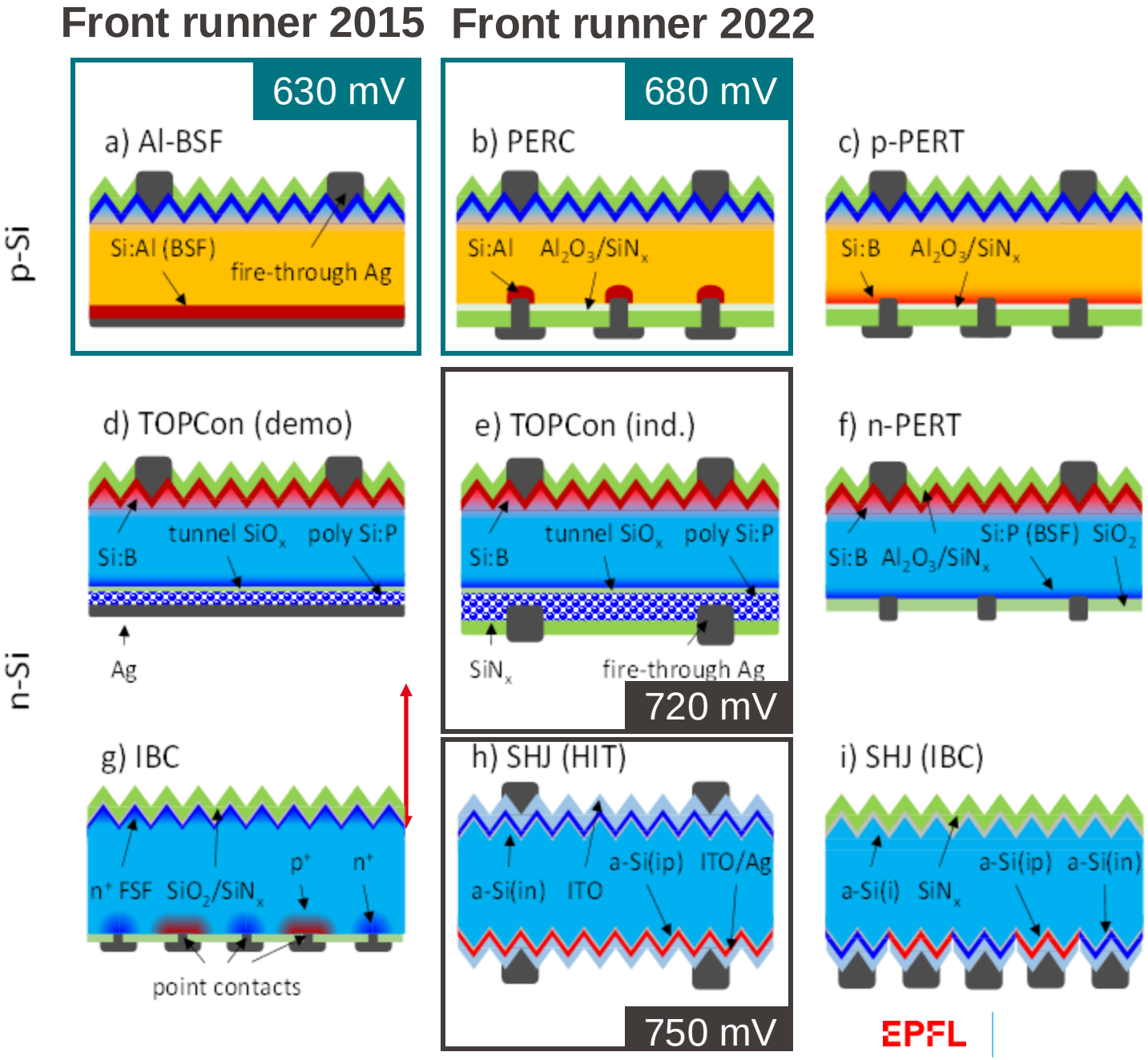
Al-BSF aluminium backsurface field

PERC: Passivated emitter and rear contact

TOPCON: tunneling oxide contact

SHJ (or HJT): silicon heterojunction

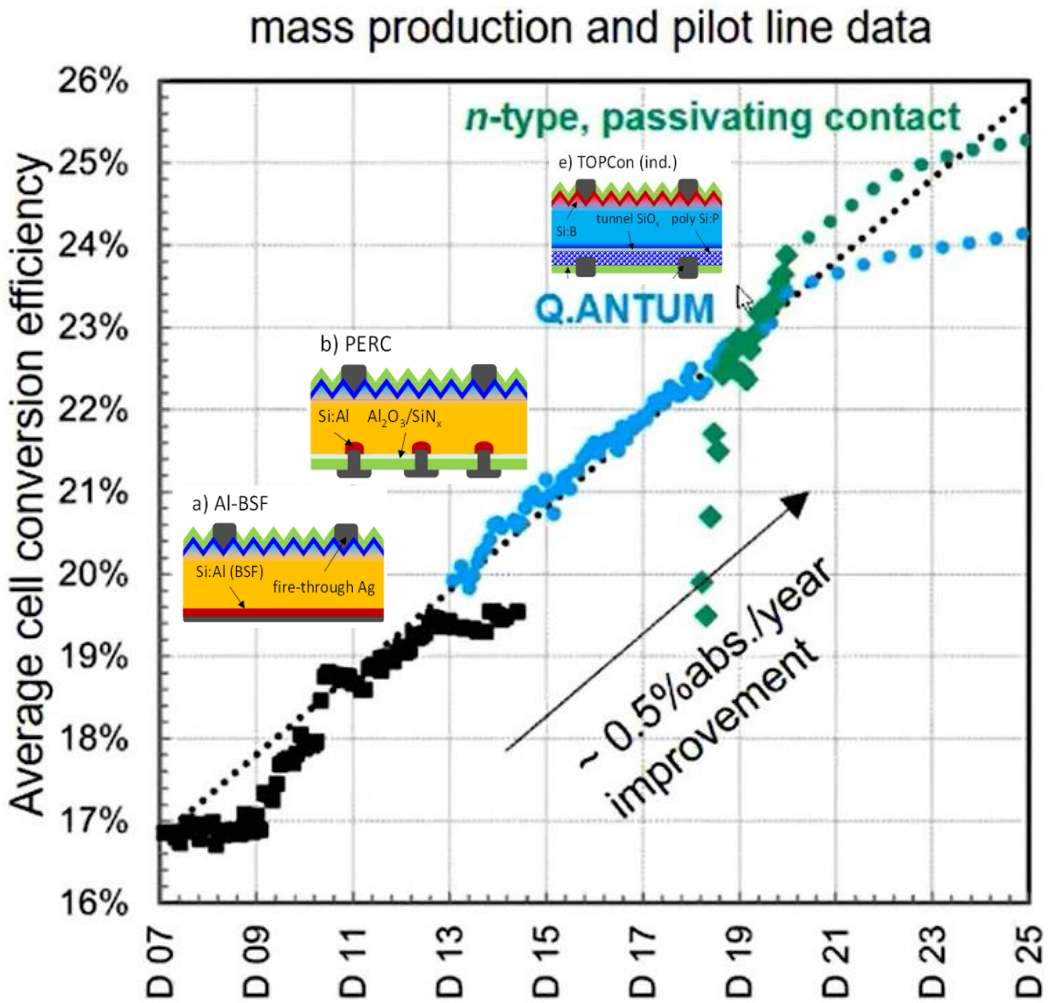
IBC: Interdigitated back-contacted solar cell



Source: Ballif/Haug *et al.* - Nat. Review Mat. 2022

27.09% world record (Dec, 2023)

Efficiency increase
a) Technology continuous improvement and changes



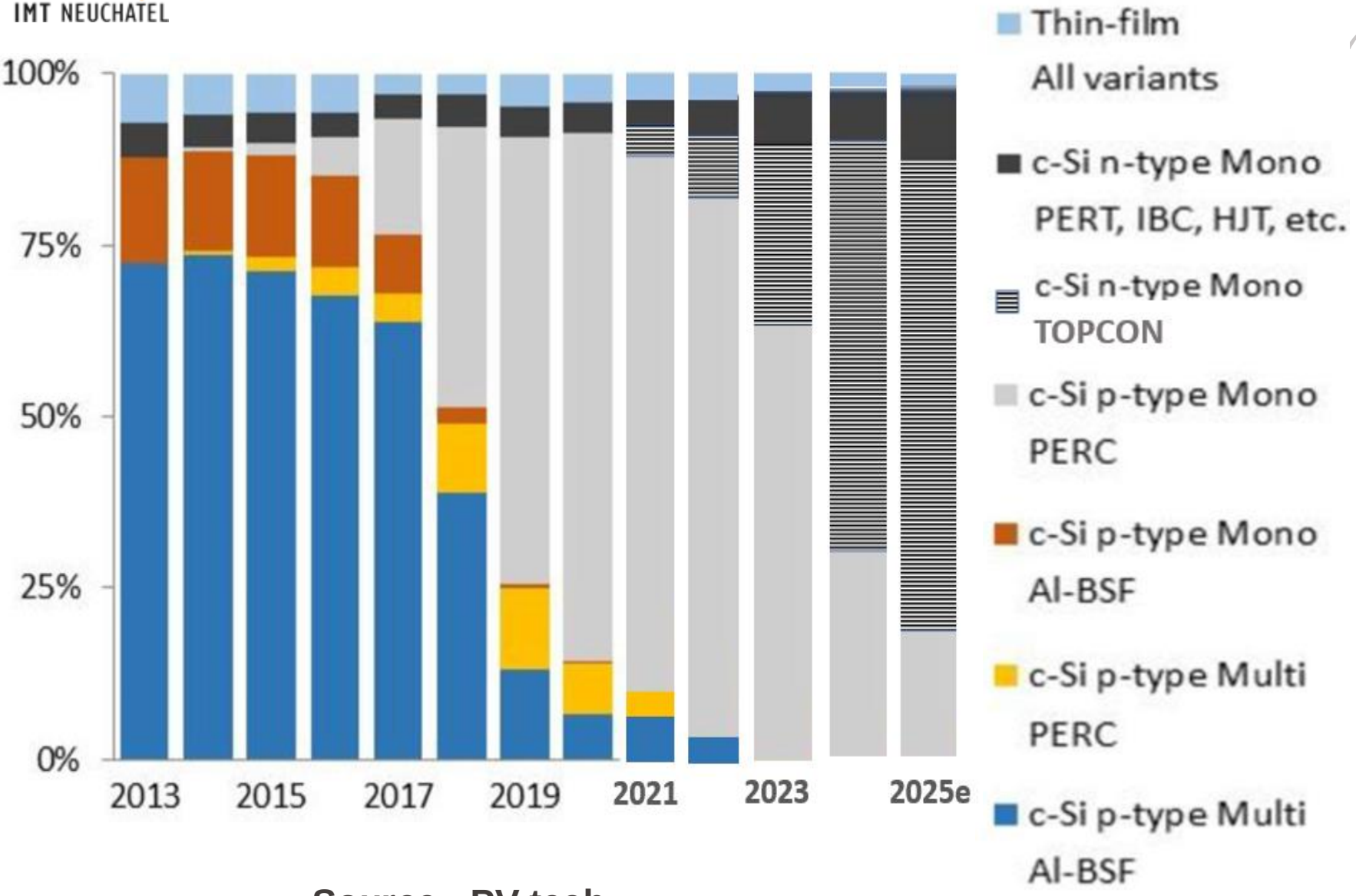
Each technology <u>evolves</u>
(lots of small improvements in wafers quality, in metalisation, in gridline width, in surface passivation…)

and then <u>saturates</u>

Because the device structures reaches its limit !

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

Drastic changes in the PV industry



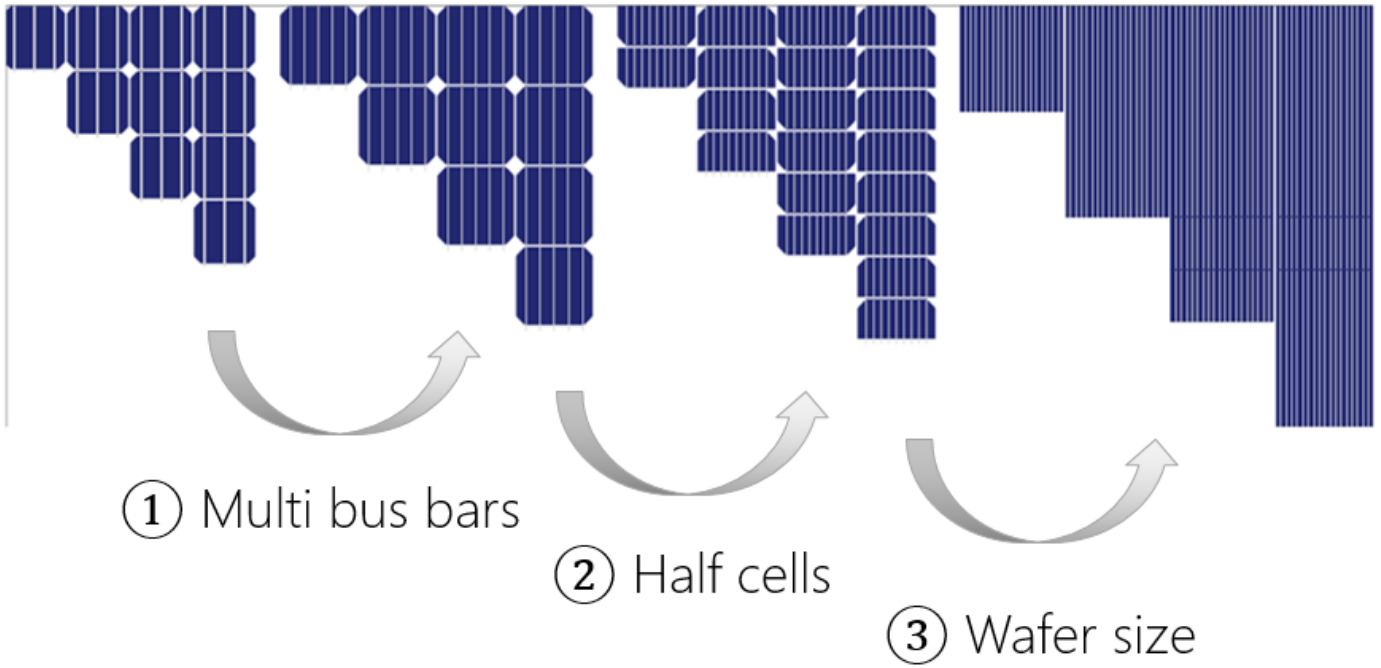
Source : PV tech

- **2015-2020 shift from multi to monocrystalline silicon**
- Thanks to progress in «crystal pulling and sawing», and high efficiency cell process

2017-2021 Shift from Al-BSF cell to PERC solar cells were taking 85% of the market in 2020

TOPCON (Mostly) and Heterojunction SOLAR CELLS will replace quickly PERC solar cells (2023-2027)

Further help to efficiency increase

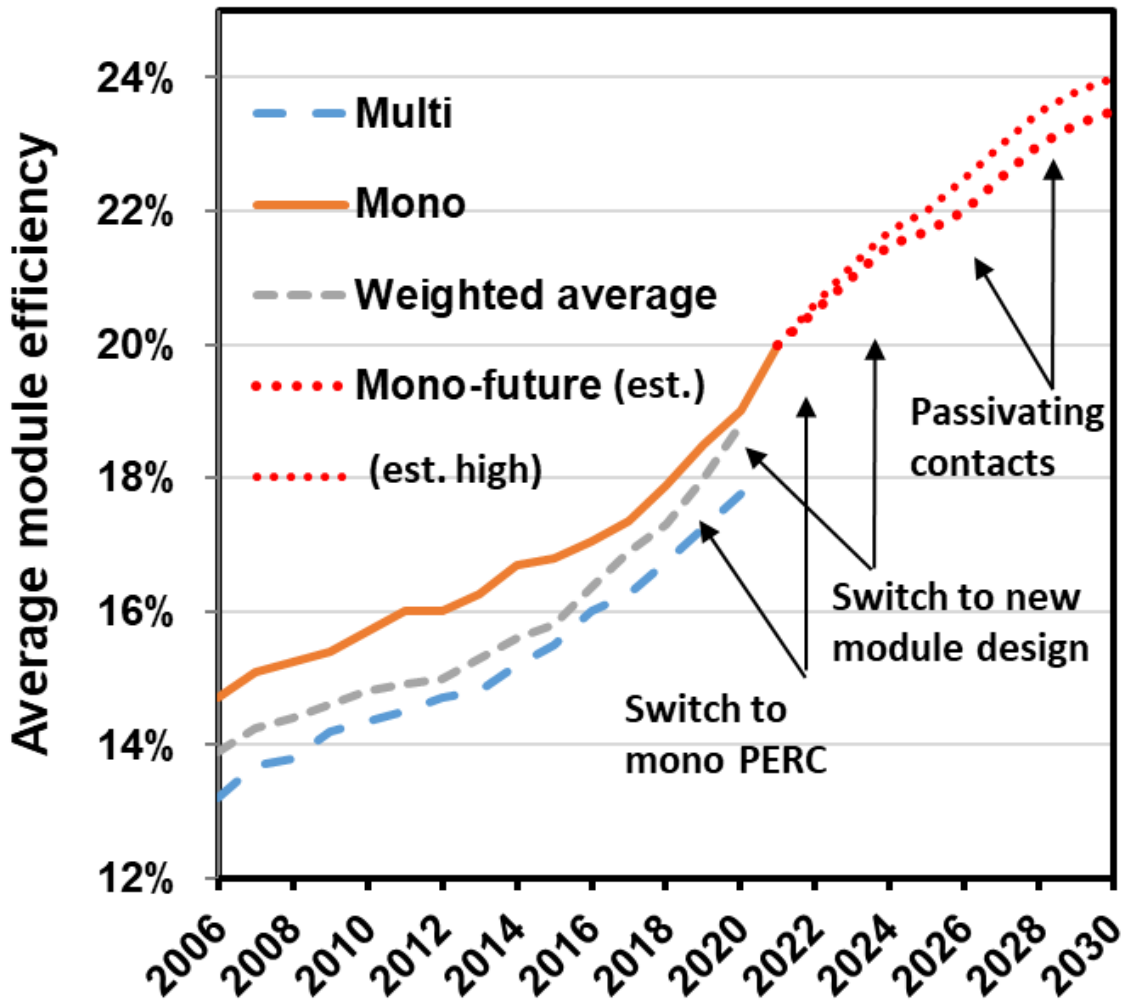


b) Module design change

(0.5-1.5% absolute gain)

1. **More bubars: reduce losses in silver finger (gain 0.1-1% relative)**
2. **Half-cells: less ohmic losses in cupper ribbon interconnects (gain 2% relative)**
3. **Larger cells: less empty area, less edges per area (up to 21 x 21 cm2 solar cells) (0.5-1% relative)**
4. **Larger modules: less spacing the edge (1-2% relative for 700 W modules)**

Summary: increase in the market average efficiency of c-Si module



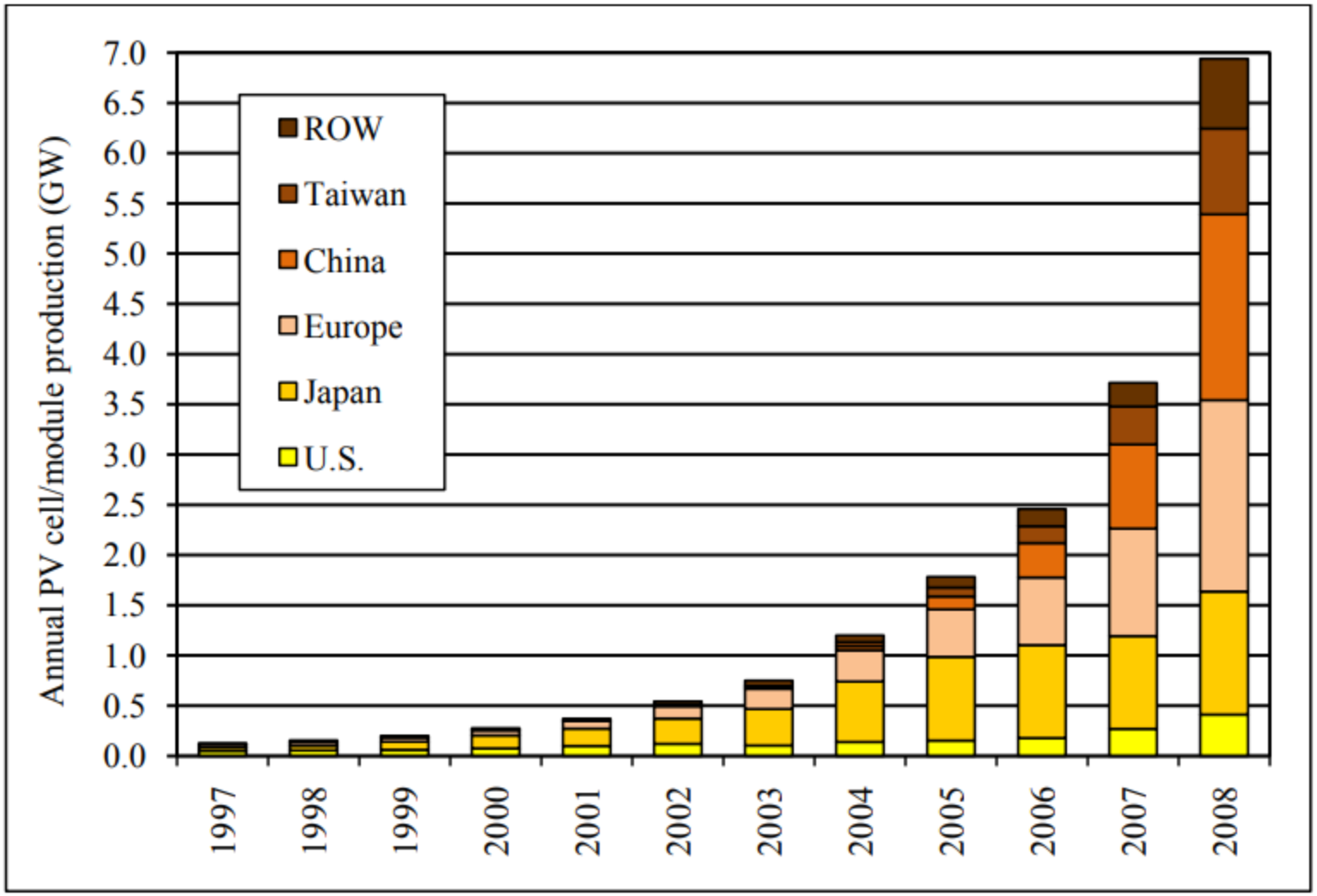
Haug, Ballif *et al.*, Nat. Rev. Materials, 2022

- **0.4-0.5% absolute gain per year**
- Efficiency of PV modules will further increase to an average ~22 % in 2025, will likely reach a 23.5-24% average in 2030
- **Practical limit at 24-25% for silicon modules under STC***

In 2025, typical monocrystalline module have an efficiency of 21.5-22.5% and incorportate cells with 23.5-25 % efficiency

*except if photomultipliers can work effectively

2. PV Market: annual module production



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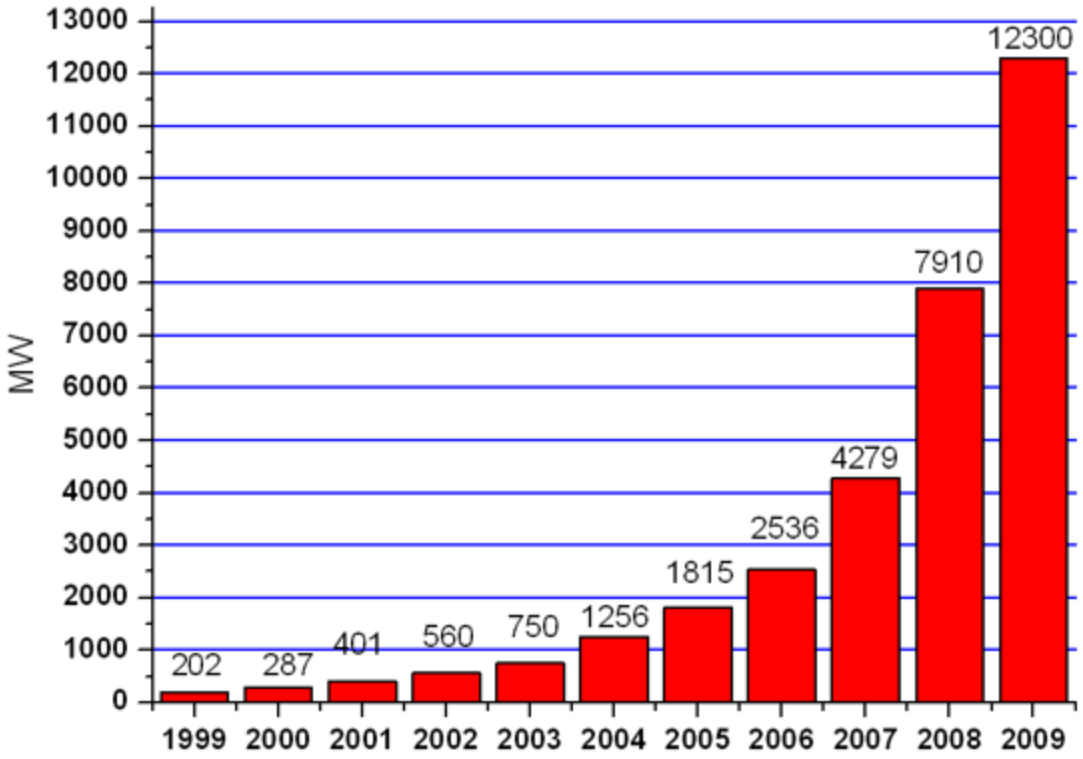

Cell and thin film module manufacture

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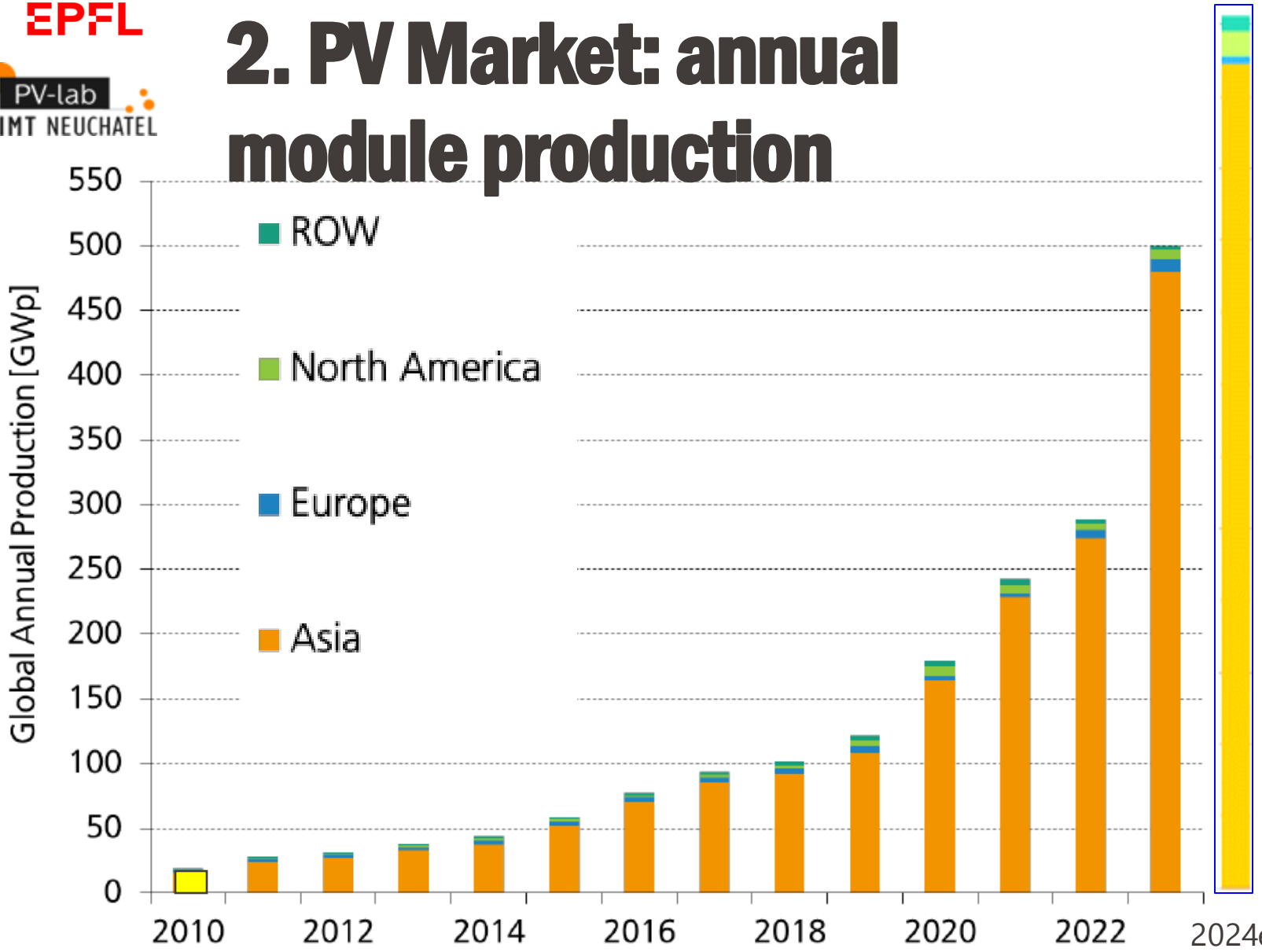
2. PV Market: annual module production



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Note: there is a delay between production and installation
Typically 6 months

Mainstream cells and modules comes now from Asia

Top 10 module makers shipped 500 GW

2024 Module shipment ranking

Rank	Company
1	Jinko
2	Longi / JA Solar
4	Trina
5	Tongwei
6	Astronergy
7	Canadian Solar
8	GCL
9	DAS Solar
10	Yingli

Source: InfoLink Database

N/ half year)

Top 5 cell makers shipped 164 GW

Cell shipment ranking 2024

Rank	Company
1	Tongwei
2	Solar Space
3	Jietai
4	Yingfa Ruineng
5	Aiko

Sell their cells to c-Si companies

Make part of their cells and purchase another

Many smaller companies produce cells (Meyer Burger, Enel,..) and mostly modules in Europe or even in Switzerland (3S, Sunage, Megasol)

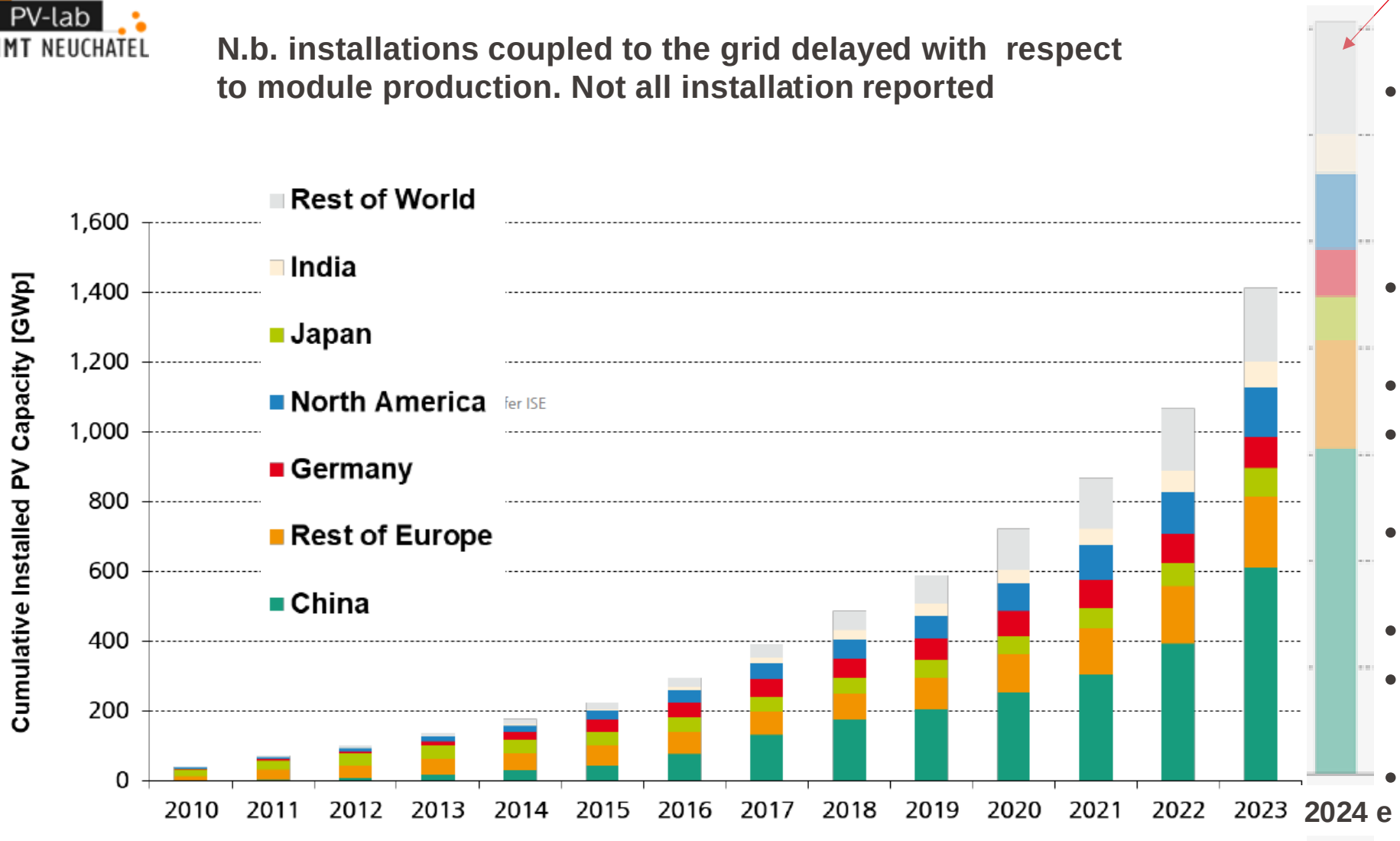
https://www.infolink-group.com/energy-article/solar-topic-2023-global-module-shipment-ranking

PV Market: total installation

Est. 2024

Electricity – Renewables 2023 – Analysis - IEA

N.b. installations coupled to the grid delayed with respect to module production. Not all installation reported



- Europe as an initiator of volume installation; stagnating since 2012
- Now: Asia and ROW
- 133-140 GW in 2021
- **375-400 GW in 2023**
- End 2023: **> 1400 GW PV installed**
- End 2024
- **2000 TW installed (esti)**
- by 2030: expect ~4.5-5 TW installed

Note: The IRENA data shown here differs from that of the IEA PVPS:
IRENA: 1,412 GWp
IEA-PVPS: 1,581 GWp

PV-Report, Fraunhofer ISE (April 2024)

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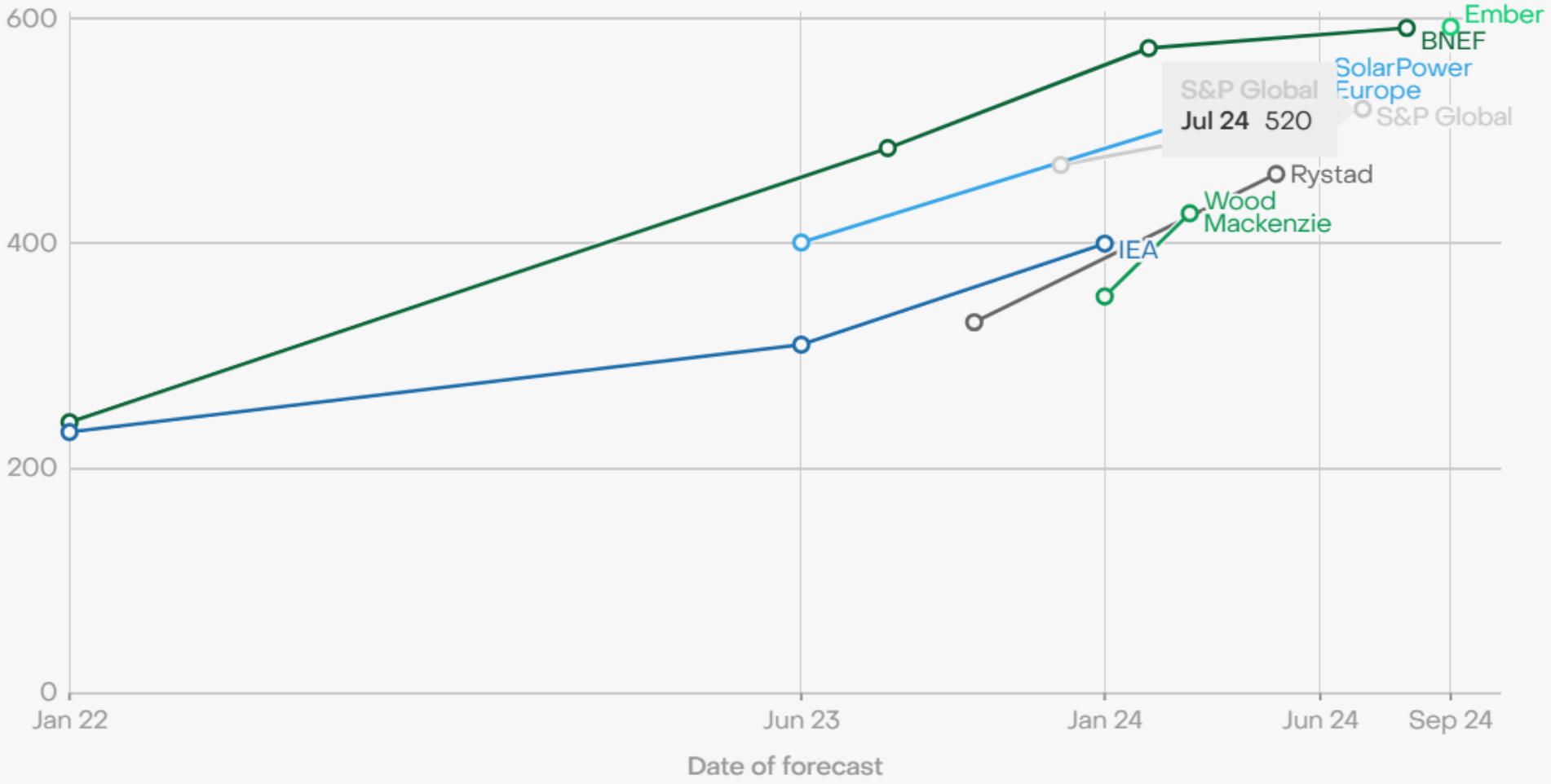
Forecasts for global solar power installations in 2024 have continuously been revised upwards

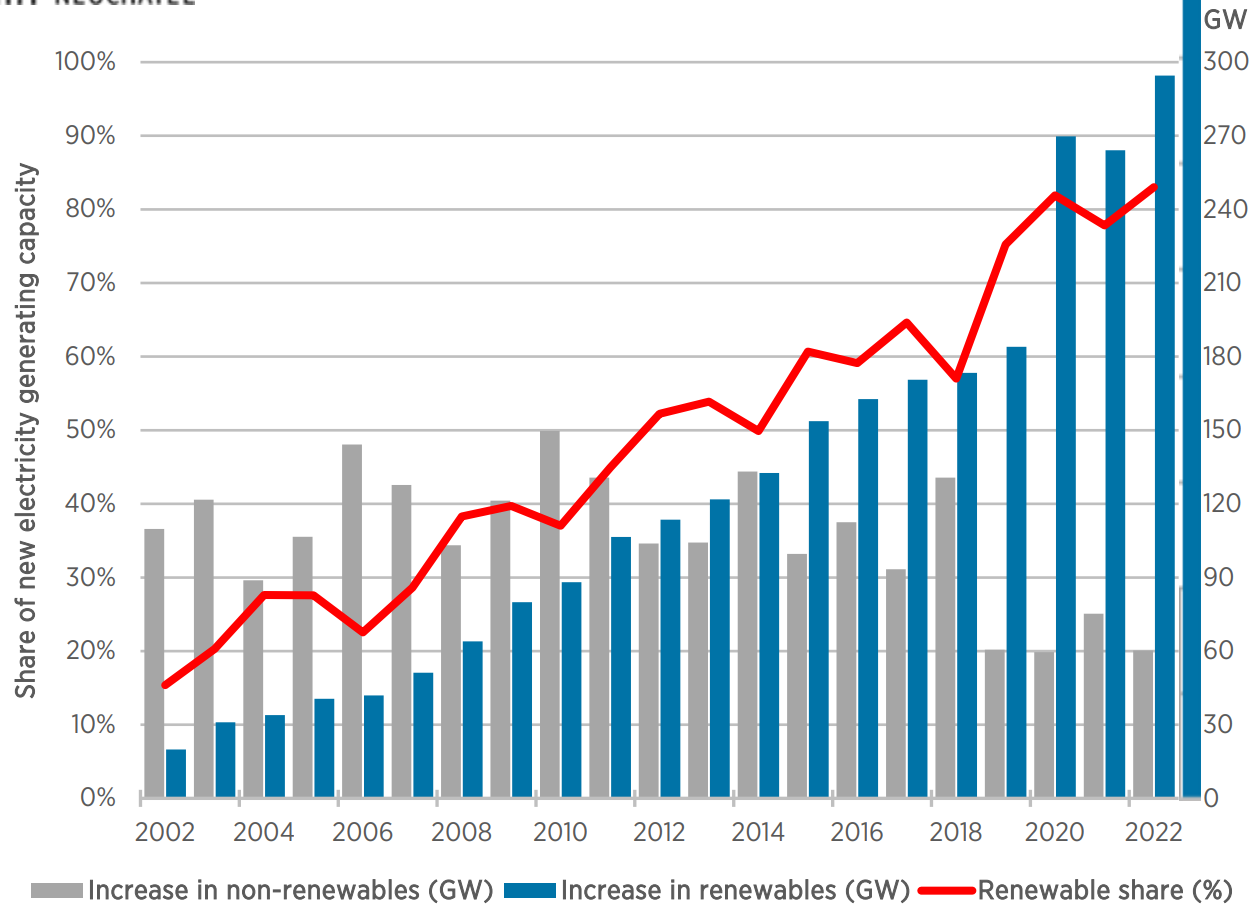
Projected capacity installations for 2024, by date of forecast (GW)

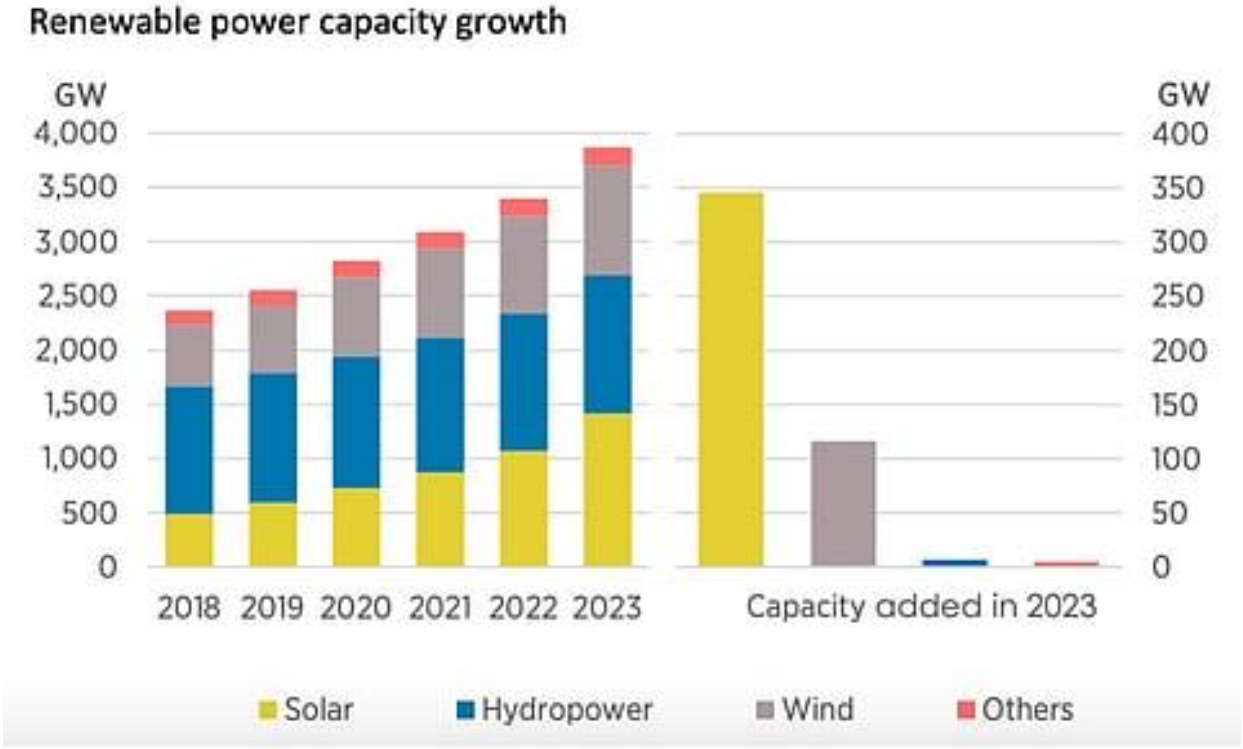


Source: Ember analysis of solar forecasts

EMBER

Renewable as new capacity in the world market





- 82% of new capacity from wind-solar and hydro in 2022. More in 23

IRENA_-RE_Capacity_Highlights_2023.pdf (azureedge.net)

- But capacity factor lower than e.g. gas or coal power plant

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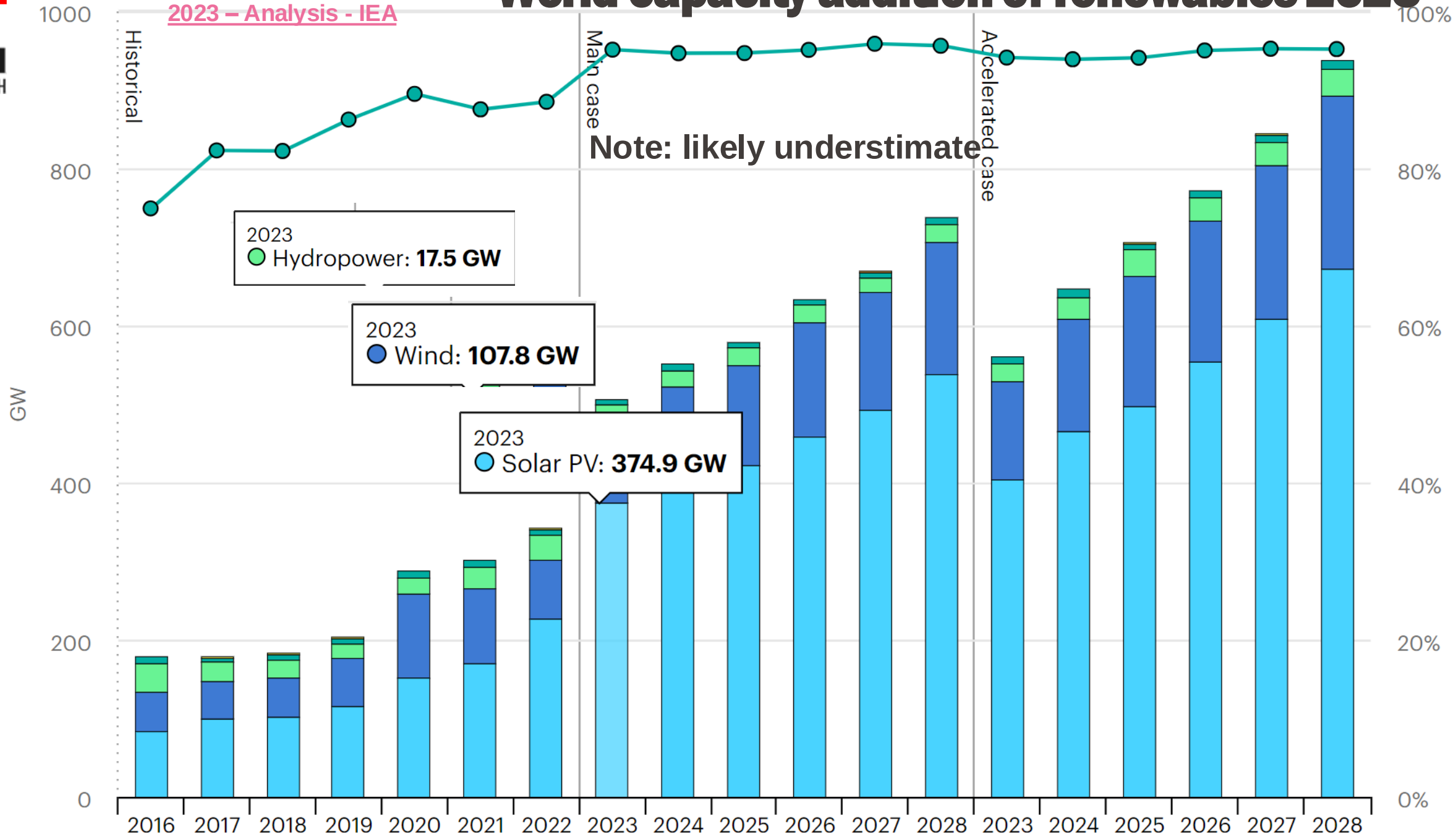
Electricity – Renewables 2023 – Analysis - IEA

World capacity addition of renewables 2023



510 GW IN 2023 NEW INSTALLATION OF RENEWABLES (SOLAR, WIND, HYDRO)….

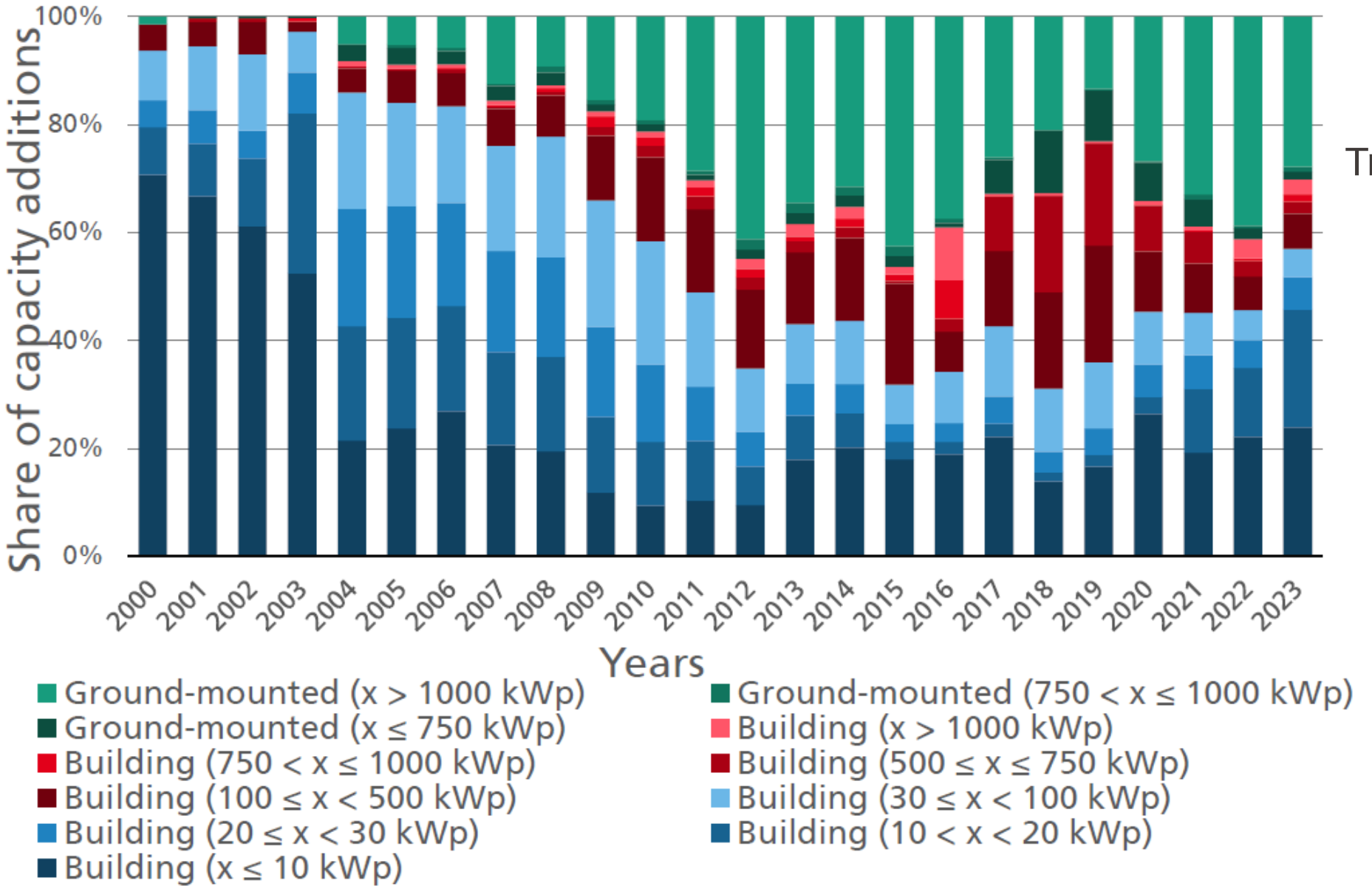
SO WE INSTALLED THE EQUIVALENT OF 100 TO 110 NUCLEAR POWER PLANT OF 1 GW EACH RUNNING 100% OF THE TIME

LIKELY 650-700 GW IN 2024, 140-160 EQUIVALENT NUCLEAR POWER PLANTS

CHINA IS DEPLOYING FASTER THAN ANYBODY ELSE AND MIGHT PEAK ITS EMISSION BY 2025

PV Market

Application of PV and system size (Germany)



Trend towards large systems (>500 kWp) since ~2011 (conservative government changed incentives) but change in 2017-2018 to midsize systems.

Depends on market and regulation

PV-Report, Fraunhofer ISE (2022)

3. Cost of solar electricity

For a complete formula (without reinvest)
https://www.pveducation.org/pvcdrom/levelized-cost-of-electricity

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Direct LCOE of grid connected solar electricity

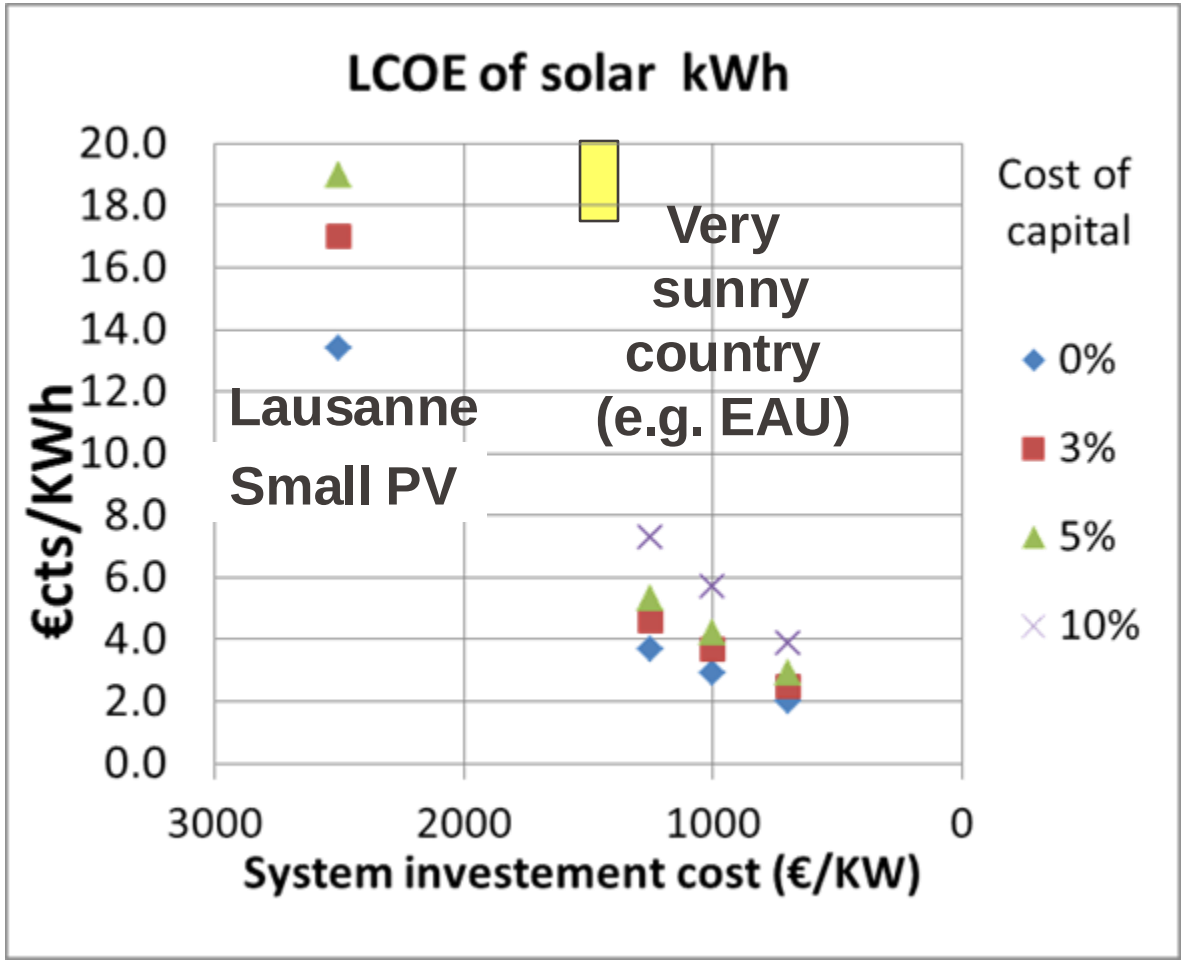
LCOE: levelized cost of electricity

$$LCOE = \frac{CAPEX + total\ OPEX}{total\ electricity\ production}$$

CAPEX= capital expenditure
OPEX = operational expenditure

Main contributors

- **Initial investment**
- **Cost of capital (or interest rate)**
- Maintenance costs (+ insurance)
- **Duration (here 25 years)**
- **Energy yield (kWh/kW) (climate)**
- **Aging behaviour (degradation rate)**



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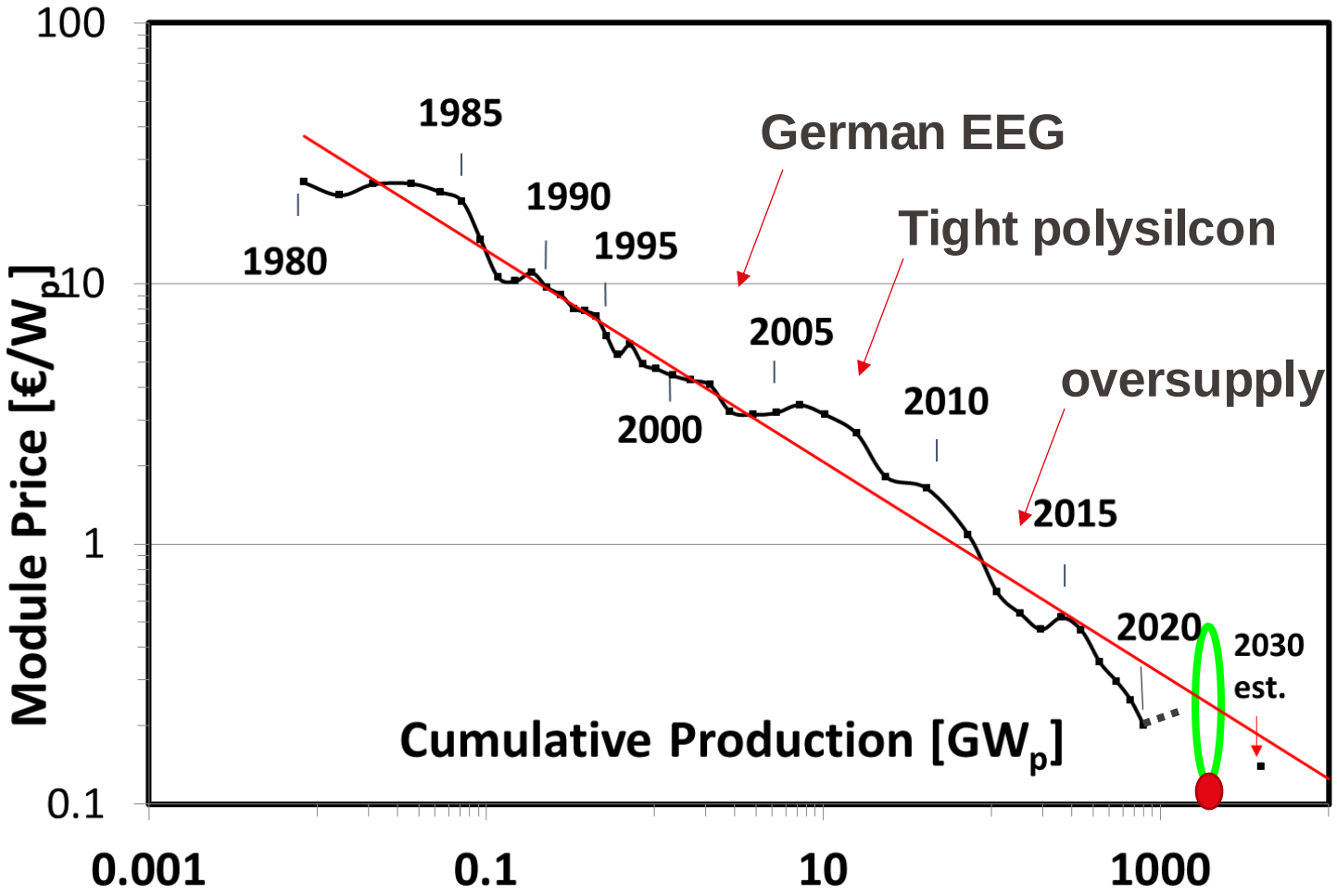
Learning curve for standard c-Si module price

Doubling cumulated production

↓

-20% less production costs



From 10$ in 1990 to 0.2€/W in 2020 ! (40$/m²)

Up again to 0.27€/W in 2022 (bottleneck in polysilicium)

Down again in 2023

10 cts/W in 2025

60 cts/W for high end modules, e.g. special building integrated

***typically ordering 1 MW modules*

Price * ○ 2025 ~ 0.1-0.7 CHF/W

Production costs ○ 2023 ~ 0.11 -0.6 CHF/W

Source ITRPV 2017 and adaption Ballif et al. Nat. Rev Mat 2022

Photovoltaics modules

- In the last 35 years from

10€/W to 12 €cts/W (2024-2025) for the lowest cost c-Si modules

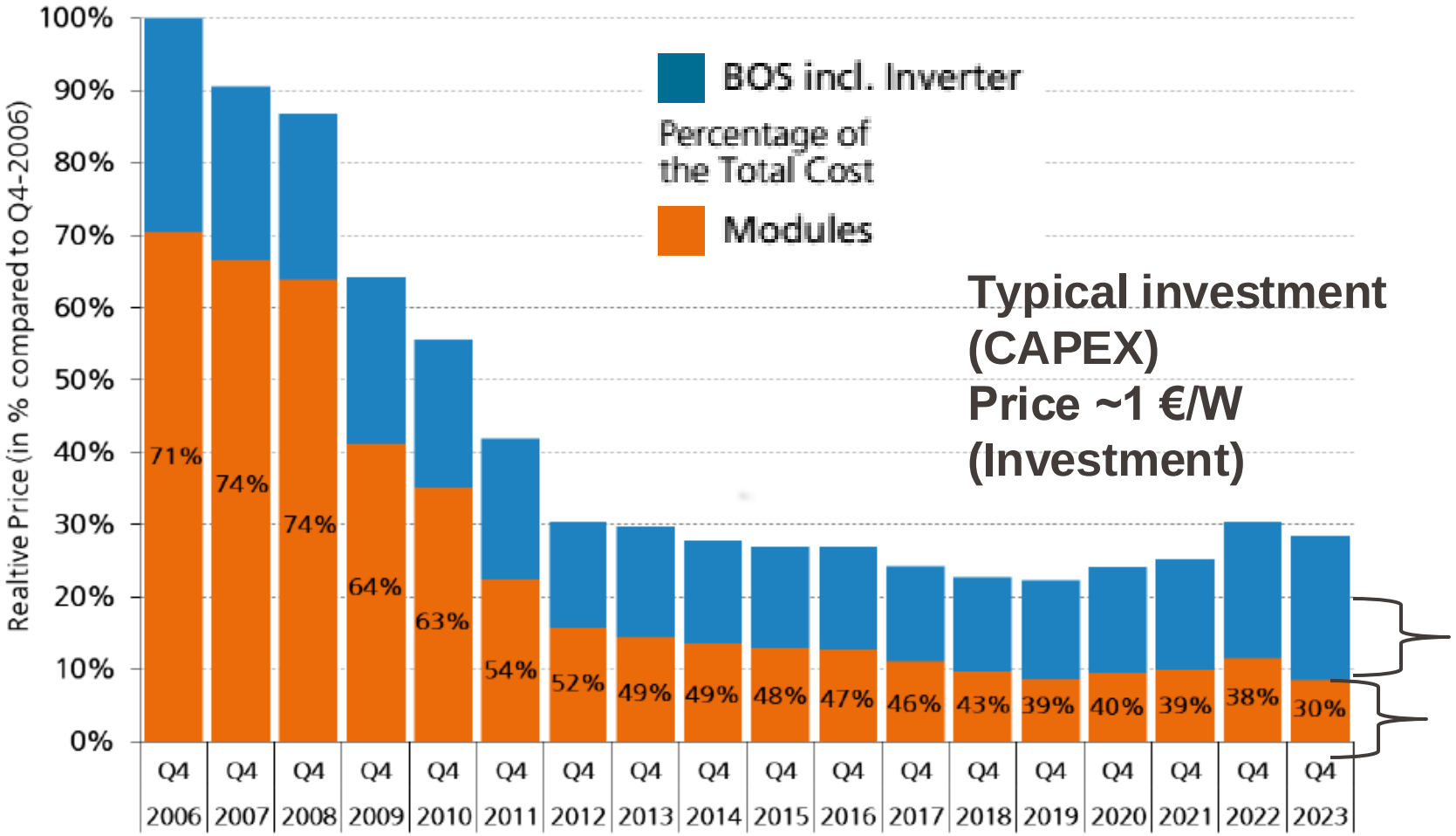
Almost a factor 100 in cost reduction

If you buy today in mass you can buy 1m2 for around 22-25 CHF !

3. Cost of solar electricity : CAPEX (capital expenditure)

Typical system cost decrease: installers also improve !

Germany: Roof-top systems (10-100 kW)



Typical investment (CAPEX)
Price ~1 €/W (Investment)

Strong demand reduced along learning curve

BOS = Balance of system costs

- Inverter
- Mounting system
- switches, wiring installation work
- Admin and engineering

- Typically BOS 3-4 times price of module (why efficiency matters)

Source: PV-Report, Fraunhofer ISE (V 2022)

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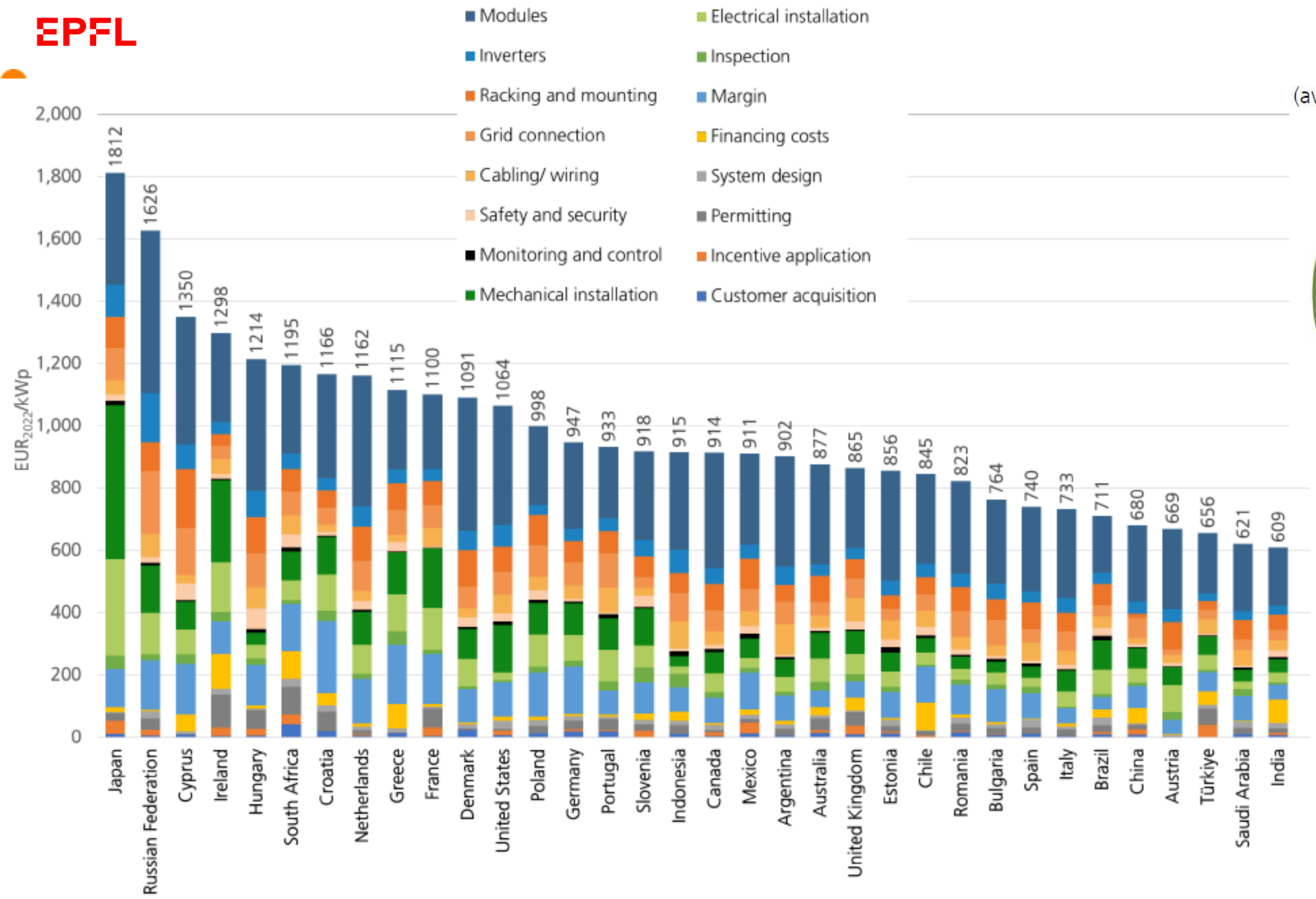
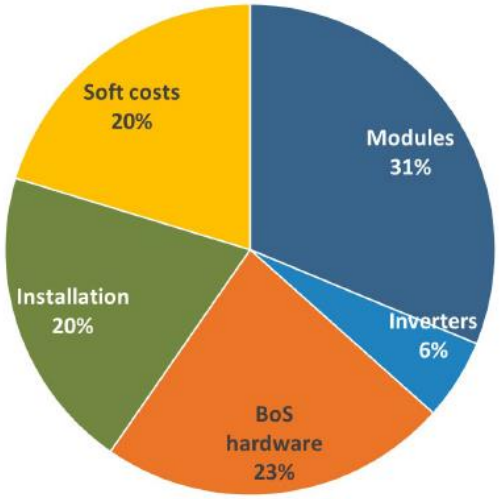


Breakdown of cost components
(average of available country data):



Went up by 15-20% in 2022 (Ukraine War)
Going 30% lower in 2024 !

Park expected at 0.35 €/W in 2024 e.g. in Maroco

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News | La plus puissante installation solaire de Suisse bientôt à Neuchâtel

Bientôt à Neuchâtel

La plus puissante installation solaire de Suisse

La plus puissante installation solaire au sol de Suisse devrait voir le jour à Cressier (NE). Quelque 19'000 panneaux photovoltaïques, un investissement de 6,5 millions de francs, produiront une importante partie de l'électricité consommée par la raffinerie Varo.

Publié: 13.01.2022 à 12:09 heures | Dernière mise à jour: 13.01.2022 à 12:14 heures

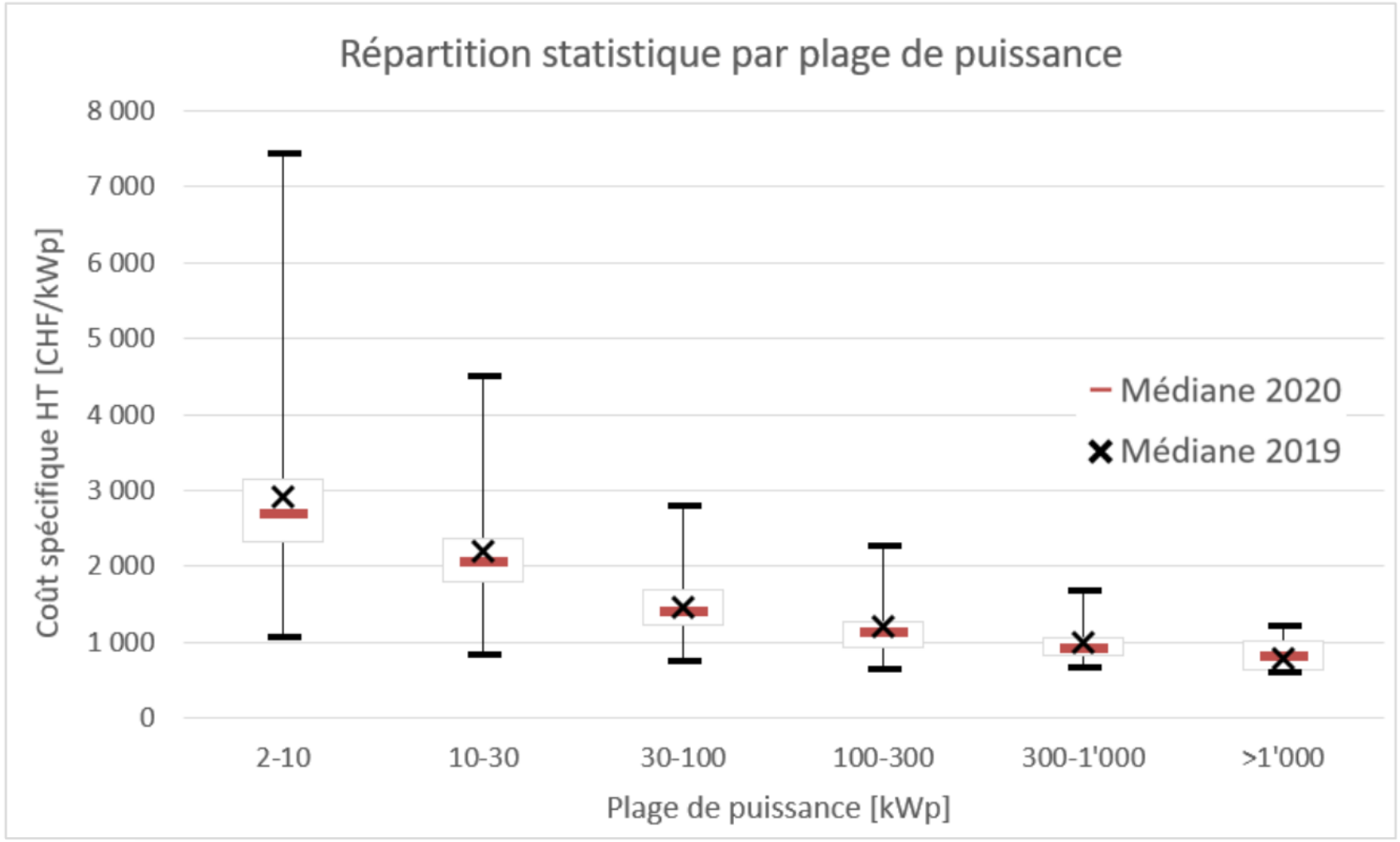
- **Rare opportunity for ground mounted systems in Swizterland.**
- **7.7 MW on industrial announced by VARO (Feb 2022)**
- **6.5 millions invest (0.85 cts/W)**

35 MW
30 millions
Invest
(announced Jan 2023

Flughafen Bern und BKW wollen die grösste Freiflächen-Solaranlage der Schweiz bauen

PV Market

Cost/ CAPEX of PV systems in Switzerland, 2021



Source planair-SFOE

- >300 kW @ 1 CHF/W
- 30 cst/W panel
- 7 cts/W inverter
- 8 cts/W mounting structure
- 15 cts/W installation
- 40 cts planning/admin/margin

Note: in 2022 – 2023, strong demand and higher system price because of personnal shortage (x 1.2 to x 1.3) 2025 going below 2021

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Cost and prices of PV system components

- The **direct production costs** for all components can continue to decrease through **mass learning effect**. At some point, the limit is the **cost** of the raw materials and the **cost of energy** to produce/process these materials. This will limit further decrease, unless less material/smarter processes are used !
- Profits in in the industry move from e.g. making silicon to making cells, to making modules, or installing modules… China company can live with 10% margin (and sometimes even loose to gain market share).. This is the case in 2024…
- Price of PV modules, cables, inverters, mounting systems depend on offer and demand. In 21-22, strong demand for glass, polysilicon (refined silicon) has led to an increase in module price, or demand for electronic components increased inverter prices. Oversupply in 2024 brings ultra low price.
- No bottlenecks are fundamental, after investment and increase in production capacity, the price can go down again….
- **Solar cell efficiency increase is the keyway to reduce all costs** ! That's why it is so important !

Reminder: CAPEX down to 0.5-0.6 €/Wp for PV for large plants, possibly 0.35€/Wp for most aggressive new parcs 1€/Wp typical for midsize system. Smaller systems tend to cost more.

Cost of solar electricity: example

Cost of solar electricity for a typical 100 kW roof top installation in CH

Good market prices in CH (2024):
50 kWp individual producer

0.15 €/W_p	Module
0.25 €/W_p	Inverter, racks
0.45 €/W_p	Installation and margin
0.85 €/W_p	Total system costs

*This is the price one should get to make the 6-7% ROI.
This means you get after 20 years your initial capital with 6% interest (componed)

Solar electricity price* (20 years, 6-7% interests)
Swiss irradiation ~ 1100 kWh/m^2 → 1 W_p → 1 kWh/year → 7.0 €cts/kWh
(South of Spain ~1800 kWh/m^2 → 1 W_p →1.7 kWh/year → 3.7 €cts/kWh)

- **This is an LCOE:** if you can use or sell at this price, you make your return on invest as planned.
- If you substitute grid with high self-consumption, returns goes up to 10% (for 20 €cts/kWh grid).
- If you don't self-use and can sell at 4 cts/kWh inCH, then you'll need to reach 25 years for 0% return

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Comparative Photovoltaic Levelized Cost of Energy Calculator

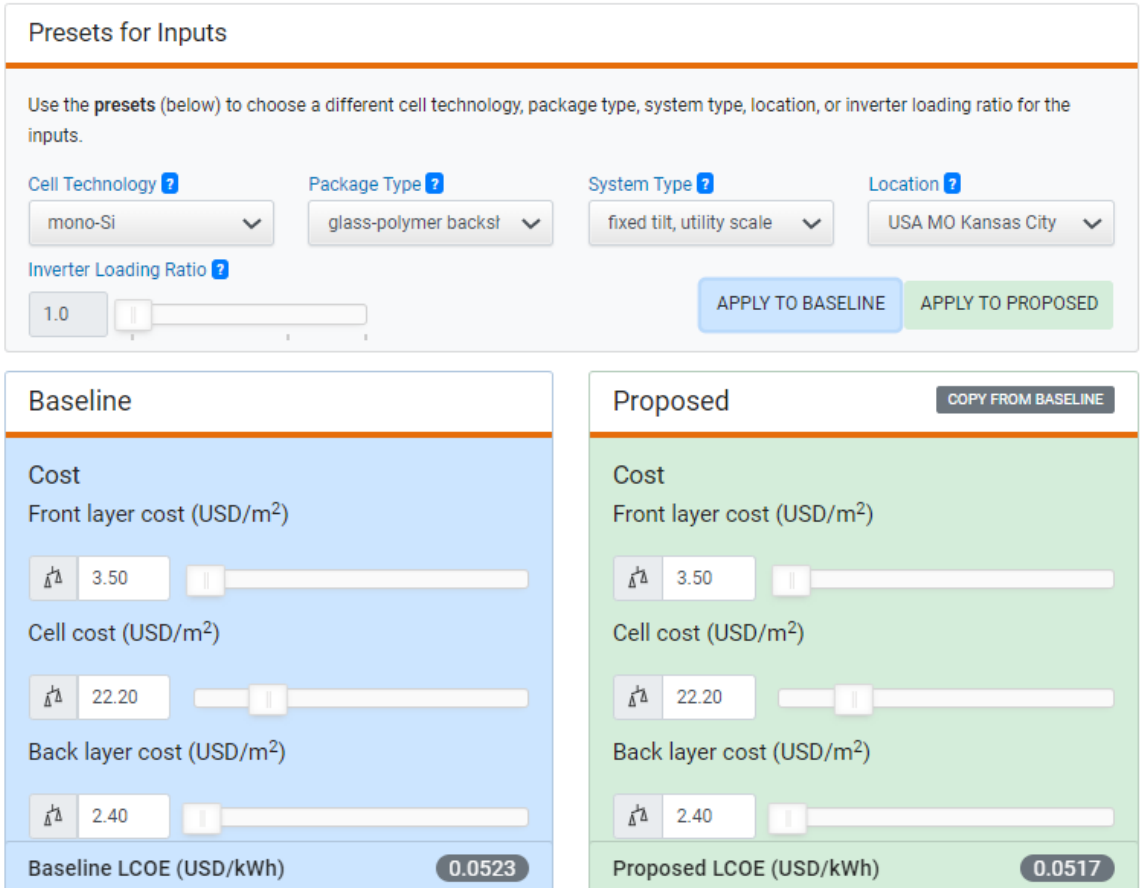
NREL Transforming ENERGY

Home Documentation

This tool calculates levelized cost of energy (LCOE) for photovoltaic (PV) systems based on cost, performance, and reliability inputs for a baseline and a proposed technology.

Choose your inputs and watch the effect on LCOE to determine whether a proposed technology is cost-effective, to perform trade-off analysis among different technology options, and to do break-even analysis of cost or performance. Each button adjusts a single input to make the baseline and proposed LCOE equal.

For more details, please consult the documentation. You may also be interested in other tools for calculating cost and performance for renewable energy.

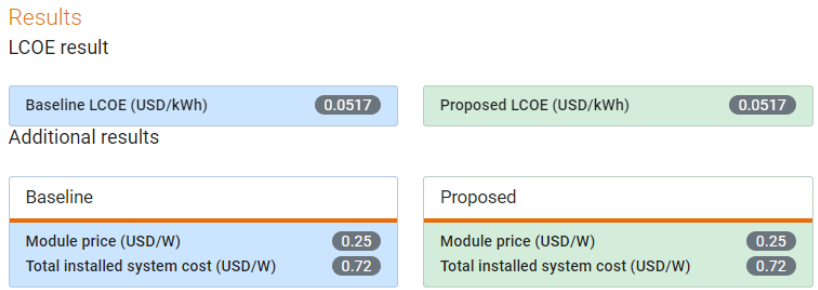


For an easy tool check
https://www.nrel.gov/pv/lcoe-calculator/
For a complete formula (without reinvest)
https://www.pveducation.org/pvcdrom/levelized-cost-of-electricity

Play with the NREL LCOESimulator

Check the impact

- Maintenance costs
- Degradation rate
- Interest rate



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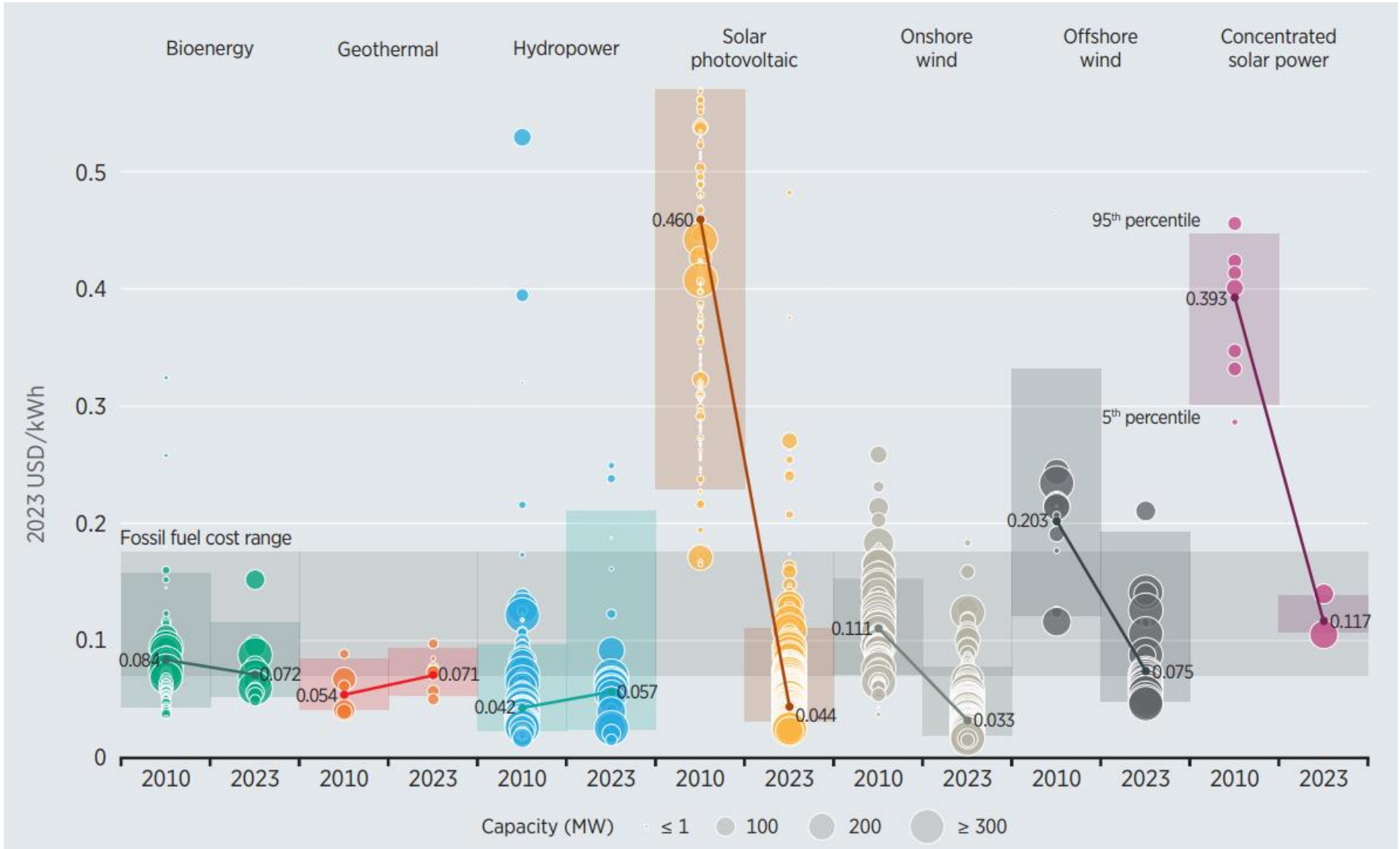
Cost of electricity

Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2024

Drop in generation costs of renewables from 2010 to 2024



FOSSILE FUEL COST RANGE 2023

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

Source: IRENA report «Renewable power generation costs in 2023"

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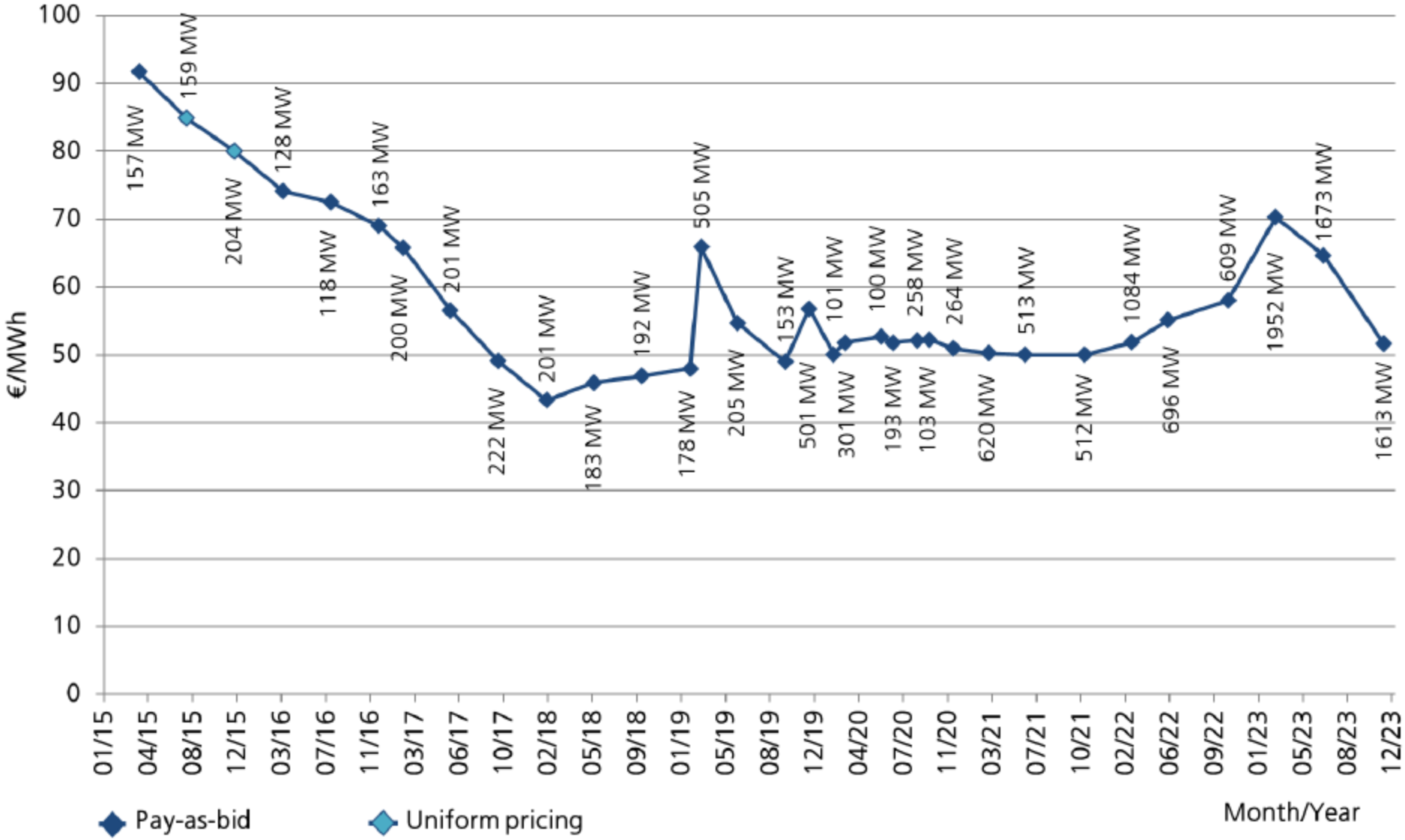
Electricity market

German price for “solar auction”: Average, quantity weighted Award Value

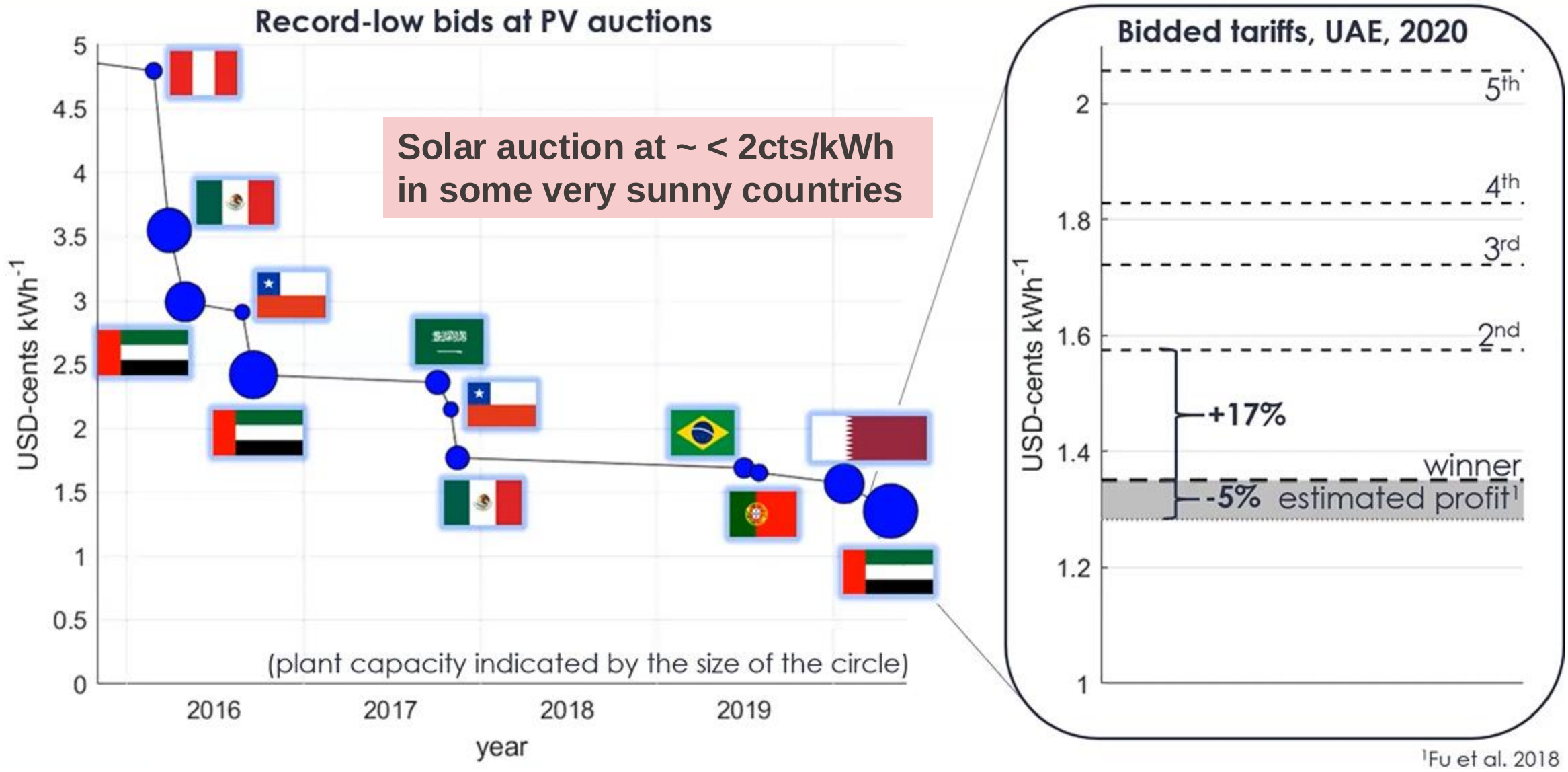


~ 4.5 cts/kWh in Germany

Sept 2024

PSE 2022 –Date of data: Jun-2022

Ultra-low cost bidding for PV**



** attention to interpretation: sometimes cost of capital not disclosed, free land, …

Example of LCOE calculations with soiling in a desert country

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Capex	**0.75**	**$/W**			
Performance (fixed mount)					
Installed power	1000	kWp			
Array cleaning interval (*ci*)	20	days			
Optimum tilt if *ci* = 0 (*β* opt,c)	32	° (yield's tilt dependence modelled for *β* opt,c = 32°)			
Offset from *β* opt,c	0	°			
Specific yield at *β* opt,c	1800	kWh/kWp			
Soiling loss rate at *β* opt,c	1	%/day (percentage points)			
System performance decrease	0.5	%/year			
System lifetime	25	years (<200)			
Soiling loss rate	**1.00**	**%/day (percentage points)**			
Specific yield	**1620.00**	**kWh/kWp**			
Operation and maintenance					
Flat rate maintenance (excl. array cleaning)	1	%/year (capex)			
Module efficiency (*η*)	20	%			
Array cleaning cost	0.1	$/m²			
Array cleaning cost	**9.13**	**$/kWp/year**			
Financials					
Tax rate (on income - for IRR only)	0	%			
Incentive (one-off at investment)	0	$/Wp			
Energy price	0.050	$/kWh	**OR**	Interest rate	3 %
Internal return rate	**6.55**	**%**		**Nominal LCOE** (without taxes)	**0.038 $/kWh**

NOTICE:

- Impact of maintenance costs
- Possible inverter changer after 15 year

Ultimate low cost PV

System costs	Very large field				
Module	0,11	$/W			
Inverter	0,03	$/W			
Work	0,08	$/W			
Fixtures	0,06	$/W			
Cables	0,03	$/W			
Land	0,02	$/W			
Permits	0	$/W			
Capex	**0,33**	**$/W**			
Performance					
Installed power	10	kWp			
Energy production	2000	kWh/kWp			
System performance decrease	0,5	%/year			
System lifetime	25	years (<200)			
Operation and maintenance					
Flat rate maintenance	1	%/year (capex)			
Financials					
Tax rate (on income - for IRR only)	0	%			
Incentive (one-off at investment)	0	$/Wp			
Energy price	0,050	$/kWh	**OR**	Interest rate	3 %
Internal return rate	**28,63**	**%**		**Nominal LCOE** (without taxes)	**0,0131 $/kWh**

Estimation for Agadir, Moroco
Fixed tilt, bifacial
3% interest rate

→
1.31 cts/kWh

In 2025 ultra low price possible

Cost of solar electricity

Important to remember

Solar modules as a raw material for energy production have become incredibly cheap

Standard c-Si modules at 21.5 % efficiency → 0.10-0.20 $/W
215 W/m^2 (Watt Peak) costs 21.5-45 $/m^2

1 W produces 1.0-1.3 kWh/year in CH (up to 30- 39 kWh in CH over 30 years)

The Direct LCOE costs of solar energy have become unbeatable in most countries in the world for new, large power plants, down to 1.3-4 cts/kWh possible, household in CH more 10 to 20 cts/kWh. 1.3 cts/kWh is 4 times cheaper than the dirtiest coal powerplant !

In 2021-2022 market disruption (covid, transport, Ukraine war …) leads to a price increase of all components. Price went down again (dramatically in 2024) because of large capacity increase in China

The improvements in PV technologies + the commitment to reduce CO2 emissions explain the strong growing PV market (> 375 GW new installation in 2023)

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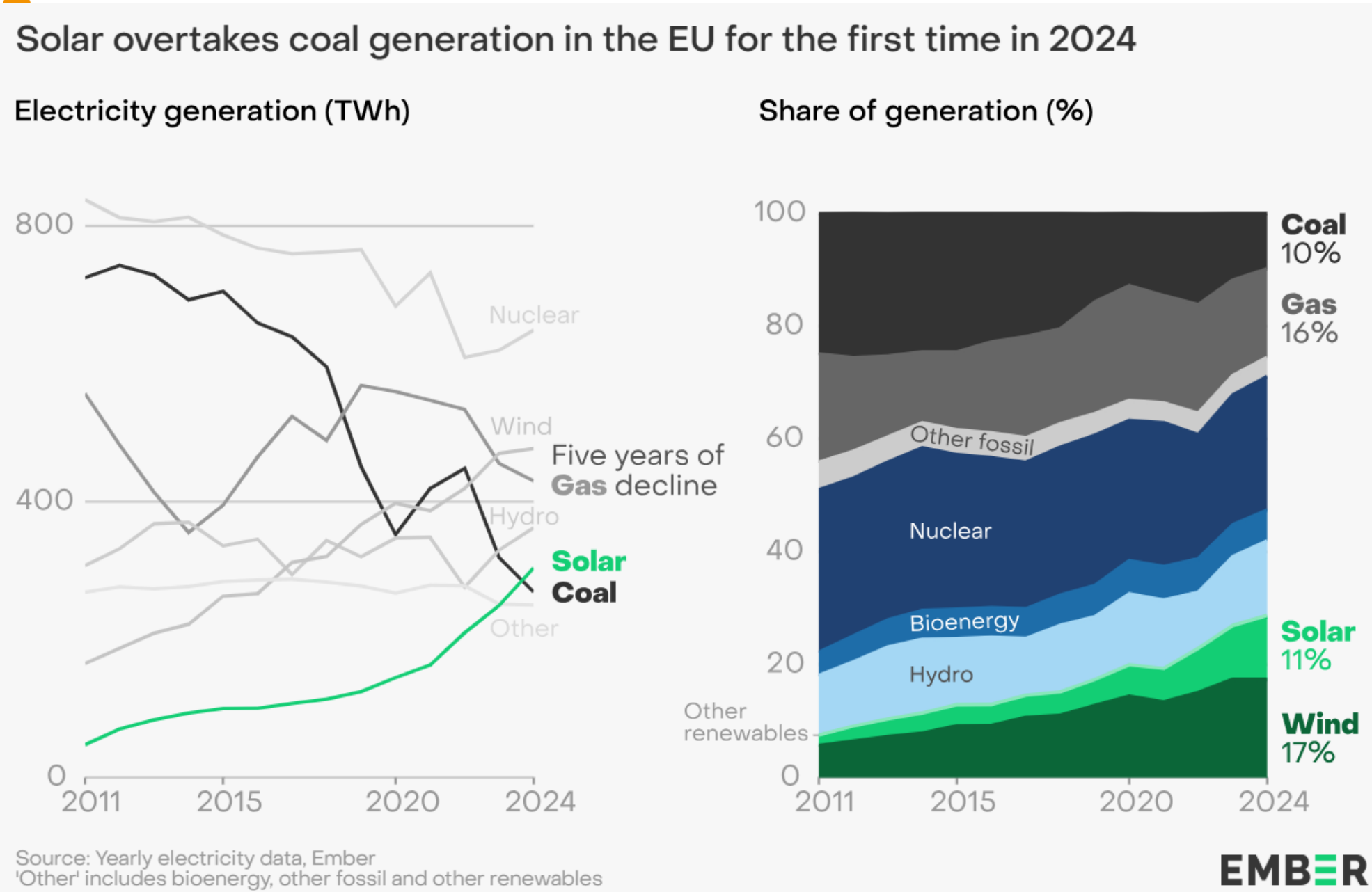
A positive note on renewable share in Europe Electricity mix

Prof. Christophe Ballif



2024: 28% from wind (17%) and solar (11%) in Europe up from 23% in 2022, and 1.5% in 2000.

Wind surpasses gas for the first time in 2023

Renewables > fossiles for electricity

4. Electricity market

How much do you pay a kWh?
At home?

a) 5 cts/kWh
b) 15 cts/kWh
c) 40 cts/kWh
d) 95 cts/kWh

On the EU market in early 2024 ?

a) 8 cts/kWh
b) 3 cts/kWh
c) 5 cts/kWh
d) 25 cts/kWh

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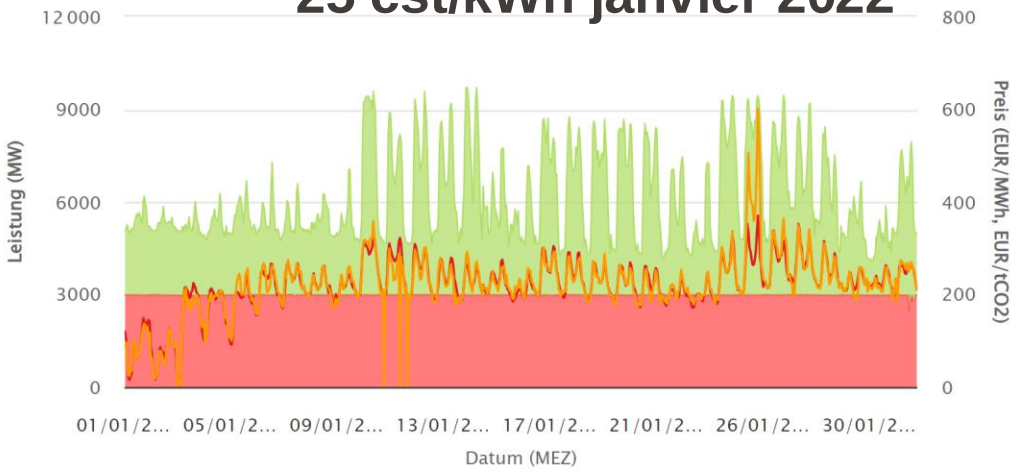
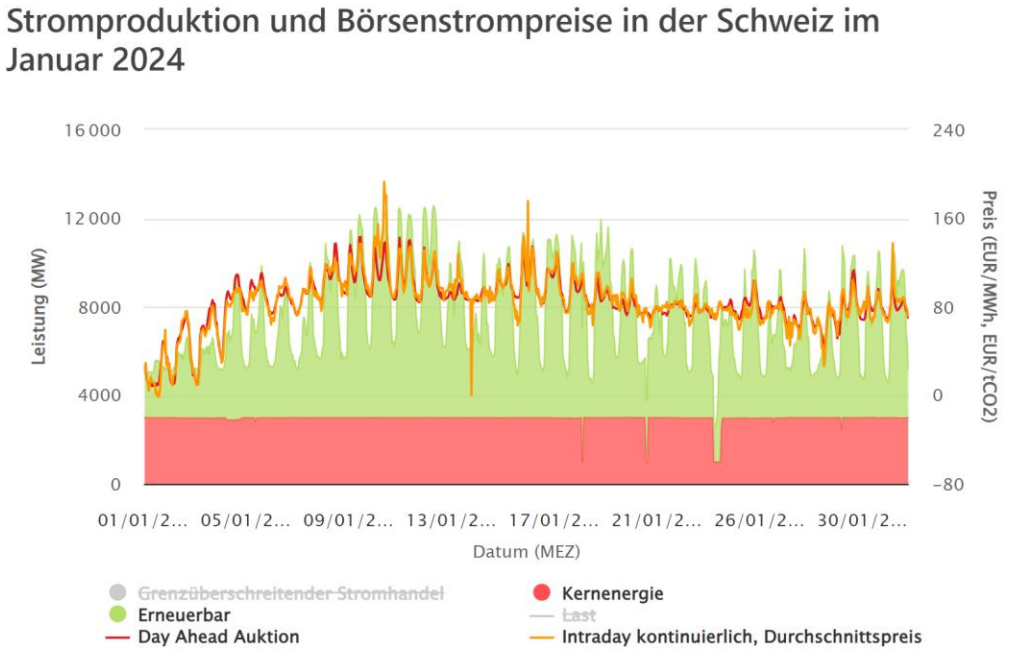
Börsenstrompreise | Energy-Charts

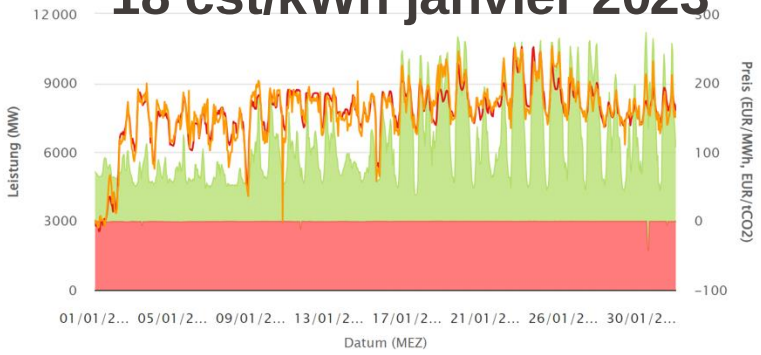
25 cst/kWh janvier 2022



10 cst/kWh janvier 2024

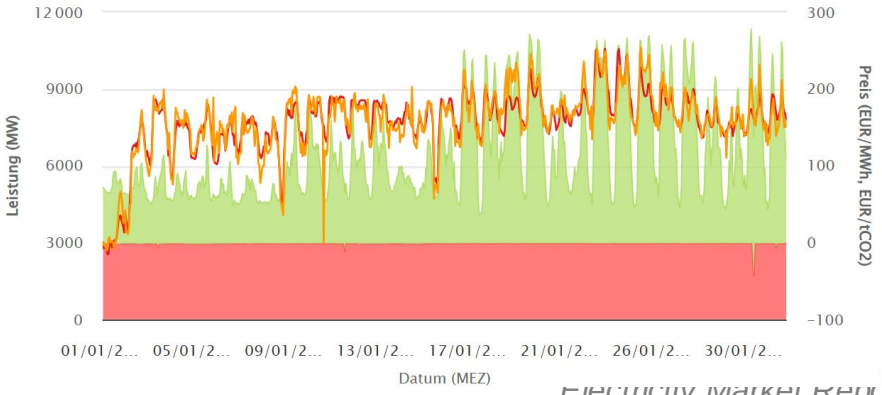


18 cst/kWh janvier 2023



Swiss spot price

17 cst/kWh janvier 2025



- Typical wholesale price 4-5 cts/kWh 2010-2019

Expected 7.5-10 cts/kWh in EU in the coming year

The risk and true challenges of PV as main option for energy transition

Prof. Dr. Christophe Ballif

- **PV reached Retail grid parity (what you buy at home or in your industry)** faster than expected in many places

Huge incentive to install, fostered by the Ukraine war and will for more independency.

- **Wholesale grid parity** reached in more and more countries

- **Grid-parity ambiguous concept**

  Real **value** of electricity? (e.g. if at noon there is too much solar and if there is no guaranteed price, then the business model fails)

- **Easy integration** of 10-15% PV electricity annualized in most countries, with no additional storage (but reducing the production of other sources

- **Changes required** for larger integration. Who pays, e.g. for grid reinforcement ? Or storage ? As will see storage comes big

The risk and true challenges of PV as main option for energy transition

Prof. Dr. Christophe Ballif

- In most cases, a suitable regulatory framework is still required for renewables (unless CO_2 is heavily taxed).
- The cost reduction in renewable (solar, wind) reduces the need for “strong” support or incentives and gives more freedom for “energy management
- Support can be: right for self-consumption, feed-in tarifs, auctions, power-purchase agreements, access to grid, contract for difference, …
- Proper anticipation for grid connection (long queues in some countries, storage, flexibility)

Prof. Dr. Christophe Ballif

TAIYANGNEWS
ALL ABOUT SOLAR POWER

TaiyangNews PV Price Index - from polysilicon to solar modules: CW 8 / 2025

		WoW (%)	MoM (%)	YtD (%)
Polysilicon RMB/kg (USD/kg)				
N-Type Silicon in China	42.0	0.0	0.0	3.7
Reusable Chinese 9N	35.0	0.0	0.0	0.0
Chinese 9N	34.0	0.0	0.0	0.0
Granular Silicon	39.0	0.0	0.0	5.4
Global (USD/kg)	20.0	0.0	0.0	0.0
Wafer RMB/piece				
p-type, 182 mm, 150 µm	1.08	0.0	0.0	0.0
p-type 210 mm, 150 µm	1.65	0.0	0.0	0.0
n-type 210 mm, 130 µm	1.55	0.0	0.0	6.9
n-type 182 mm, 130 µm	1.18	0.0	0.0	9.3
n-type 210R mm (130µm) (New)	1.30	-2.3	0.0	4.0
Cells RMB/W				
PERC bifacial - p-type, 182 mm	0.28	0.0	0.0	0.0
PERC bifacial - p-type, 210 mm	0.28	0.0	0.0	0.0
TOPCon - n-type, 182 mm	0.30	0.0	0.0	3.5
TOPCon - n-type, 210 mm (New)	0.30	0.0	0.0	1.7
Bifacial 210R TOPCon Cell (Above 24.3%) (New)	0.30	0.0	0.0	3.5
Modules RMB/W				
PERC monofacial - p-type, 182 mm (540-550W)/(420-495W)	0.65	0.0	0.0	0.0
PERC bifacial - p-type, 182 mm, 72 cells (540-550W)/(420-495W)	0.67	0.0	0.0	0.0
PERC bifacial - p-type, 210 mm, 55 cells (540-550W)	0.67	0.0	0.0	0.0
TOPCon bifacial - n-type, 182 mm, 72 cells (580-590W)	0.69	0.0	0.0	-1.4
TOPCon bifacial - n-type, 210 mm, 60 cells	0.69	0.0	0.0	-2.8
210mm HJT Module (615-635W)	0.75	0.0	0.0	0.0
Solar Glass RMB/m²				©TaiyangNews
3.2 mm	19.5	0.0	0.0	0.0
2.0 mm	12.0	0.0	0.0	0.0

The data was collected by Chinese market research firm Gessey Information Technology Co. Ltd. More details about prices from individual companies and analysis is available for paid subscription from Gessey (pvpriceindex@gessey.info).
Disclaimer: TaiyangNews does not guarantee reliability, accuracy or completeness of this price index' content. TaiyangNews does not accept responsibility or liability for any errors in this work.

Which role for PV in the energy transition ?

Scenarios and models needed

- Take into account all sources of energy as well as demand (but not always flexibility)
- Sector coupling
- Industry needs
- Difference between what should happen ideally, what might happen and what will happen (e.g. countries pledges)

Large variations in models depending on :

- Who writes/makes the scenario (with sometimes a lack of knowledge or non realistic assumptions)
- How you consider storage/hydrogen/power to gas/industrial heat (trend to emphase power-to-gas)

In particular, if a lot of hydrogen is considered, it needs typically 3-4 times more electricity (because of losses in the transformation) for the same service as direct electricity usage. The less hydrogen and the more intelligence and flexibility the better !

Integration of large fraction of PV in mid term vision of a mostly electrified world

Bulk energy
- Combination with wind → «high annual capacity factor»
- + hydro + nuclear
- + geothermal + …

long term management (days to weeks/month)

Security
- Peak electricity from waste/biomass
- Maintain fossile reserve assets operational (e.g. 300 GW gas powerplant in Europe 1000 TWh Gas storage)
- Emergency generators
- Long-term Power-to-gas (H2, NH3,..)

Support with flexibility
- Large industries with contracts
- Cooling/heating needs
- Electric charging
- Hydro

Tens of GW In + or -

Short term management (second to days) + intelligence

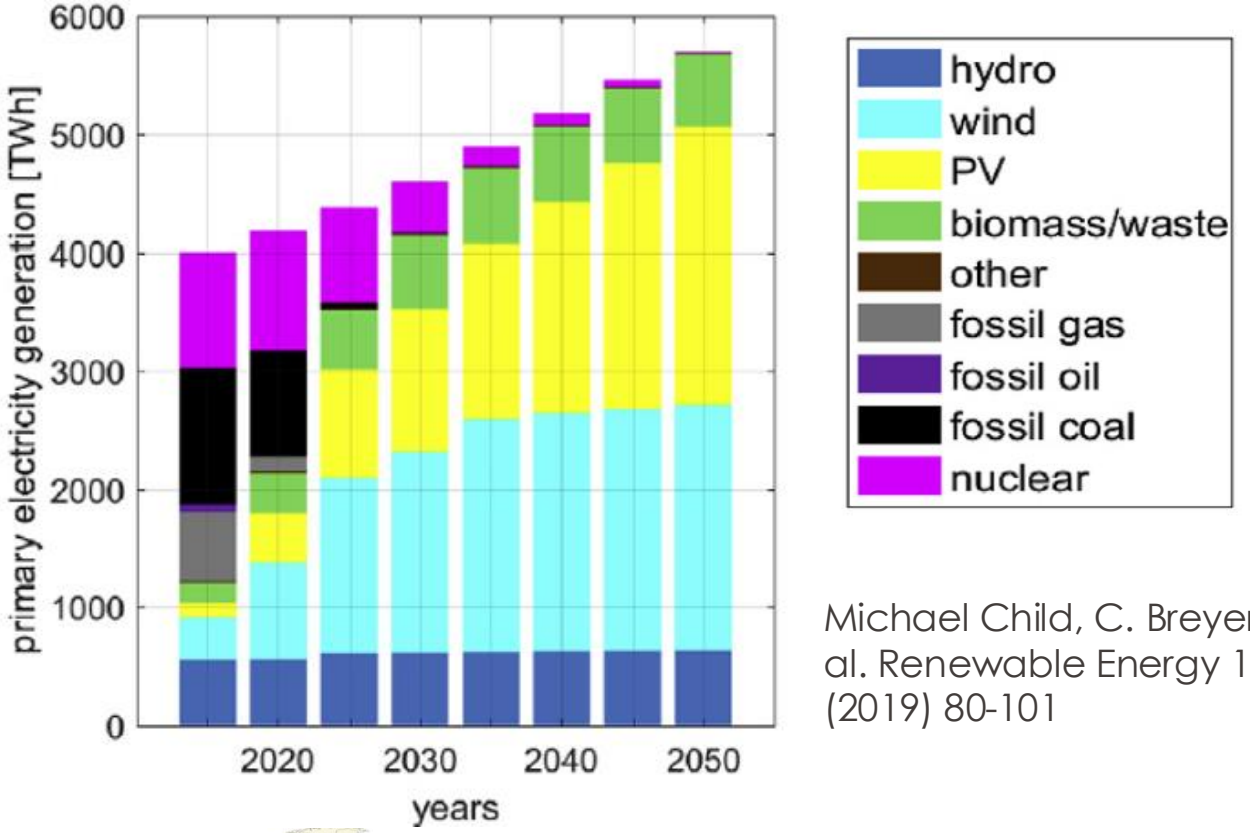
Grid support
- Curtailement (cut excess PV)
- Battery storage
- Pumped-hydro
- Grid reinforcement (!)

- **Ideal complement: hot water storage from summer to winter)… don't go back to electric**

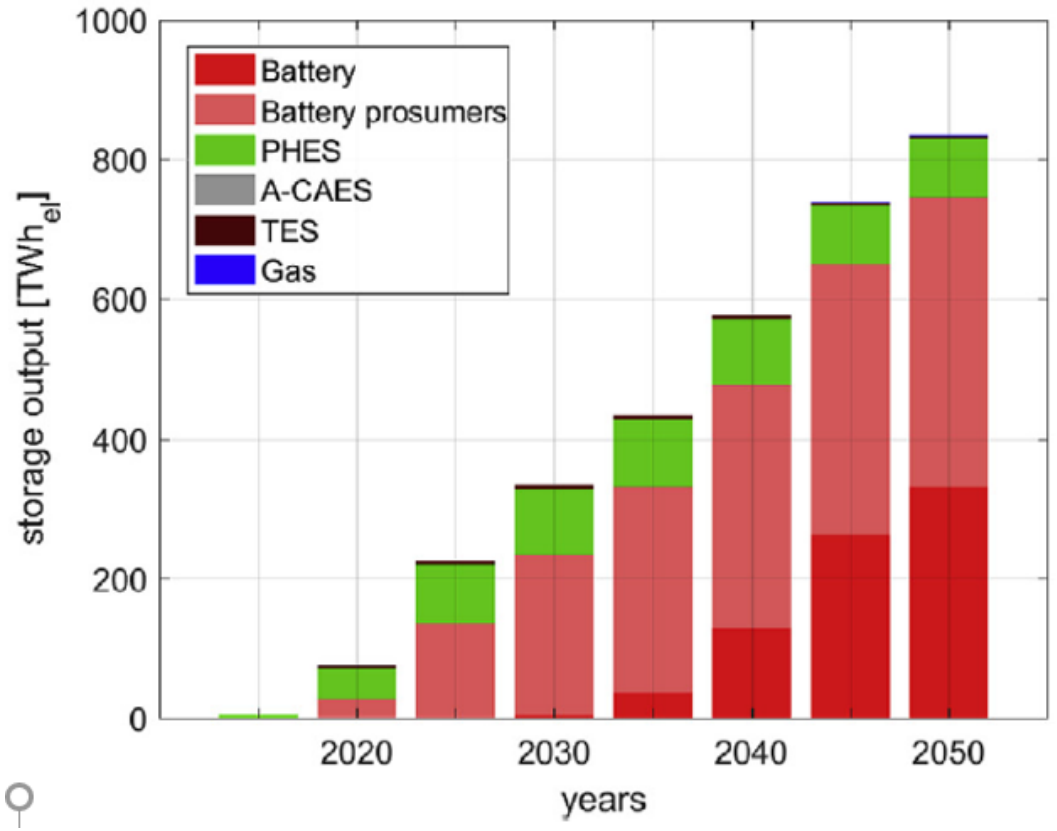
A short look at Europe

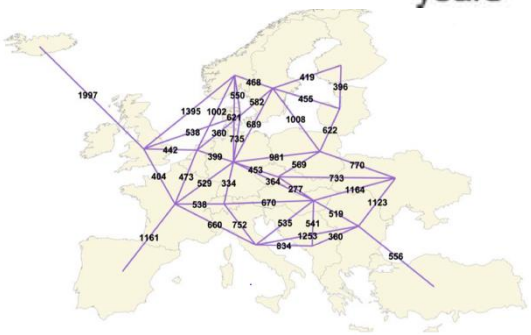
PV-lab IMT NEUCHATEL

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

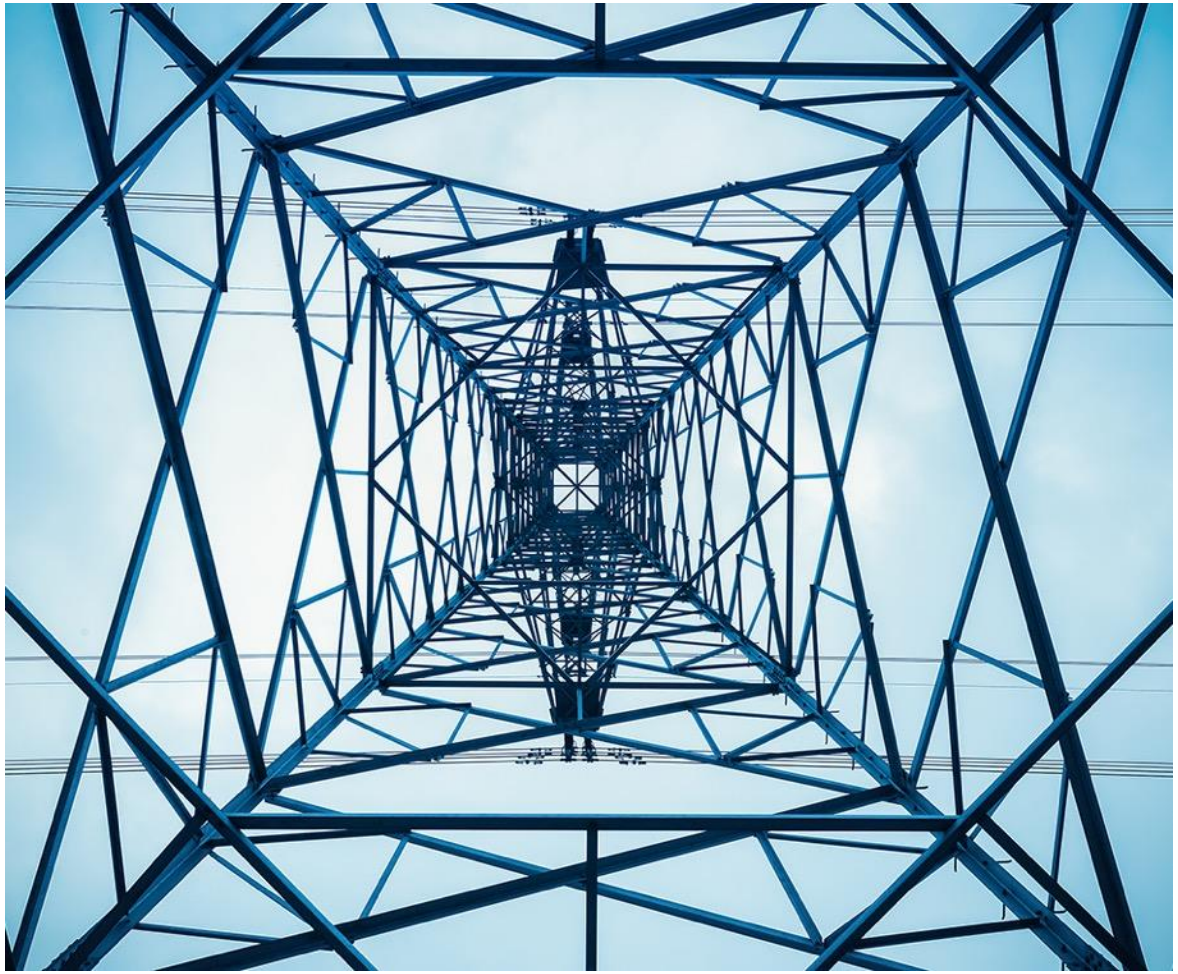




In Europe: good complementarity between wind and sun on a monthly base. System stable on an hourly base thanks to storage

Battery storage and pumped hydro necessary to balance the grid on hourly bases → Overall cheaper cost per kWh (6-7 cts/kWh)

With massive wind and solar, European grid can be balanced on an hourly/weekly basis but short-term storage (batteries mostly and pump storage) required



A complete world scenario with 63 TW of PV for 2050

D. Bogdanov, M. Ram, A. Aghahosseini et al. Energy 227 (2021) 120467

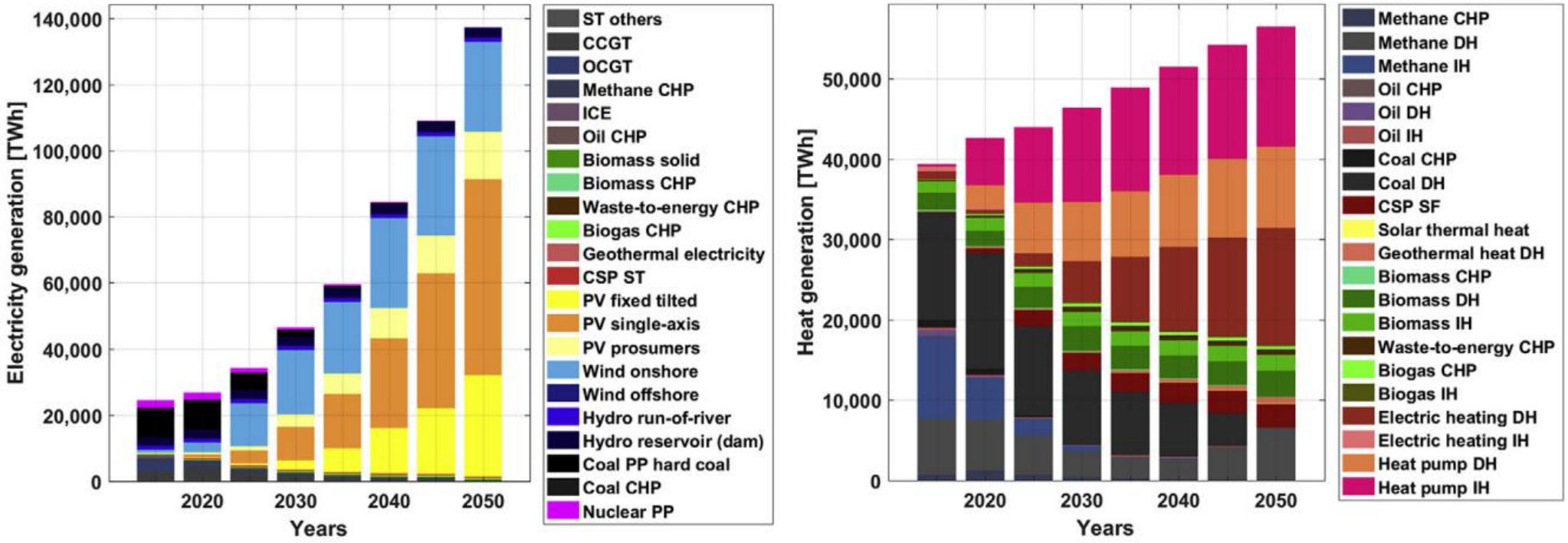


Fig. 2. Global – Technology-wise electricity generation (left) and technology-wise heat generation (right) during the energy transition from 2015 to 2050.

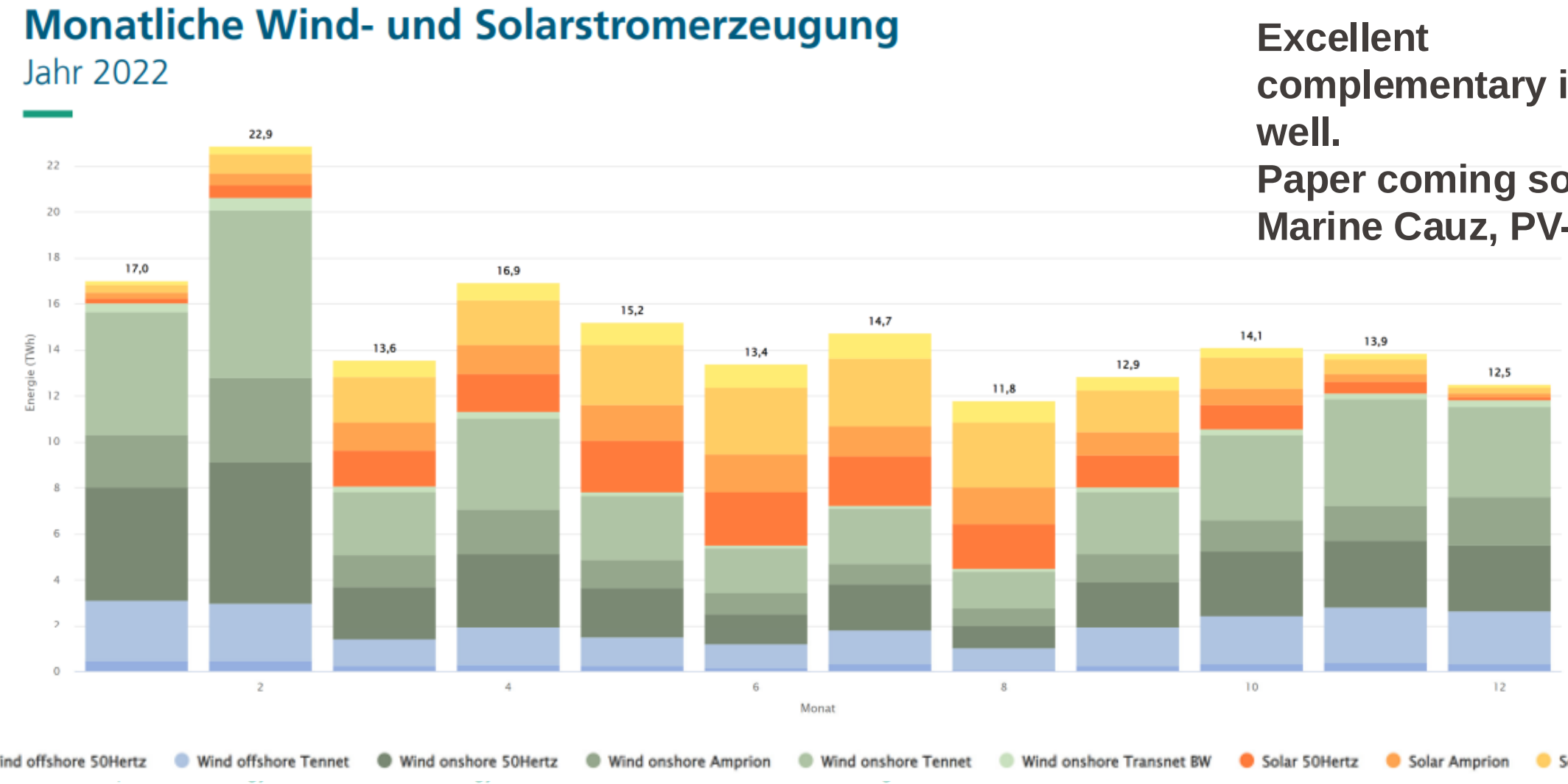
Because of its low LCOE, PV tends to grow in share in such scenario, which reserves more space for Power-to-gas

Low-cost renewable electricity as the key driver of the global energy transition towards sustainability - ScienceDirect

Prof. Dr. Christophe Ballif

Electricity market

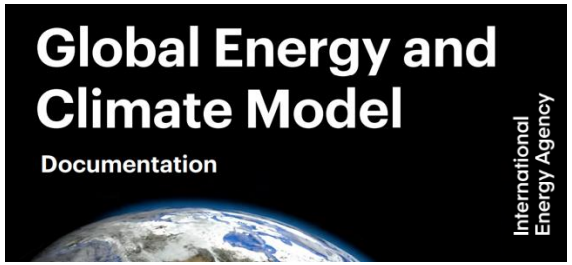
Wind vs. PV : a good complementarity winter-summer in Europe, CH, and Germany



Excellent complementary in CH as well.
Paper coming soon by Marine Cauz, PV-lab !

Electricity generation from wind and solar PV in Germany in 2022. Chart by Fraunhofer ISE, 2022.

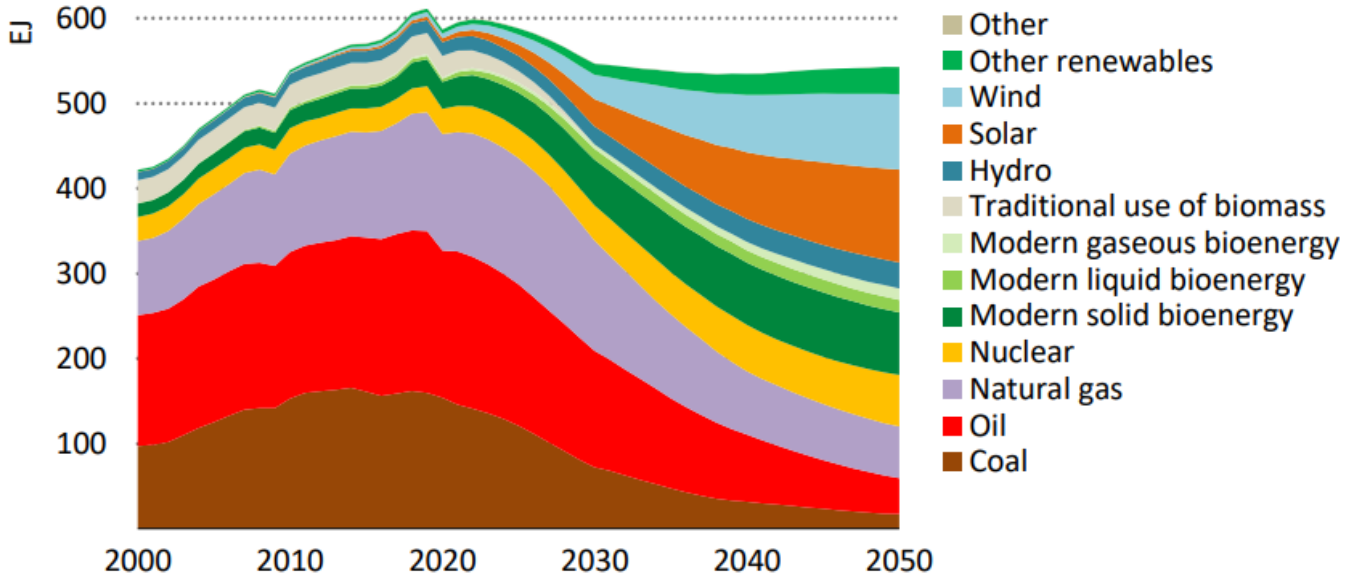
The IEA scenarios



[Global Energy and Climate Model Documentation (windows.net)]

[Net Zero by 2050 - A Roadmap for the Global Energy Sector (windows.net)]

Figure 2.5 ▷ Total energy supply in the NZE (net zero emission)



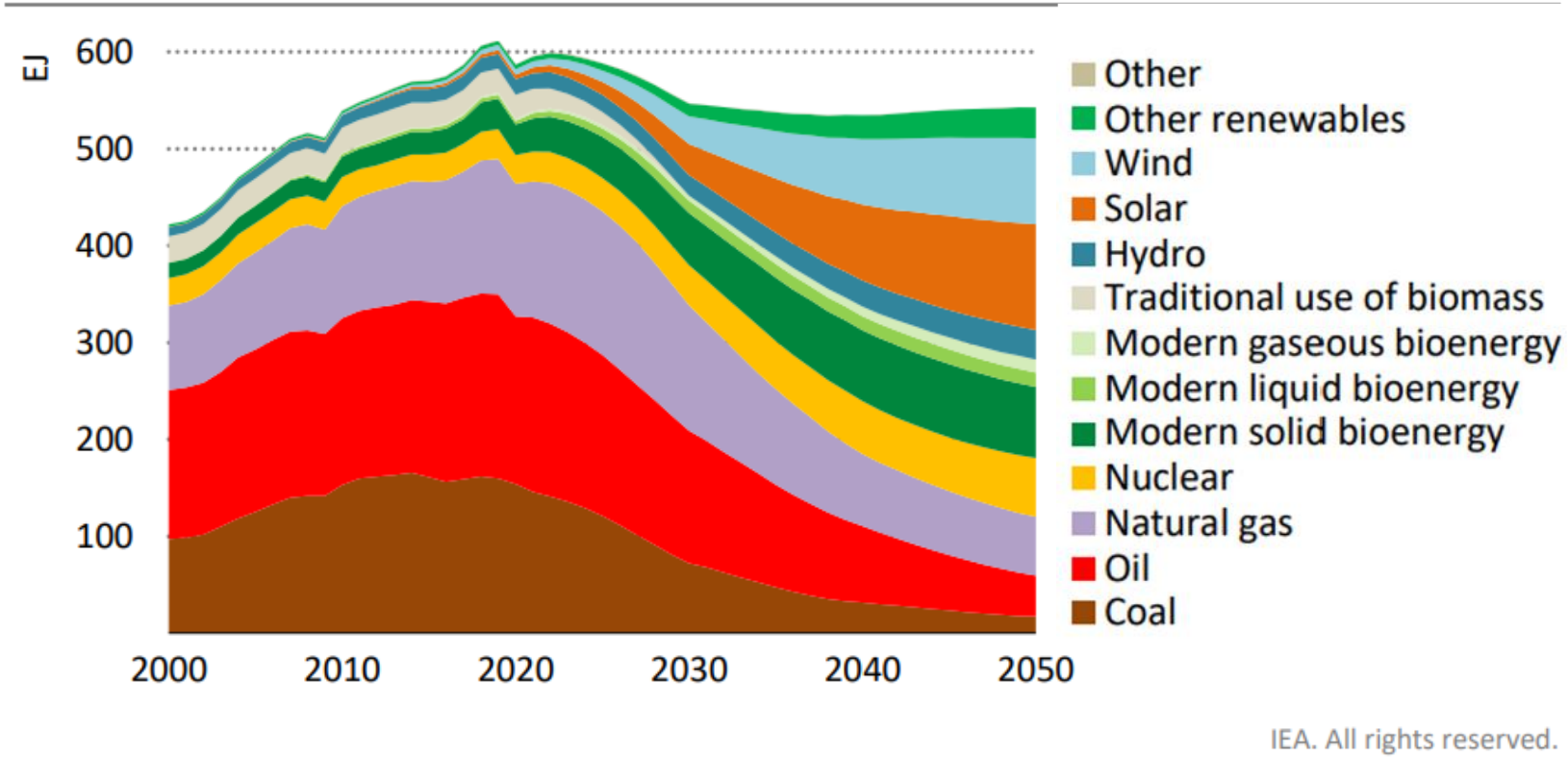
Renewables and nuclear power displace most fossil fuel use in the NZE, and the share of fossil fuels falls from 80% in 2020 to just over 20% in 2050

The 2021 NZE scenario of IEA also relis on new renewable. But it also bets on carbon sequestration to compensate for fossiles emissions, and a significant amount of bioenergy.

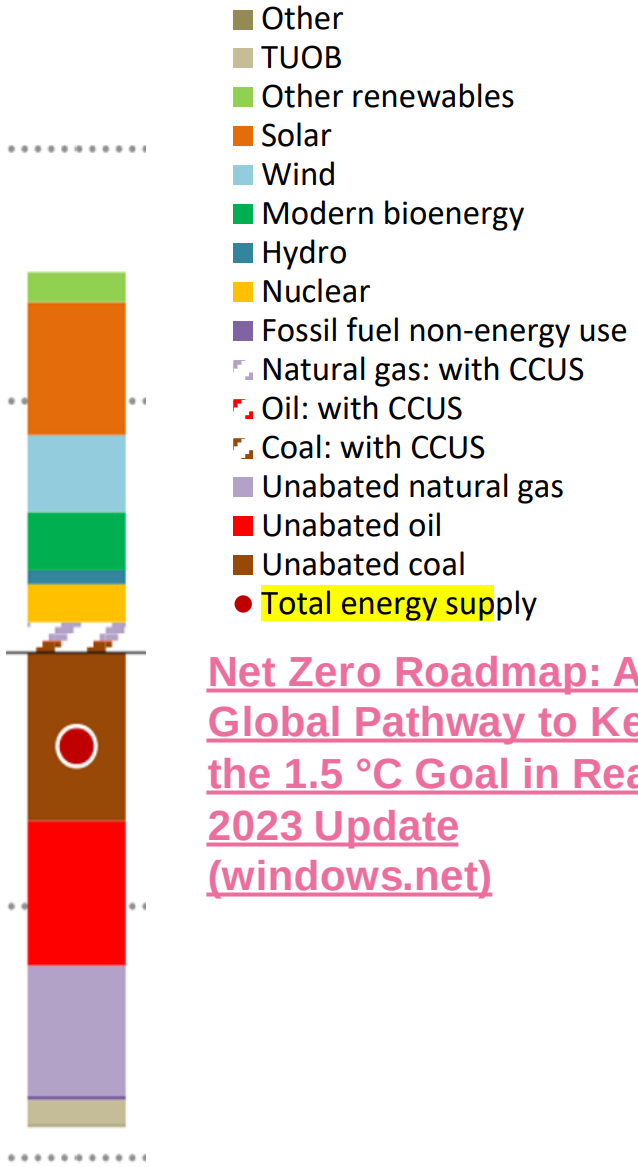
Note on IEA data: kWh of wind, hydro solar counted directly (not muliplied by 2.5 as in BP reports). The thermal kWh for all thermal source counted as such (including for nuclear). The NZE 2021 would mean around 30'000 TWh solar, 27'000 TWh wind by 2050, Nuclear ~ 4300 TWh (from 2700 today)

The IEA scenarios

Figure 2.5 ▷ Total energy supply in the NZE 2021 scenario



(net zero emission) 2023 scenario: changes compared to to today



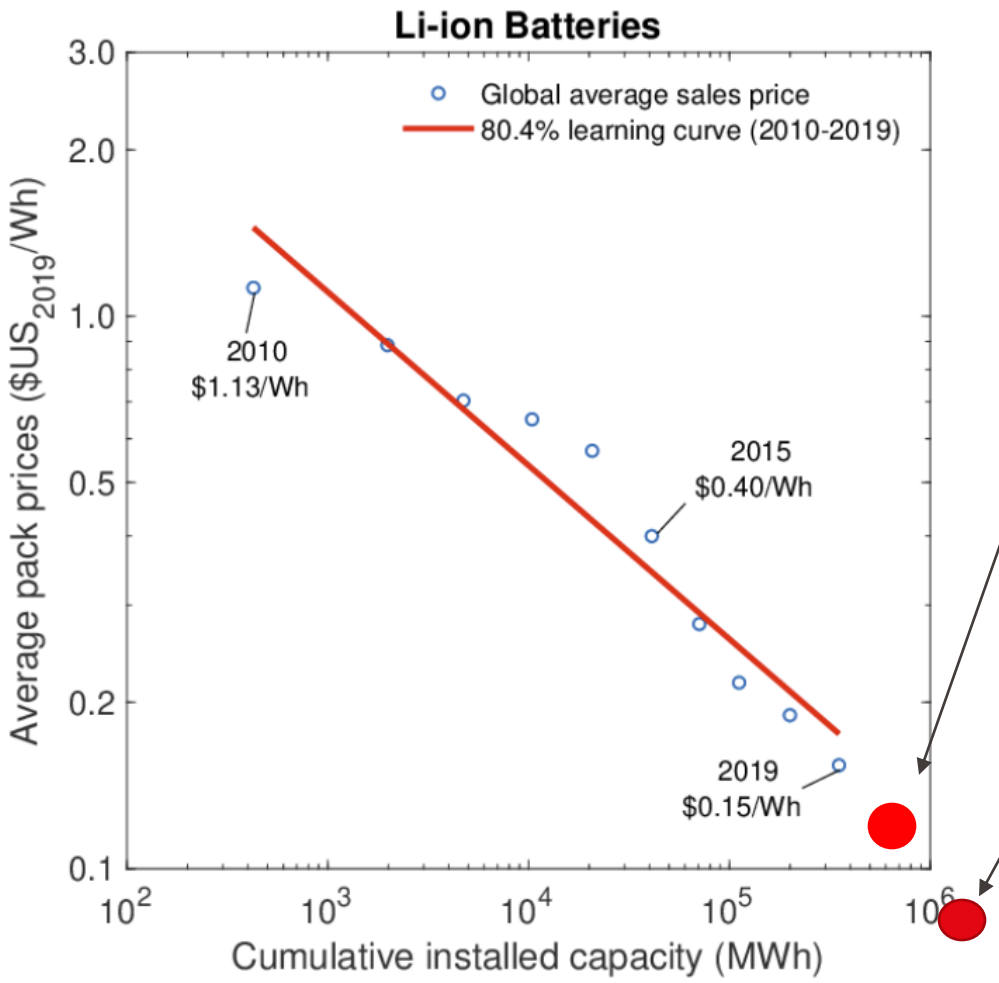
The 2023 Net zero scenario of IEA sees much less carbon squesestration and much more solar, and more nuclear. (almost 30% increase in PV compared to 2021 scenario → around 39'000 TWh PV….).

[Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach - 2023 Update (windows.net)]

Storage stimulated by the automotive market

Prof. Dr. Christophe Ballif

Automotive Battery learning curve



Cost Dynamics of Clean Energy Technologies, Glenk et al.

Today automotive battery pack at 120-150 $ /kWh

"We expect the price of an average battery pack to be around $94/kWh by 2024 and $62/kWh by 2030"

Bloomberg NEF (before the Ukraine War)

Tesla announcements/and today's cell price….

Note: some stationnary batteries can have different chemistry and be slightly more expensive (more material) but with more cycles. Large car batteries Can be used in second life for stationnary storage

Batteries are already the cheapest way To cover short term (up to minutes) peak demand in $/W

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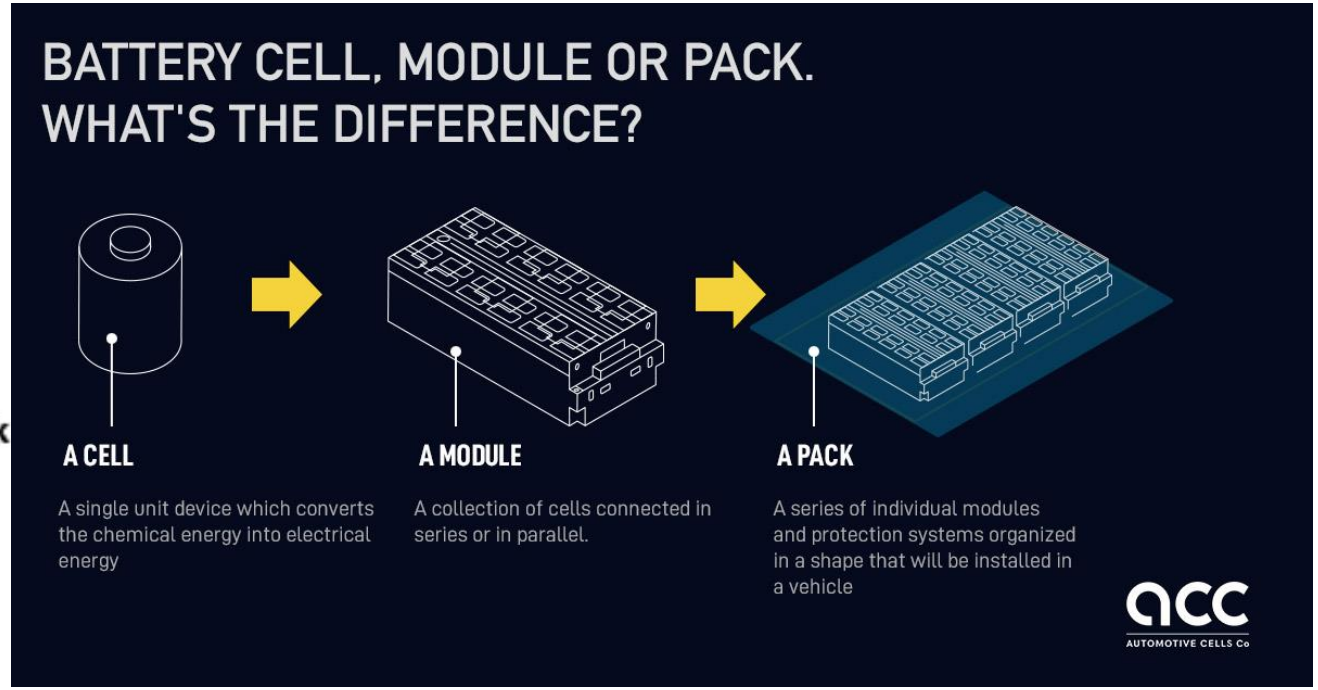
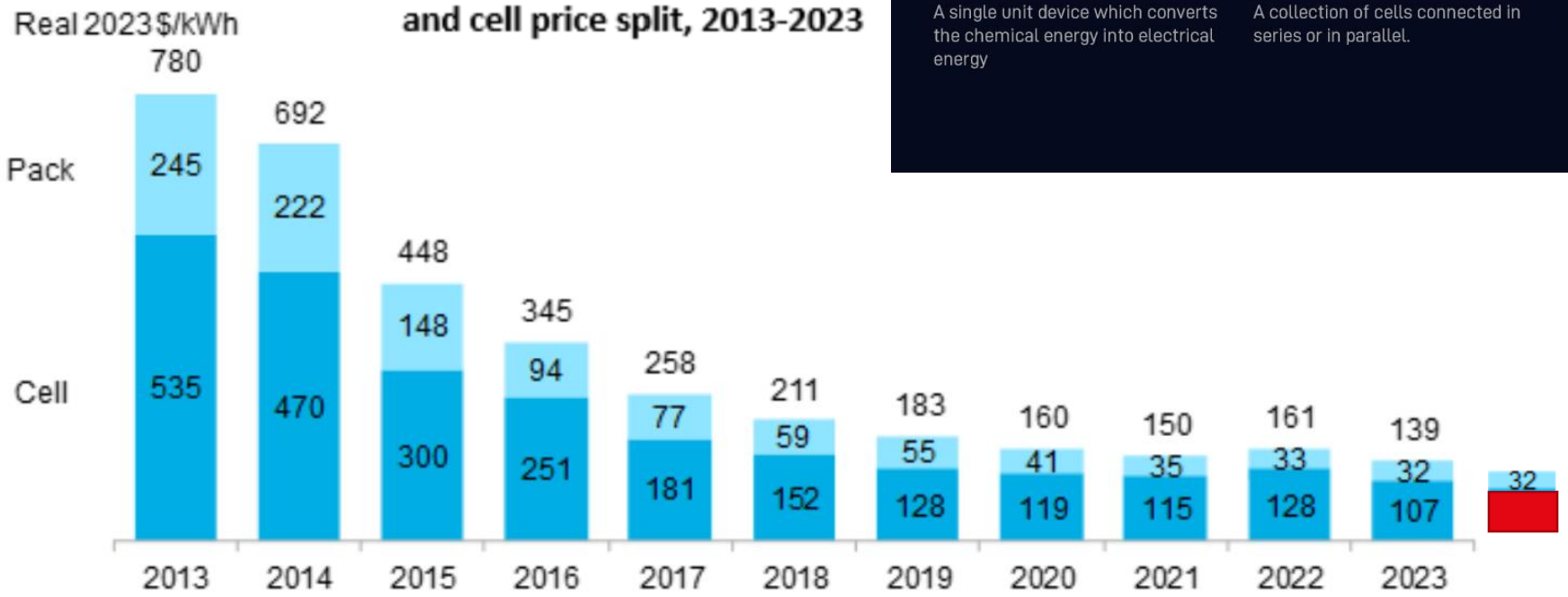


Figure 1: Volume-weighted average lithium-ion battery pack and cell price split, 2013-2023



Source: BloombergNEF. Historical prices have been updated to reflect real 2023 dollars. Weighted average survey value includes 303 data points from passenger cars, buses, commercial vehicles, and stationary storage.

Storage

Several tens of new companies/products are developing storage solutions, mostly based on batteries

Home storage
Possible Vehicle to Grid

… MW

> 20’000 cycles
with Li-titanates of Leclanché

Currently many wind and solar parks installed with 1 to 2 hours storage (at ~300$/kWh all included). PV and Wind becomes «dispatchable)
means an extra 7-10 cts/kWh stored

Small storage systems (typ 10 kWh) are expensive in Switzerland, in the range of 600-1000 CHF/kWh,… Makes currently little economic sense (25-33 cts/kWh stored)

A near-midterm goal 100 US$/kWh of storage capacity over 5000 cycles →
~ 2-3 cts additional per kWh stored on a PV system.

Batteries

- Due to large increase in investement in China, huge capacity in place

- 4800 GWh by end 2025 of battery manufacturing (enough for e.g. 100 Millions cars battery).

→Price war and lower battery costs

2025: Cells down at 50 $/kWh, new packs at below 100$/kWh,

And DC storage system at 145 $/kWh or much below

Courtesy of CATL

CATL, BYD To Slash Battery Prices By 50% In 2024. BOOM! EVs Win!

1 week ago Steve Hanley 65 Comments

Dutch developer Lion Storage planning 1.5GWh BESS for 2026 operation

By Cameron Murray

February 19, 2024

Europe Grid Scale Business

LinkedIn Twitter Reddit Facebook Email

A render of the project in North Netherlands. Image: Lion Storage via Linkedin

Battery energy storage system (BESS) project developer Lion Storage is planning a 364MW/1,457MWh project in the Netherlands for operation in two years' time.

Netherlands: Lion Storage planning 1.5GWh battery project (energy-storage.news)

The Edwards & Sanborn solar-plus-storage project in California is now fully online, with 875MWdc of solar PV and 3,287MWh

Masdar, EWEC announce 5 GW/19 GWh solar-plus-storage project in Abu Dhabi

Masdar and Emirates Water and Electricity Co. (EWEC) plan to build a $6 billion, 5 GW/19 GWh solar-plus-storage project in Abu Dhabi, with operations set to start by 2027.

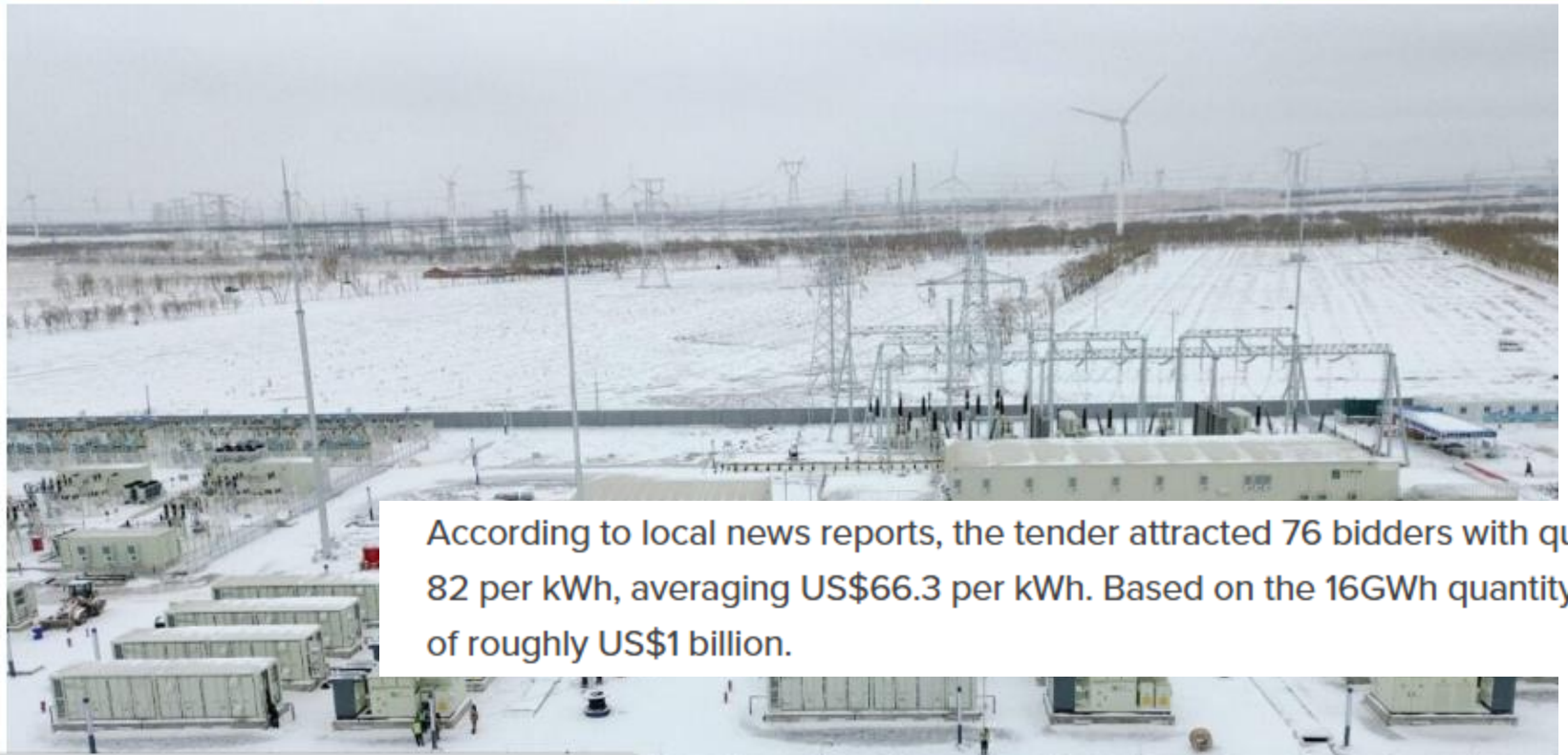
JANUARY 14, 2025 BLATHNAID O'DEA

‘Mind-blowing’ bids in Power China’s 16GWh BESS tender as state-owned firms squeeze market share

By Cameron Murray

December 19, 2024

Asia & Oceania, Central & East Asia | Grid Scale | Market Analysis, Business, Materials & Production



According to local news reports, the tender attracted 76 bidders with quoted prices ranging from US$60-82 per kWh, averaging US$66.3 per kWh. Based on the 16GWh quantity, that implies a total contract value of roughly US$1 billion.

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Mid-long term expected development by 2030

Cost of solar components will stabilise at 9-12 cts/Wp, electronics at 2-3 cts/Wp , efficiency will likely reach 24-25% at module level. In all parts of the world, solar park producing electricity at 1 to 2.5 cts/kWh.

Possibilities:

- **NH3 economy from H2 + Haber Bosch process (easier to liquefy and transport) for fertiliser and later energy (navigation first, then retransform to H)**
- Long distance electricity HV-DC supply
- H_2 economy (direct hydrolysis) hydrogen (strong current EU Push)
- CH_4 (natural gas) economy by H_2 hydrolysis + combination with CO_2 (closed cycle or from CO_2 direct air capture), or H_2 with Liquid Organic carrier

Strong EU and worlwide inniative for green hydrogen (but beware… : Cost of transport, compressors, and management/storage often understimated: not all announced hydrogen project will take place)

Hydeal Espana: starting now (?)
Production starting in 2025 with 9,5 GW solar and 7,4 GW electrolysers by 2030. Cost of H_2 including transport and storage < 1.5€/kg

www.hydeal.com
www.dh2energy.com

https://www.dh2energy.com/project-hydeal

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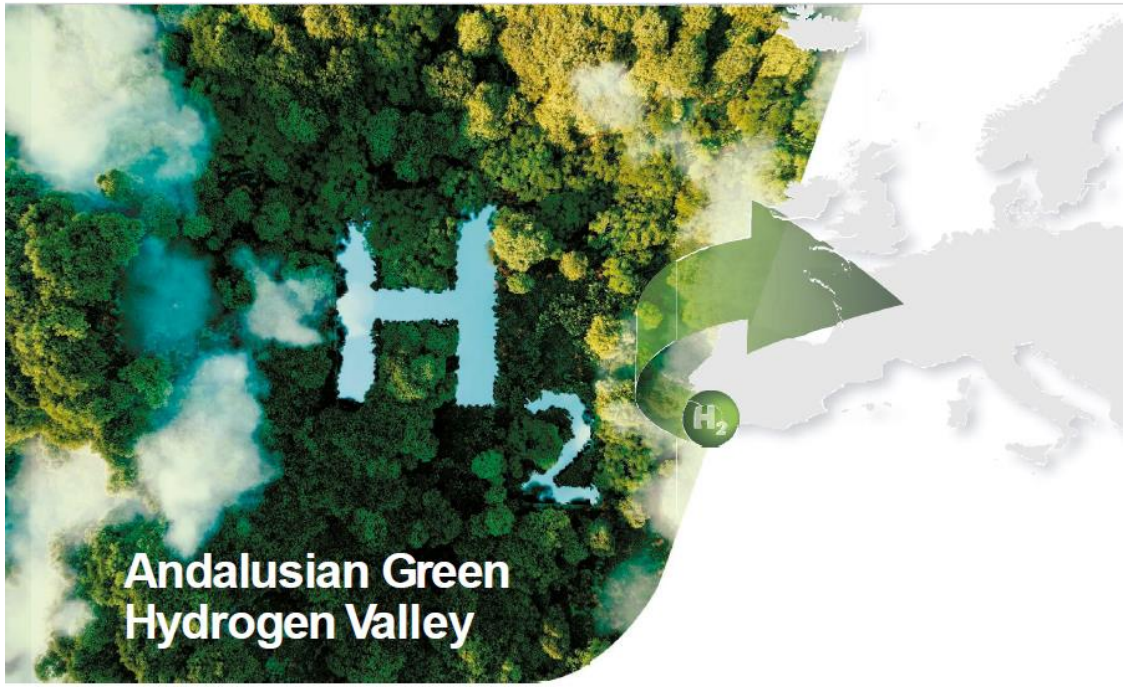
HIVE HYDROGEN AND GENESIS ECO-ENERGY DEVELOPMENTS SIGN WIND POWER AGREEMENT FOR $5.8BN COEGA GREEN AMMONIA PLANT

February 27, 2024



Cepsa launches Europe's largest green hydrogen project in Andalusia

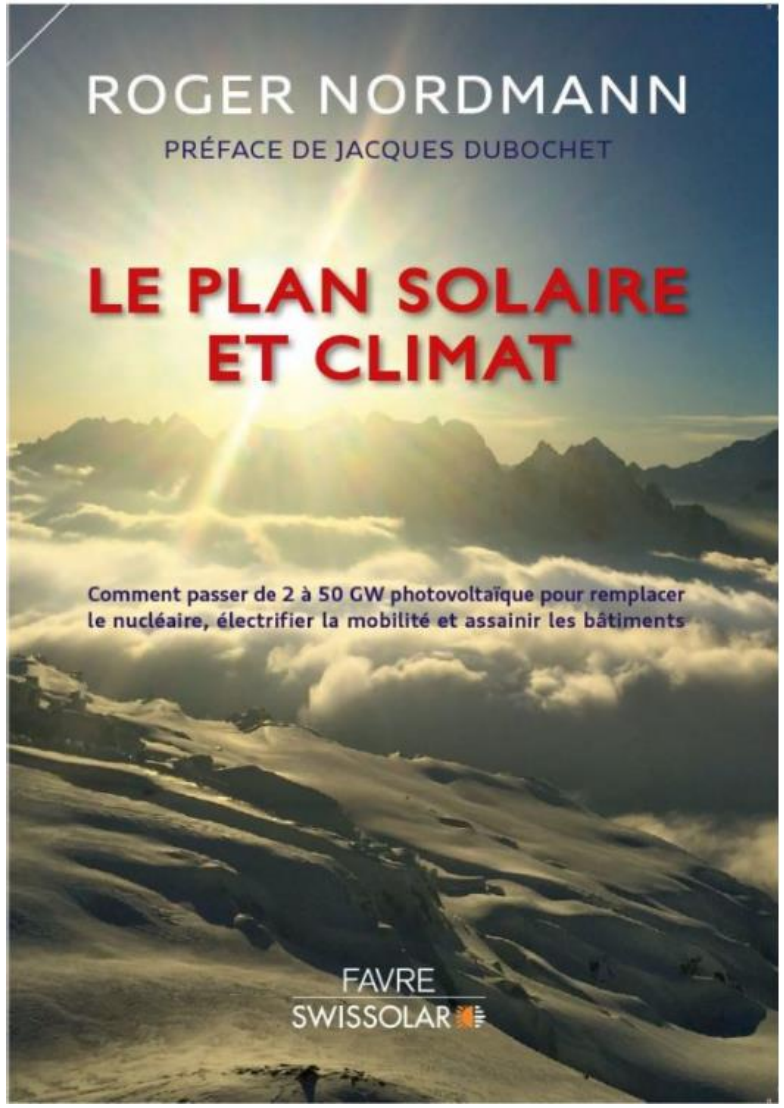
CEPSA

[**'Chinese are catching up technologically' | Longi's new hydrogen electrolyser is more efficient than almost anything made in the West | Hydrogen news and intelligence (hydrogeninsight.com)**]

Ultra-low cost electrolysers
Down to 250-300 $/kW from China
With ~70-75% Efficiency

PV Market: the Swiss case

What it really takes to decarbonize? The example of Switzerland: the various scenarios



Scenario for a partially decarbonised Switzerland: Typically 50 GW (by 2050) PV, working in conjunction with hydro + wind (~ 5-7TWh) + biomass (e.g. distance heat, biogas)

- Efficiency
- Electric cars
- Heat-pumps

→ 86-100% CO_2 reduction

Keeps CO_2 emissions for 9 TWh winter (not enough solar), e.g. gas power plant
or use H_2 (import or local), or produce/import wind electricity or alpine solar electricity.

Upsides: More hydro, delay dam emptying, more solar in high altitude, more wind……

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OBJECTIF D'UNE SUISSE NEUTRE POUR LE CLIMAT EN 2050

Study
Of Swiss
Federal office
For Energy
26.11.2020

37 GW PV
For 9 millions
people
By 2050
(n.b. 50 GW in
Nordman
scenario)

Now 45 TWh
new renewable
in gov plan for
2045.

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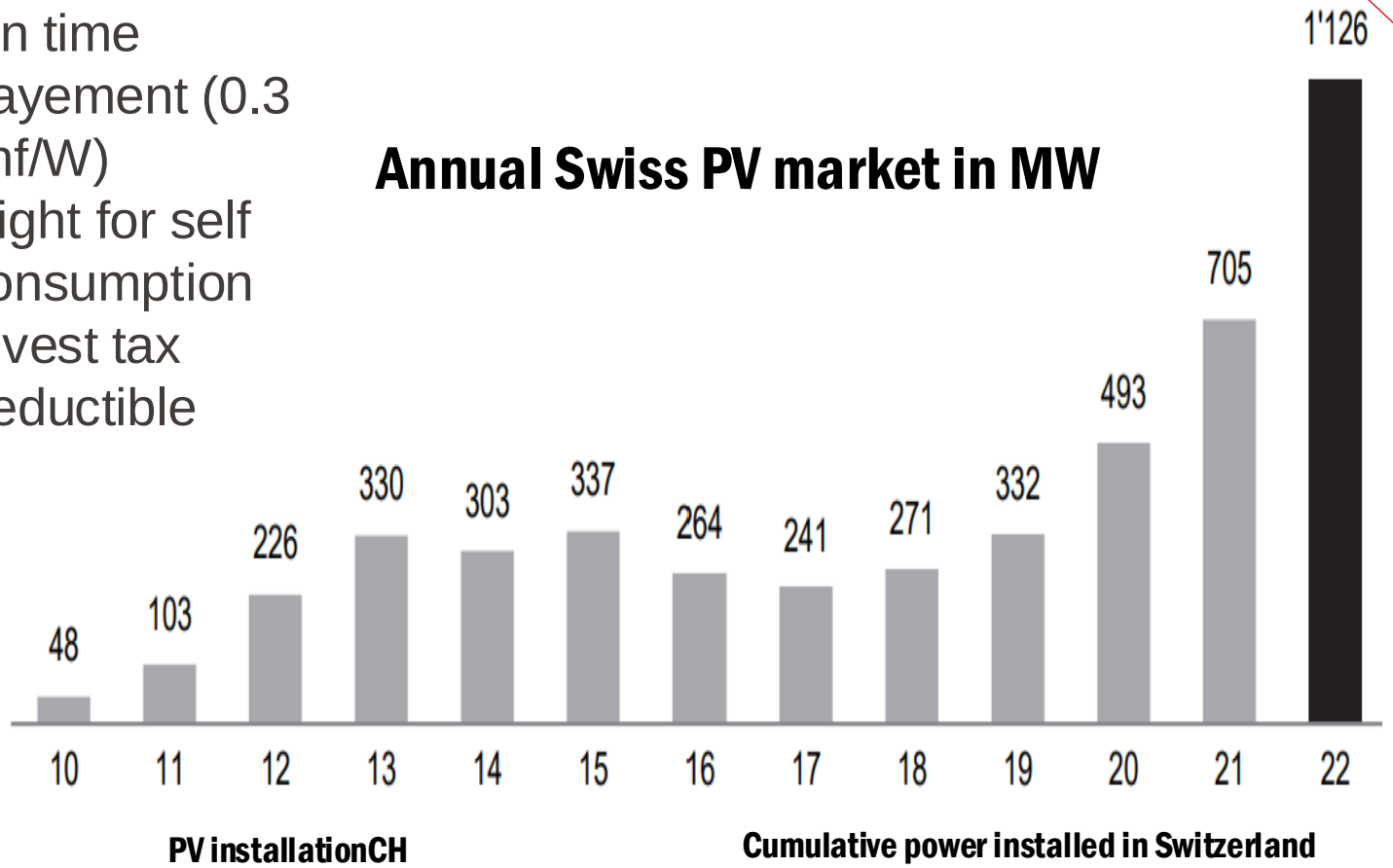
PV Market

End 2023: 6 GW installed
~10 % of annual CH electricity consumption of 2024

Currently support:
- On time payement (0.3 chf/W)
- Right for self consumption
- Invest tax deductible

Est. 1.5 GW 2023



2023 - 2045

Min > 1.7 GW year

For scenarios with 50 GW solar

* Including renewal

Orders of magnitudes starts to be ok !

Source: Swissolar/internal data

PV Market

A macroeconomic reason why you need to shift to renewables

Importation of 50 GW of solar pannels

(30 years of energy) → 7 Billions CHF

=

1 years of fossile fuels import

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Conclusions

PV as a main way of decarbonization

If mankind is serious about global warming,
PV can/will be a major way to decarbonize…

Rich Coal/Oil/Gas Lobbies and related media/politicians

- Increase world PV module production to at least 1-1.5 TW annual by 2030 (x 10 vs 2020)
- → min 40 TW installed by 2050 → at least 60’000 TWh

Reminder:

- 2023 world electricity production of ~ 29’500 TWh
- World primary energy consumption in 2023: 172’000 TWh

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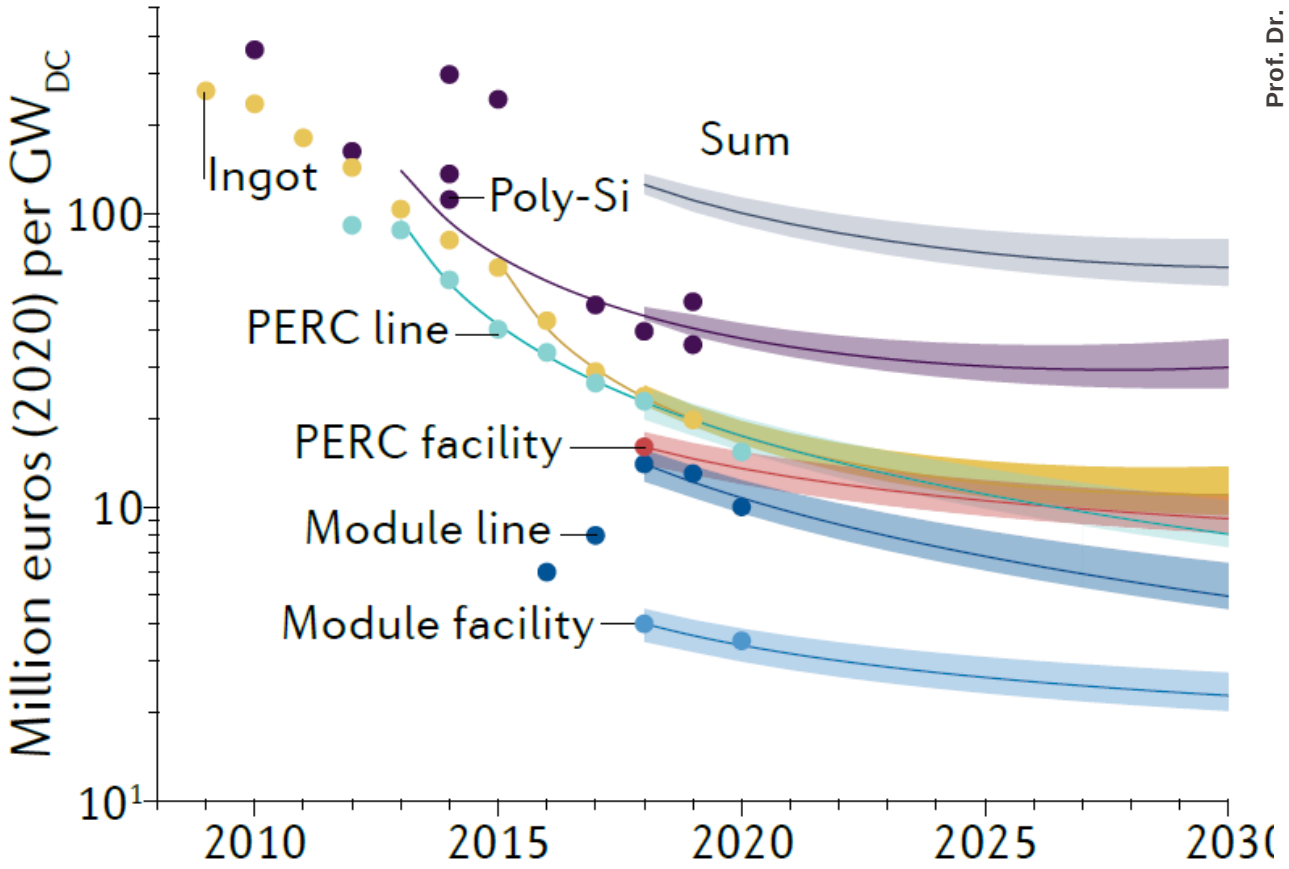
Capital investment costs for 1.5 TW annual PV module production

Prof. Dr. Christophe Ballif

- How much does it cost to put in place 1.5 TW of production ? (from sand to modules): with recent «CAPEX» decrease (china based equipment)
- 120 M€/GW → 180 billions € or 18 billions € per year over 10 years
- With 18 billions €/year*, all production could be in place to provide > ½ of the world energy by 2050



* Globally, fossil fuel subsidies were $5.9 trillion in 2020

231. Altermatt, P. P. et al. in Proceedings of the 38th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC, 2021).

And do you know what ??

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- China has done it during COVID

Bringing capacity to 1400 GW for 2024 ….

During the 3 years of COVID, chinese companies have invested massively in

PV, batteries, electric cars and Wind.

In PV close to 1400 GW of production capacity are online (500 GW PERC, 800 GW topcon, 100 GW SHJ and IBC.

For batteries, soon capacity for 4800 GWh (100 millions car per year equivalent).

Ultra-harsh competition,
Overcapacity (factor 2.5 to 3 for 2024)

PV at 12cts
Battery cell at 70$/kWh
Windturbine at 40 cts/W
Inverters at 3cts/W
Electrolysers systems at 30 cts/W


扬州已实现
Yangzhou has achieved travel times of
• 到南京 1 小时 (驾车)
• 到深圳 2 小时 (飞机)
• 扬州泰州国际机场累计开通
• 到上海 1 小时 (高铁)
• 到北京 4 小时 (高铁)
主导产业 / Leading Industrie
扬州已发展形成 6 大主导产业集群
新能源
NEW ENERGY
新材料
NEW MATERIALS

Perspective for PV

- Ultra-low price should make the market dynamic !
  2024 could see much more installation than IEA predicts

- Expectation to reach 1 TW annual module production by 2028 to 2030

- So PV seems on its way and, and with support of wind and hydro CO_2 emssion should peak in 2024-2025…..

- PV and wind will be particularly well suited for the future for

1. Desalination of waters
2. Direct air capture of CO2 (n.b. first we stop emitting, then we start making direct air capture)

World Energy Outlook 2022 (windows.net)

Fighting global warming: «what should happen» globally

- **Develop massively wind and solar**

Other sources: biomass, hydro, geothermal

Maintain (or develop) nuclear base to facilitate transition

Keep and optimise fossile fuel assets for flexibility (but low capacity factor)

Capitalise on electrochemical storage (batteries) and synergies with mobility

Necessary amount of power-to-gas… (industry, heat, peak power). Keep small !

Keep biofuels mostly for peaks, air and maritime transport where difficult to replace

Agriculture

Sequestration through biomass and soils

Less cattle emitting CO_2

Strategy

Local production (including of energy products)

Ressources (metals, lithium, …)

Manpower: educate, prioritize and pay better

Intelligence: control and flexibility of energy systems

- **Energy efficiency**

Switch to electrical (transport, heat pumps)

Isolate building

Track losses (ventilation pumps),…

Sufficiency

Rethink consumption (smaller room, no flight, no read meat)

Accept less in critical period (e.g. lower heating T of buildings)

Long term: Sequestrate carbon (from the air)

Quiz

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Question 1

Assuming a PV power plants gives 2kWh/Wp (annually) with initial investment of 0.4 €/Wp (possible today) and no maintenance required. The cost of capital is 0%. If the system lifetime is 30 years, the direct price of solar electricity would be:

a) 0.66 €cts/kWh
b) 6.6 €cts/kWh
c) It depends on the module efficiency

Question 2

Assuming that gas power plants costs nothing, no running costs and that gas costs 20€/MWh (chemical energy).

a) Gas from electricity produced with a 58% efficient gas power plant is the lowest in price
b) Is more expensive than solar of question a

Question 3

1m^2 of a 21% chines modules typically costs in 2024

a) 30 CHF
b) 90 CHF
c) 120 CHF

Appendix (only for info)

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A good read for the week-end and a quick upgrade to crystalline silicon technologies

REVIEWS

NATURE REVIEWS | MATERIALS

Check for updates

Status and perspectives of crystalline silicon photovoltaics in research and industry

Christophe Ballif[1] ✉, *Franz-Josef Haug*[1], *Mathieu Boccard*[1], *Pierre J. Verlinden*[2,3,4,5] *and Giso Hahn*[6]

Abstract | Crystalline silicon (c-Si) photovoltaics has long been considered energy intensive and costly. Over the past decades, spectacular improvements along the manufacturing chain

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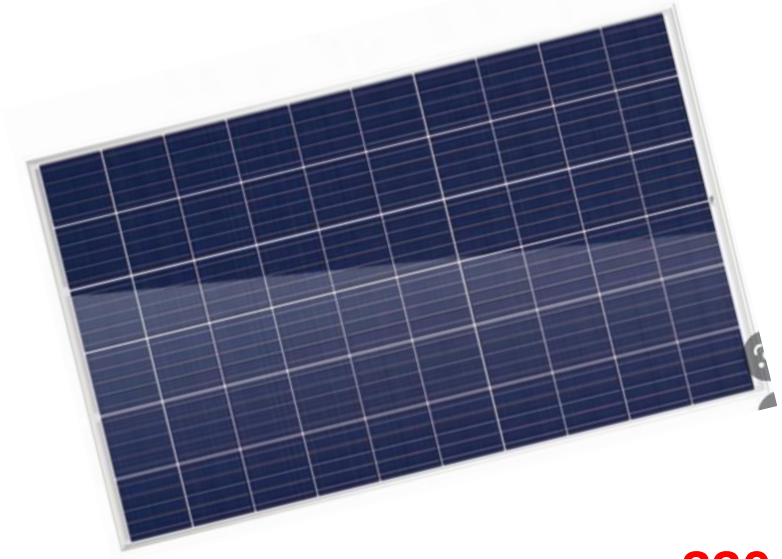

At constant size, the power output of modules is constantly increasing

For 6 inches cells

60 cells modules

Optimised cells / smart wire

260 W
270 W
280 W
290 W
300 W
310 W
320 W
330 W
340 W
350 W
360 W
370 W

Al-BSF
PERC
Adv PERC
PERT
SHJ
Pass
cont
IBC

30
Zone
ENDS

29.4%
limit

c-Si
19-20%

C-Si PERC
20-23%

Heterojunction
Pass. Contacts
24-26%

IBC
24-27%

Cell effiency
Usually 2-3% higher (abs) than module efficiency

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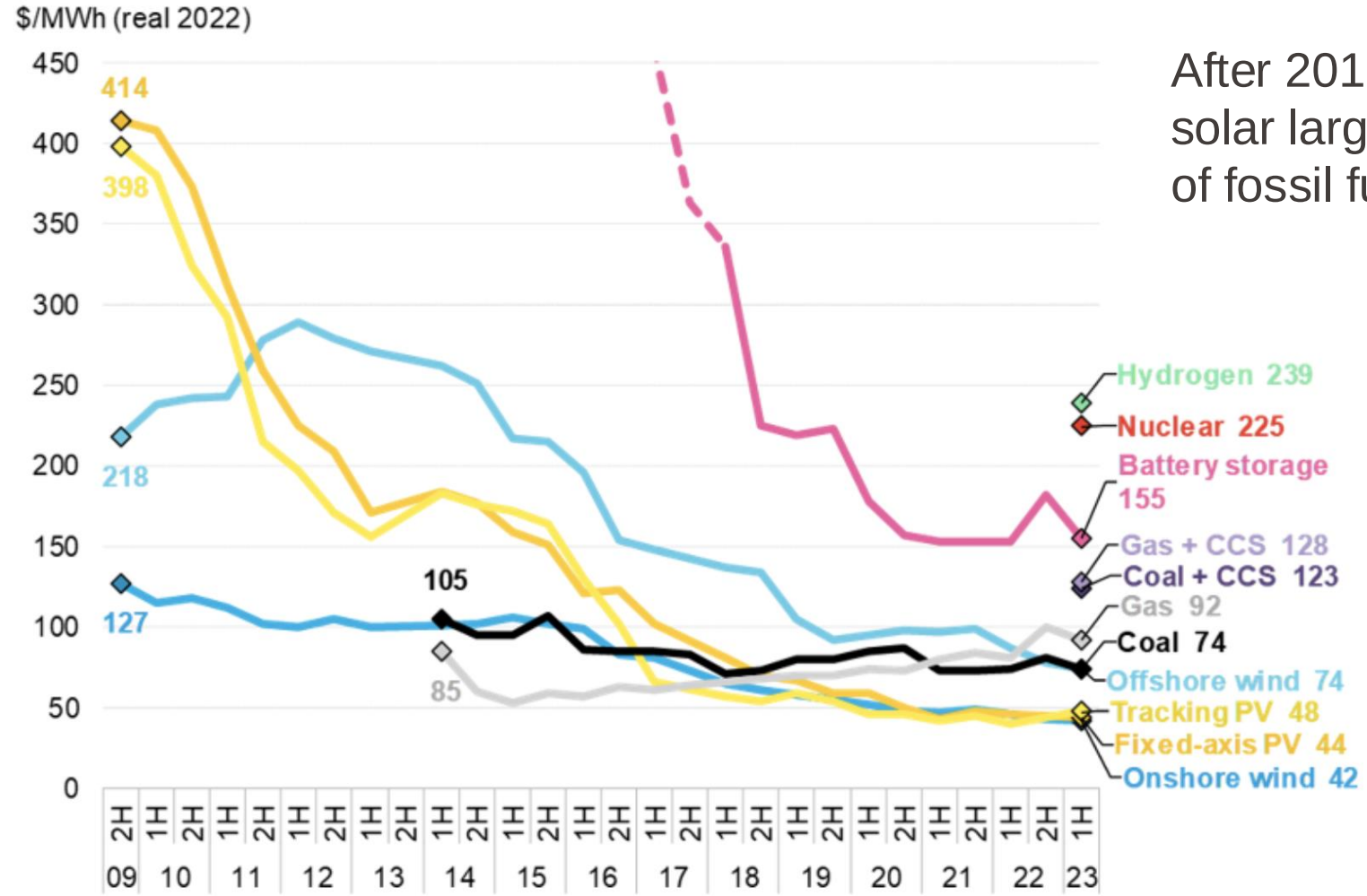
Cost of electricity

UPDATED

Drop in generation costs of renewables from 2009 to 2023 1H

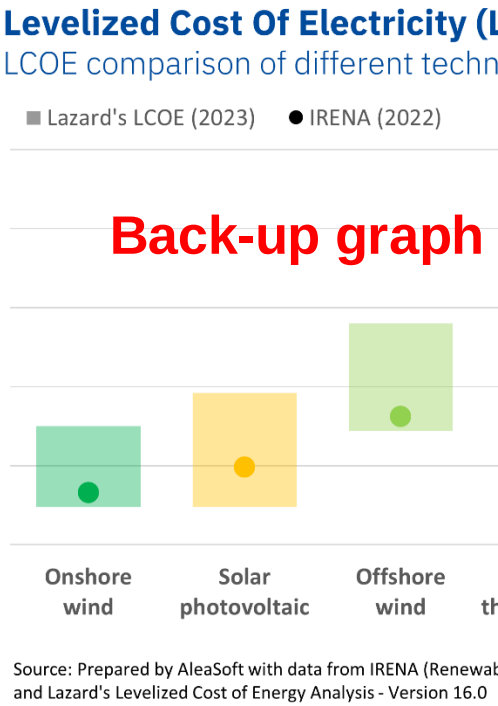
Figure 1: Global levelized cost of electricity benchmarks, 2009-2023



After 2017-2018 – on-shore wind and solar large parks are well below LCOE of fossil fuels !

FOSSIL FUEL COST RANGE

Back-up graph



BNEF, 2023

Electricity market

Other markets: a growing number of consumers

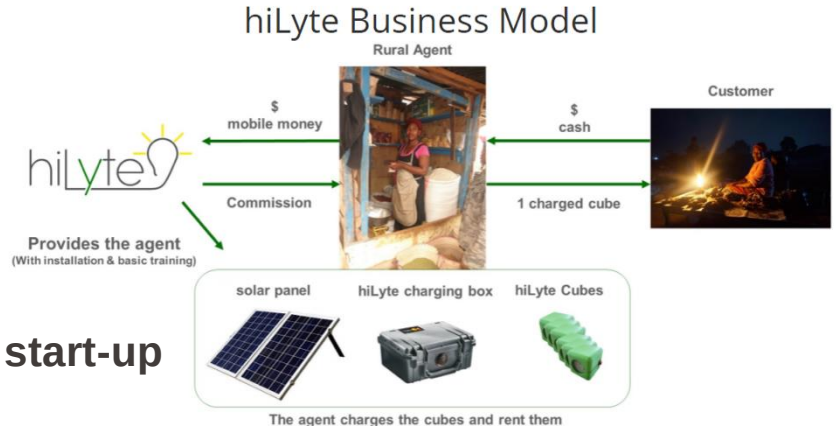
4 million solar products sold by members of the Global Off-grid Lighting Association (GOGLA) in the second half of 2015.

2 millions in Sub-Saharan Africa.

+ Micro-credit
+ Smart Phone payments

"Caterpillar Takes Equity Stake In Africa Microgrid Company Powerhive"

Microcity start-up Hilyte



Electricity market

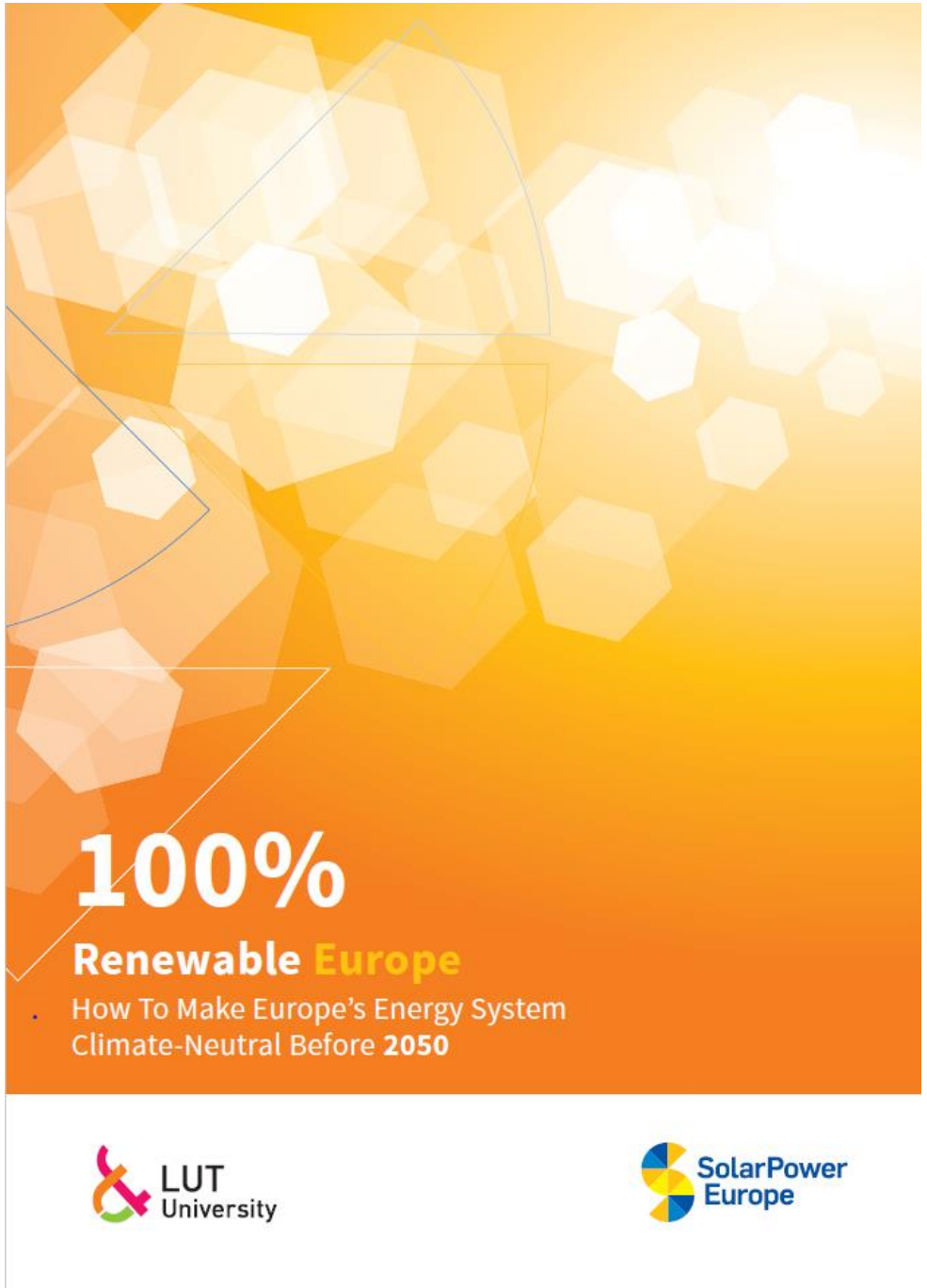
Further impact of low cost PV

- Substituting diesel generator (make a kWh at 30-40 cts)
- Small autonomous light/computer electricity management
- Autonomous region
- Etc.

enerwhere New business models in UAE

Prof. Dr. Christophe Ballif

One full scale European Scenario[100]



- Solar
- Wind
- Hydrogen
- Electrochemical storage
- Electric cars
- Heat pumps
- Biomass

100% Renewable Europe study - SolarPower Europe

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FIGURE 3.9 ELECTRICITY GENERATION

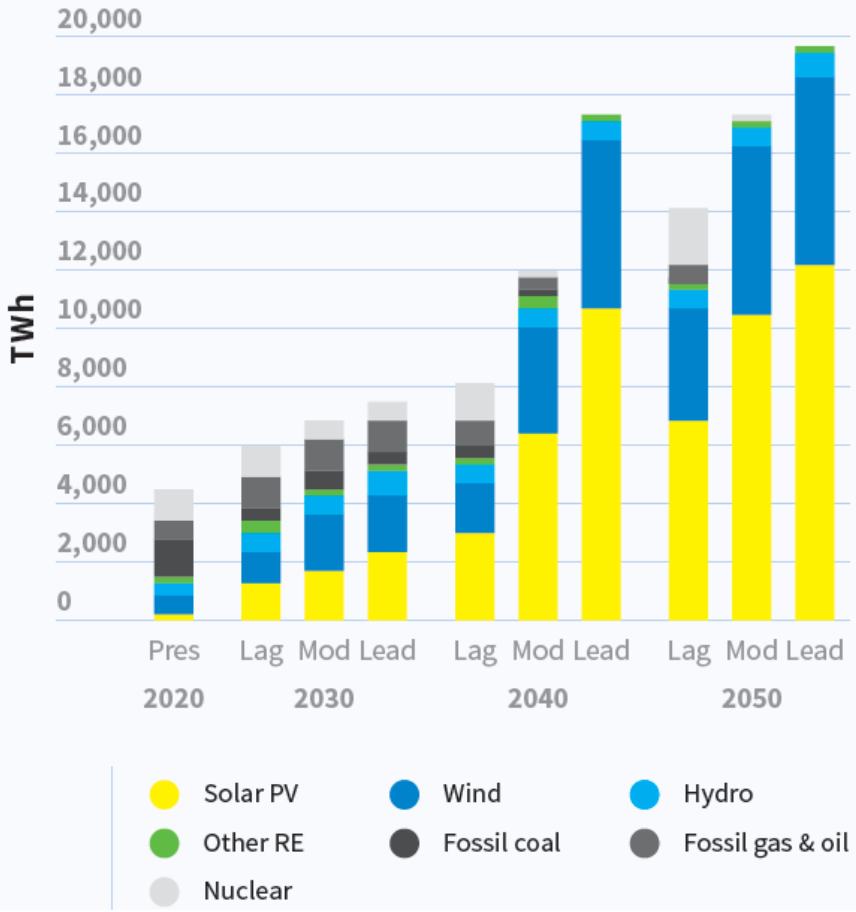
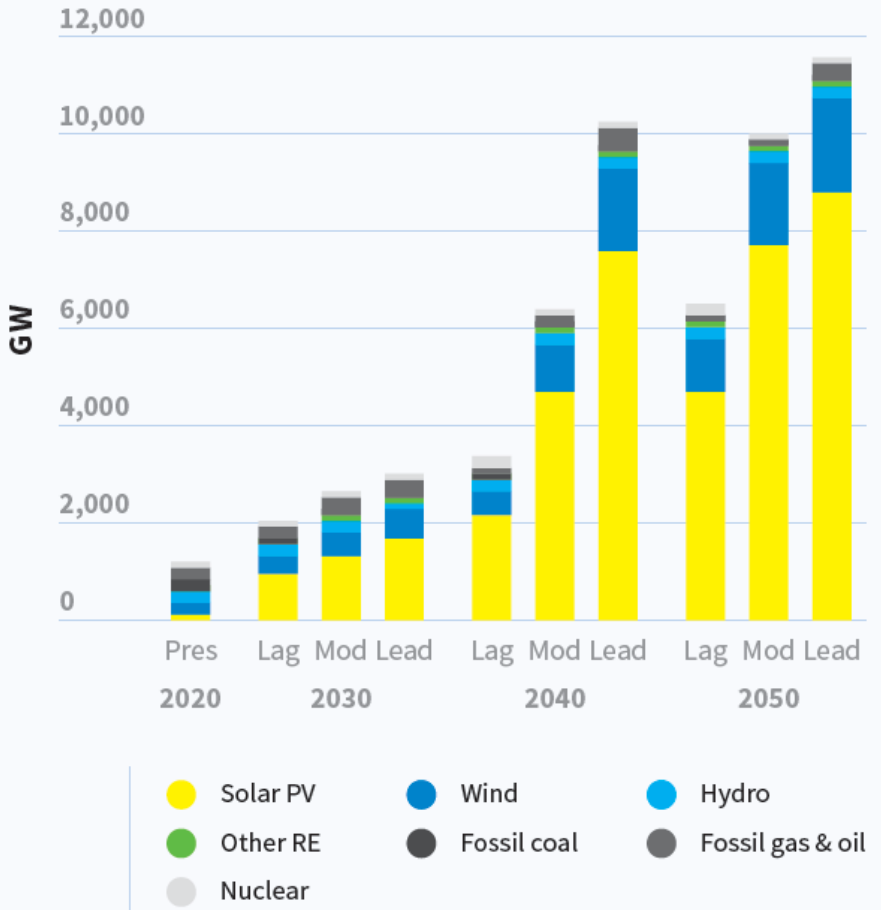


FIGURE 3.10 ELECTRICITY INSTALLED CAPACITY



Moderate scenario

- 5500 TWh by wind
- 10’000 TWh by Sun
- 3-5x times EU electricity consumption

Batteries and hydrogen are important !

Data given in 1-s2.0-S0360544221007167-mmc1.pdf (els-cdn.com)

In “Low-cost renewable electricity as the key driver of the global energy transition towards sustainability” - ScienceDirect