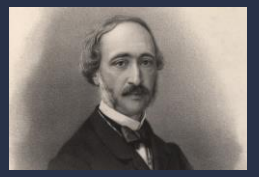
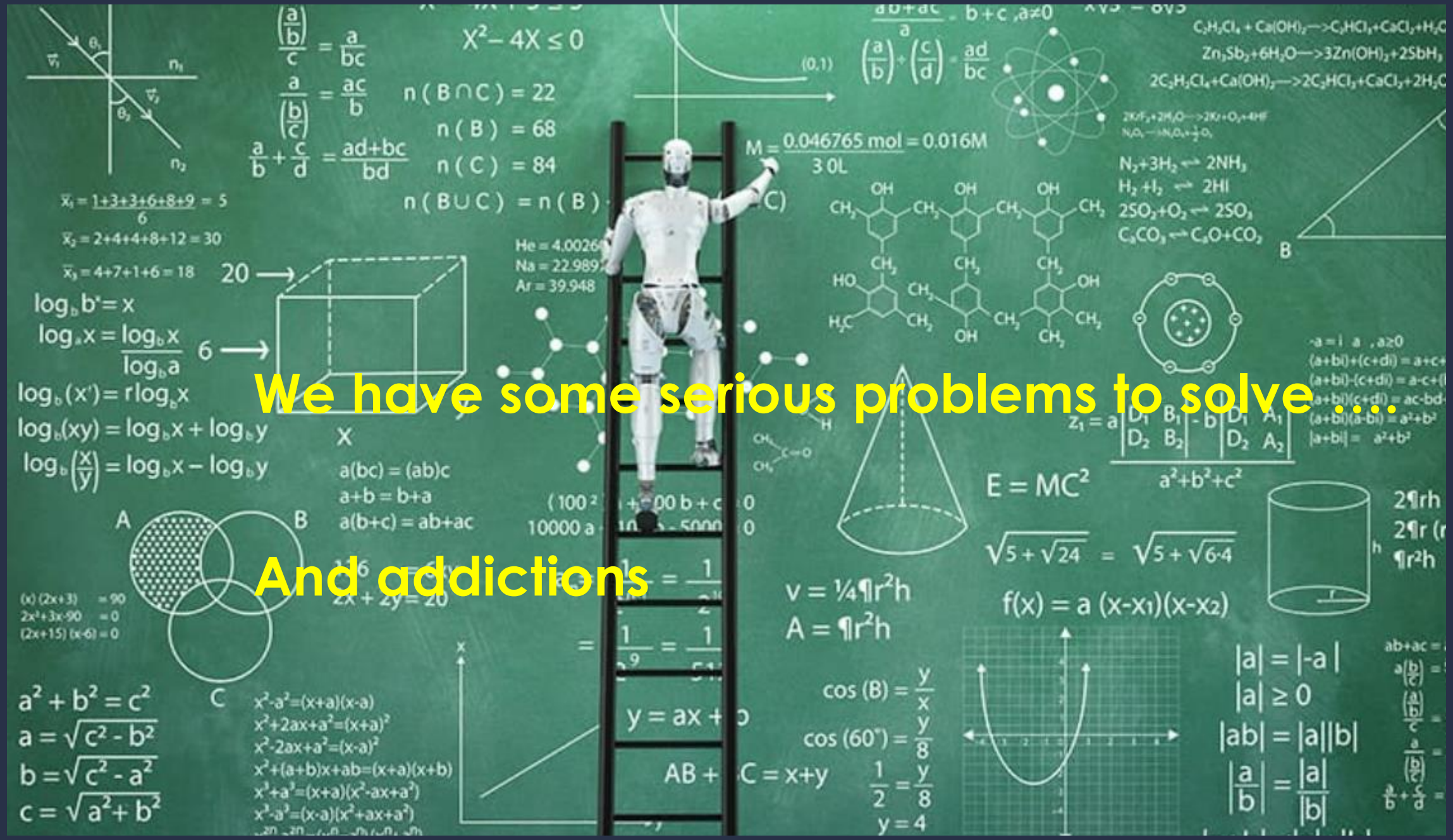
Photovoltaics go fast: improved technologies and carbon footprint for a wider range of applications

Prof. Christophe Ballif
EPFL & CSEM—Neuchâtel
Switzerland

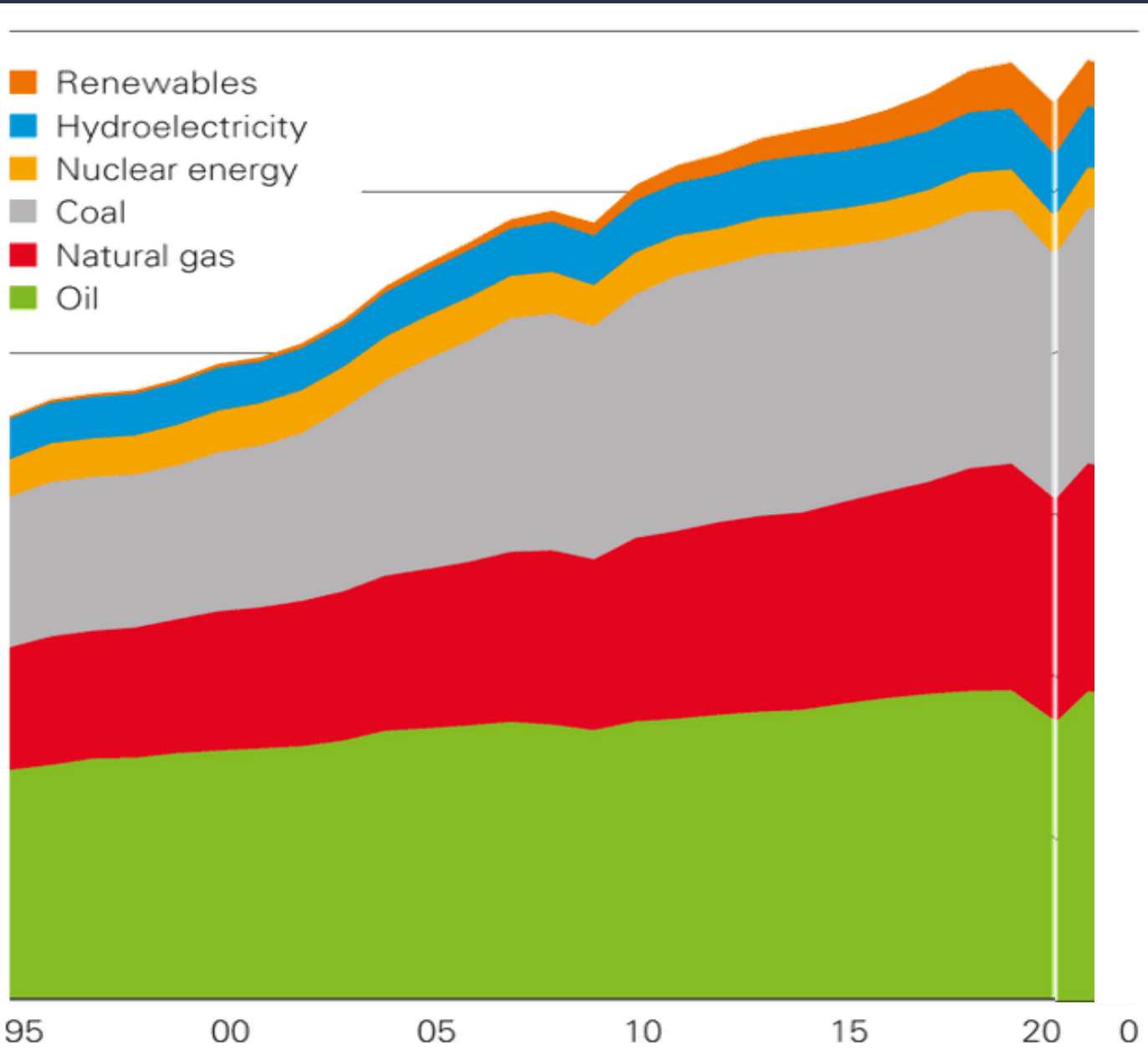
COST Action PEARL PV's Conference

Enabling the PV Terawatt Transition. March 2022




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

Primary energy consumption



~ 166'000 TWh

Still 80% fossile fuel

Electricity + heating, transport, industrial processes

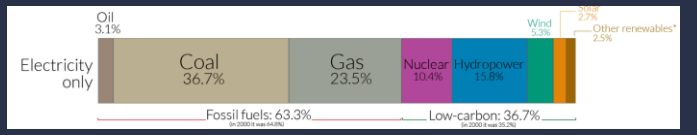
*Electricitiy of biomass, hydro, solar, nuclear wind taken with a factor 1/0.38 to be shown as primary energy source

*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

c) Carbon sequestration

d) Don't care

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

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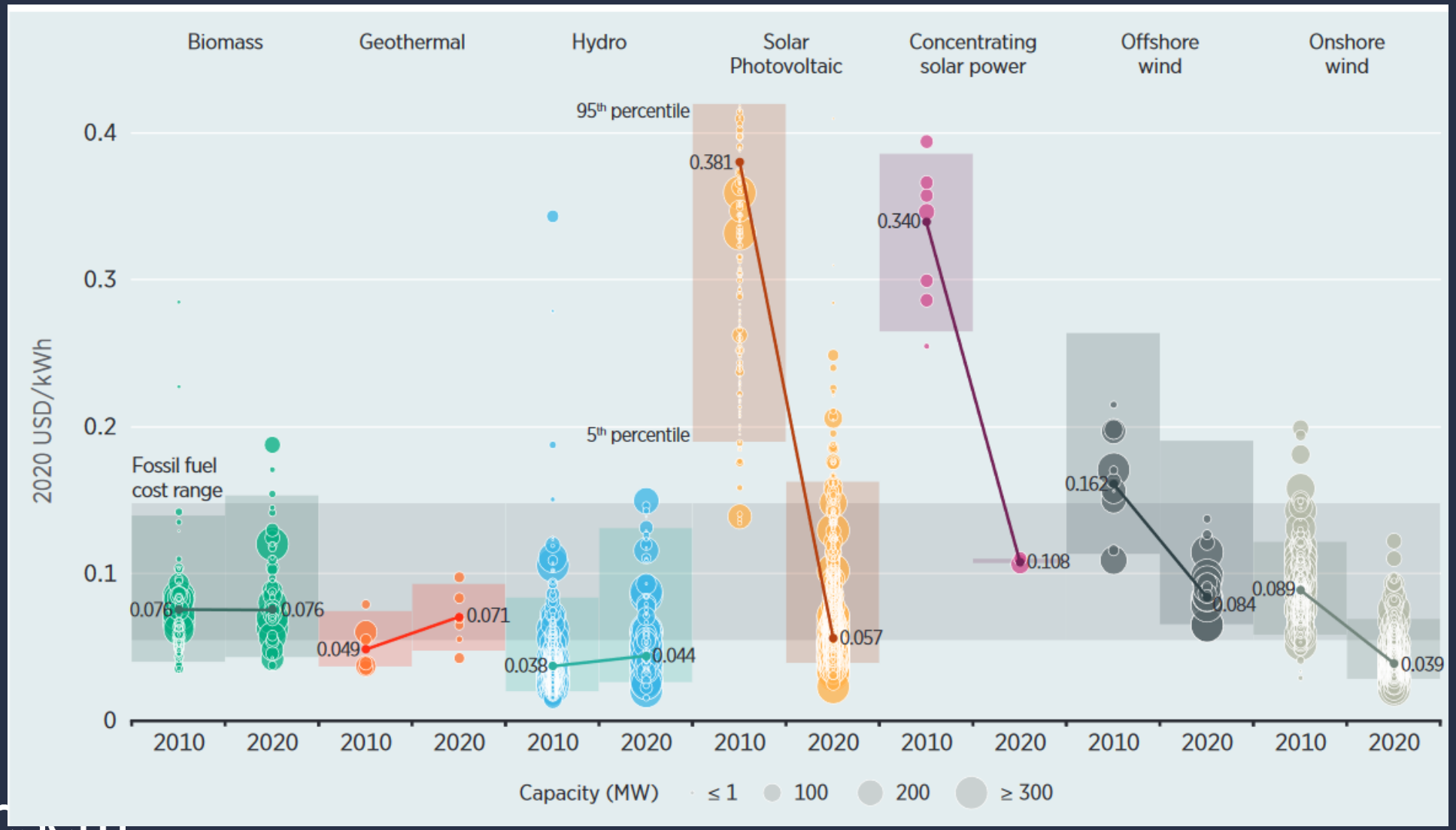
Electricity market

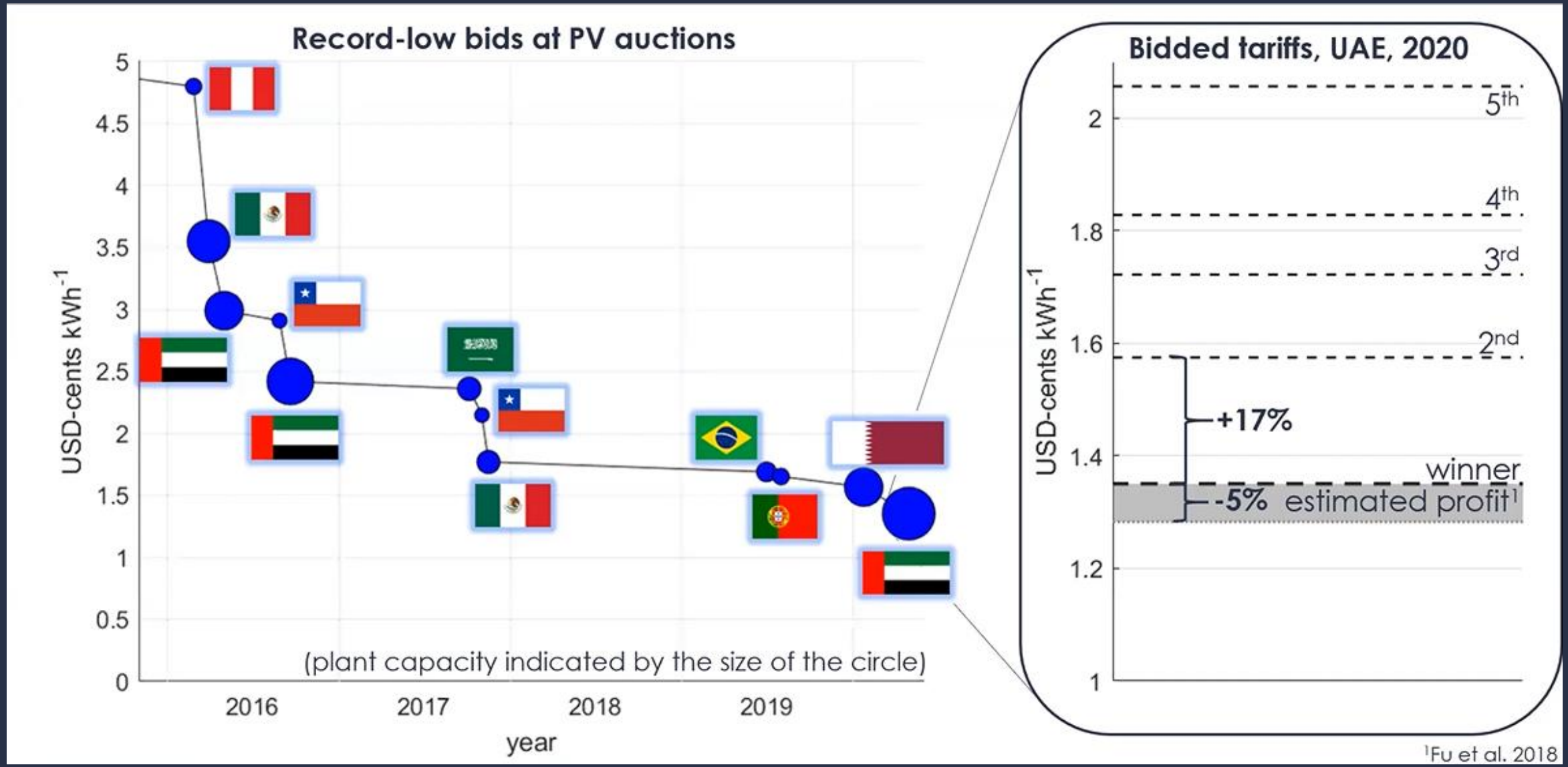
Global LCOEs from newly commissioned, utility-scale renewable power generation technologies, 2010-2020

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"



In 2030. less than 1.3 cts/kWh in Sunny country

→ hydrogen for < 1$/kg (or NH3…or others)

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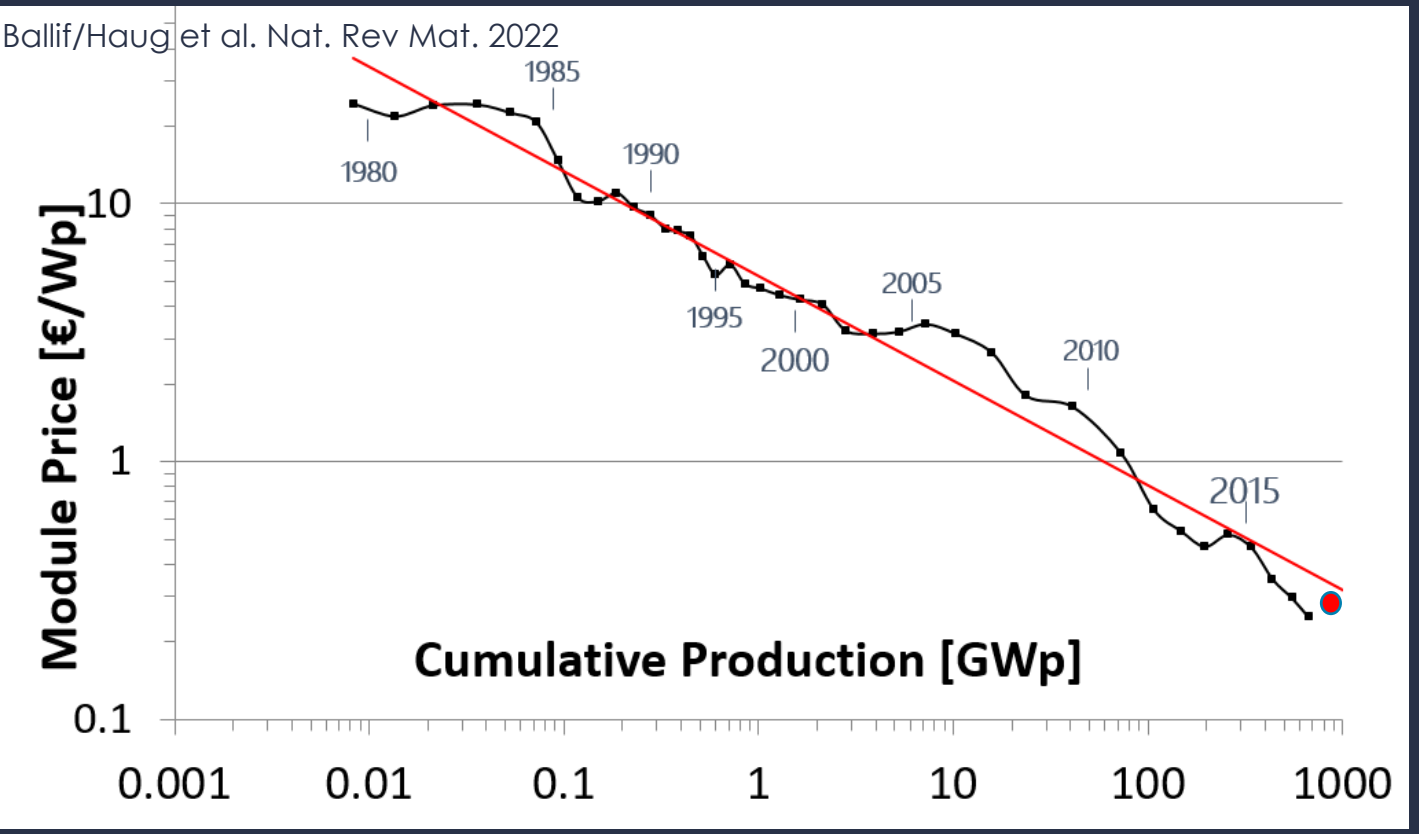
At the core of PV systems: learning curve of PV modules



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

- 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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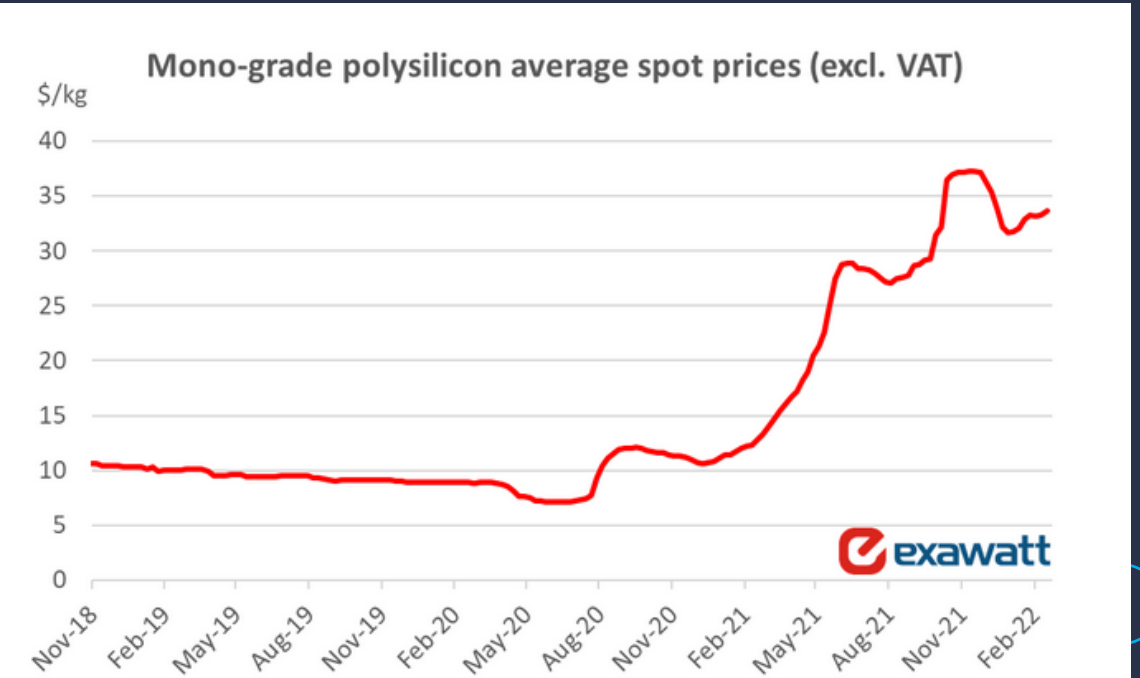
But

- 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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Disclaimer

No, Solar can't do it alone !

Yes, it would help a lot if we would consume less of all (individual transport, meat, IT, goods) and reflect about our world and habits

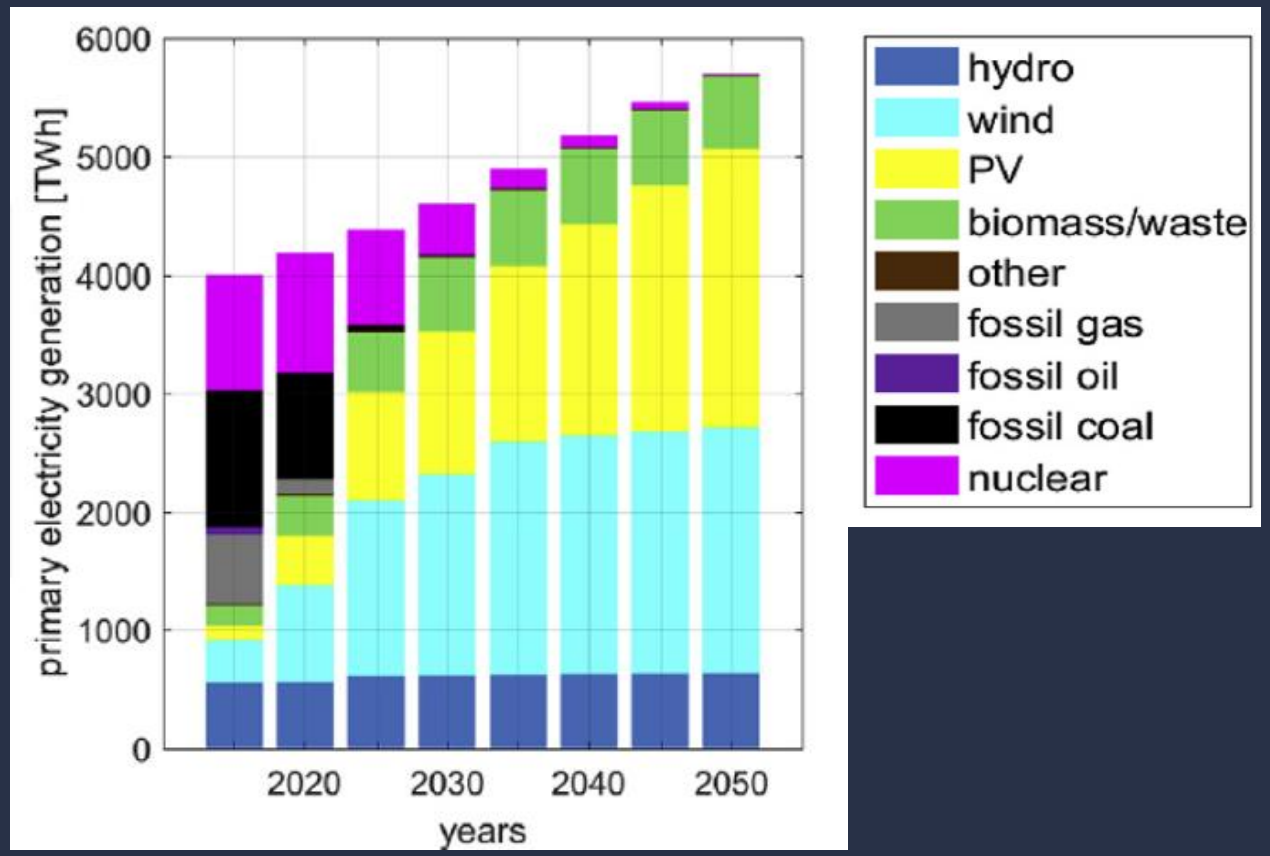
Energy efficiency is a must… Isolate, and move to electric when possible..

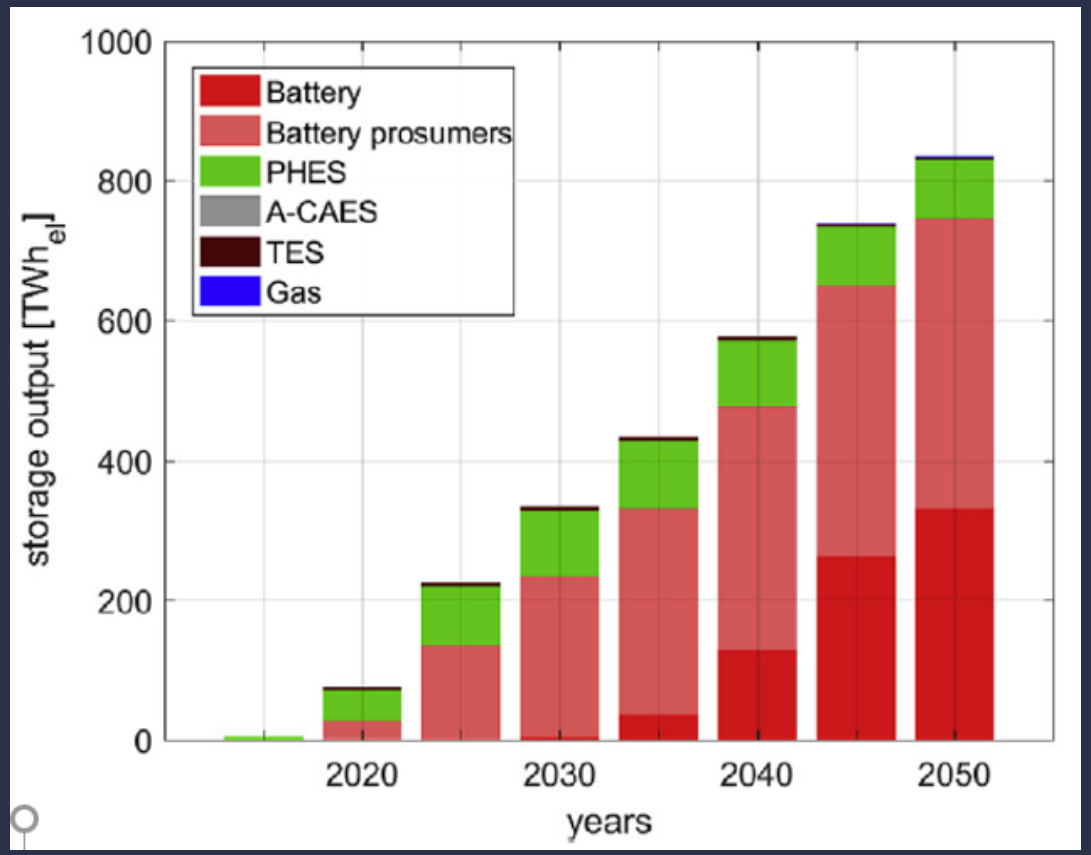
There is enough fossile fuel with coal and coal-to-liquid for the next hundred years

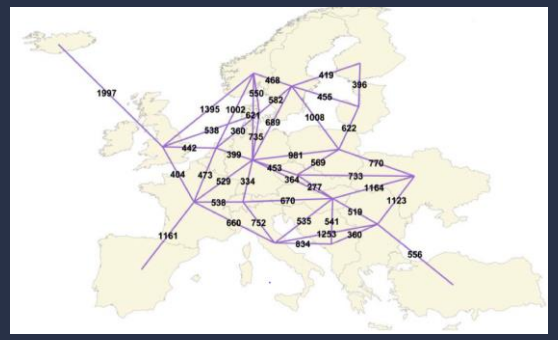
Scenarios

- What should be !
- What will likely happen

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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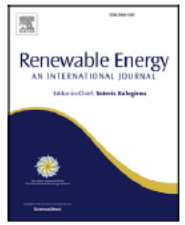
Renewable Energy 184 (2022) 430–442

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Zero air pollution and zero carbon from all energy at low cost and without blackouts in variable weather throughout the U.S. with 100% wind-water-solar and storage

Mark Z. Jacobson*, Anna-Katharina von Krauland, Stephen J. Coughlin, Frances C. Palmer, Miles M. Smith

Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, 94305-4020, USA

- Possible even in US !

See scenarios by Solar Power Europe (a lot of Solar), ETIP Wind (not so much solar….)

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Scenario for a decarbonised future

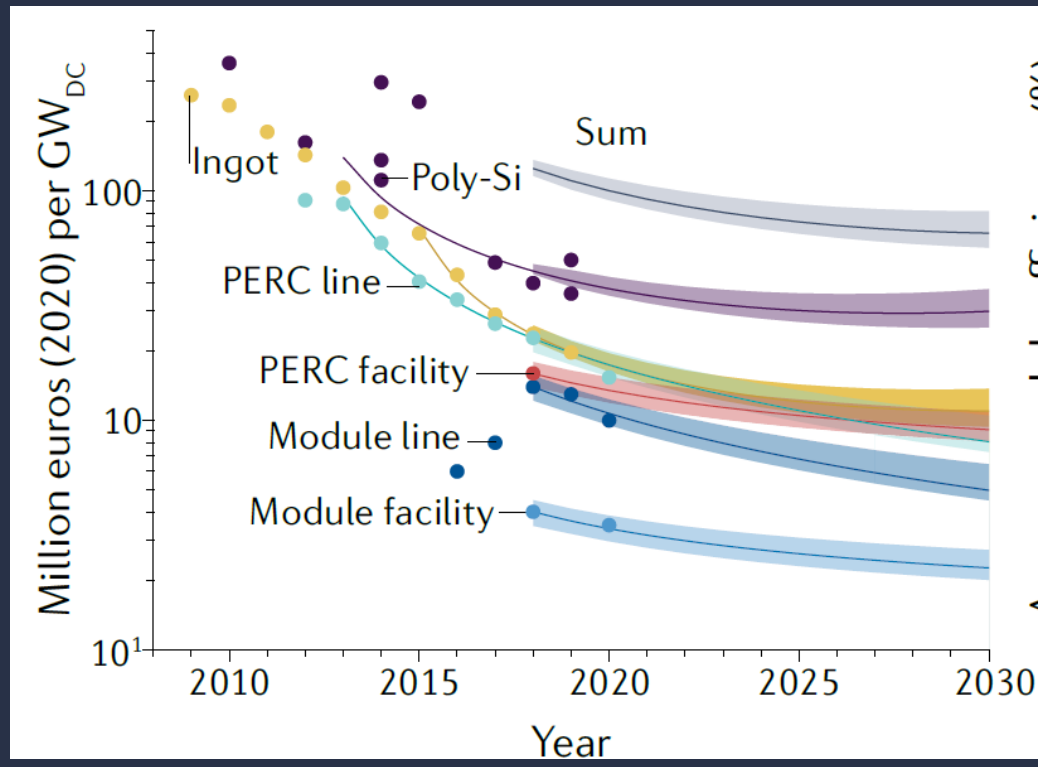
Implication for PV

- If the world is serious: at least 30-40 TW of PV by 2050 (NL 70-120 GW ?)
- Increase production volume to 1 – 2 TW annual from 0.15 TW/year today

- How much does it cost to put in place 1.5 TW of production ? (from sand to modules)

with recent «CAPEX» decrease ~ 120-150 M€/GW → 180 billions € or 18 billions per year over 10 years (PERC lines in China)

- Still a lot place for research and innovation !



Source P. Altermatt, EU PVSEC

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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

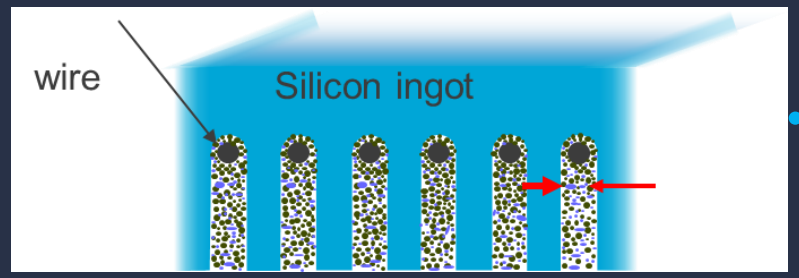
- Siemens silicon recrystallation process

200 kWh/kg of Si in 2000 !!!

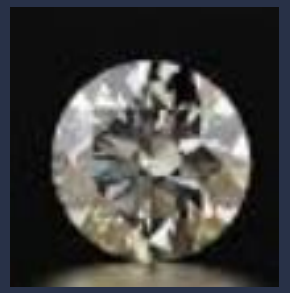
Today:
Can make 10 tons of silicon per run, tubular filaments, cold reflected coated walls.
Only 40-45 kWh/kg

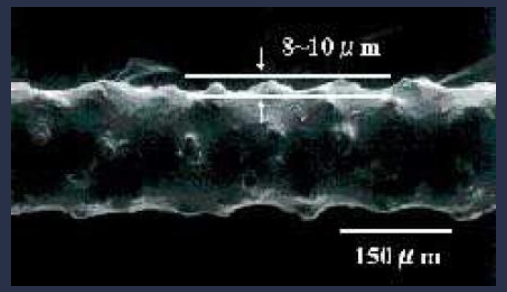
Durability of PV

2nd major improvement: Wafer sawing

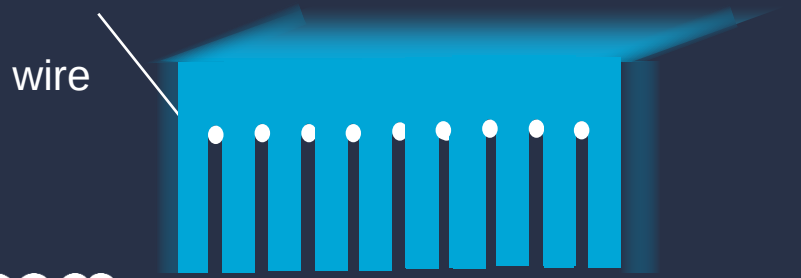


- Yesterday, multi-wire sawing, SiC particles loose 200 microns

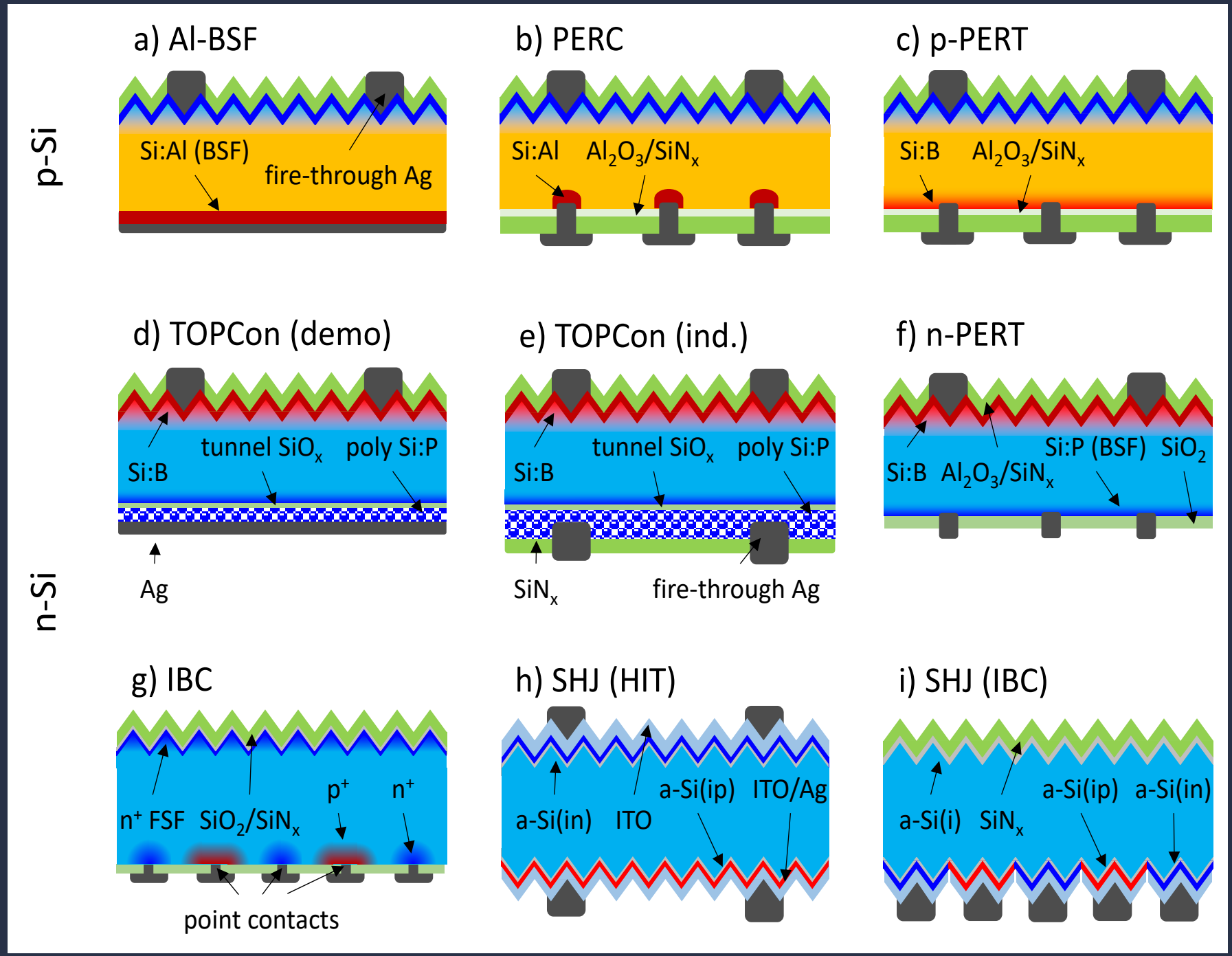




Today, diamond wire for mono loose 60 microns
→ 60 % more wafers than 5 years ago !



The various types of silicon technologies



Ballif/Haug et al.

Nat. Rev Materials 2022

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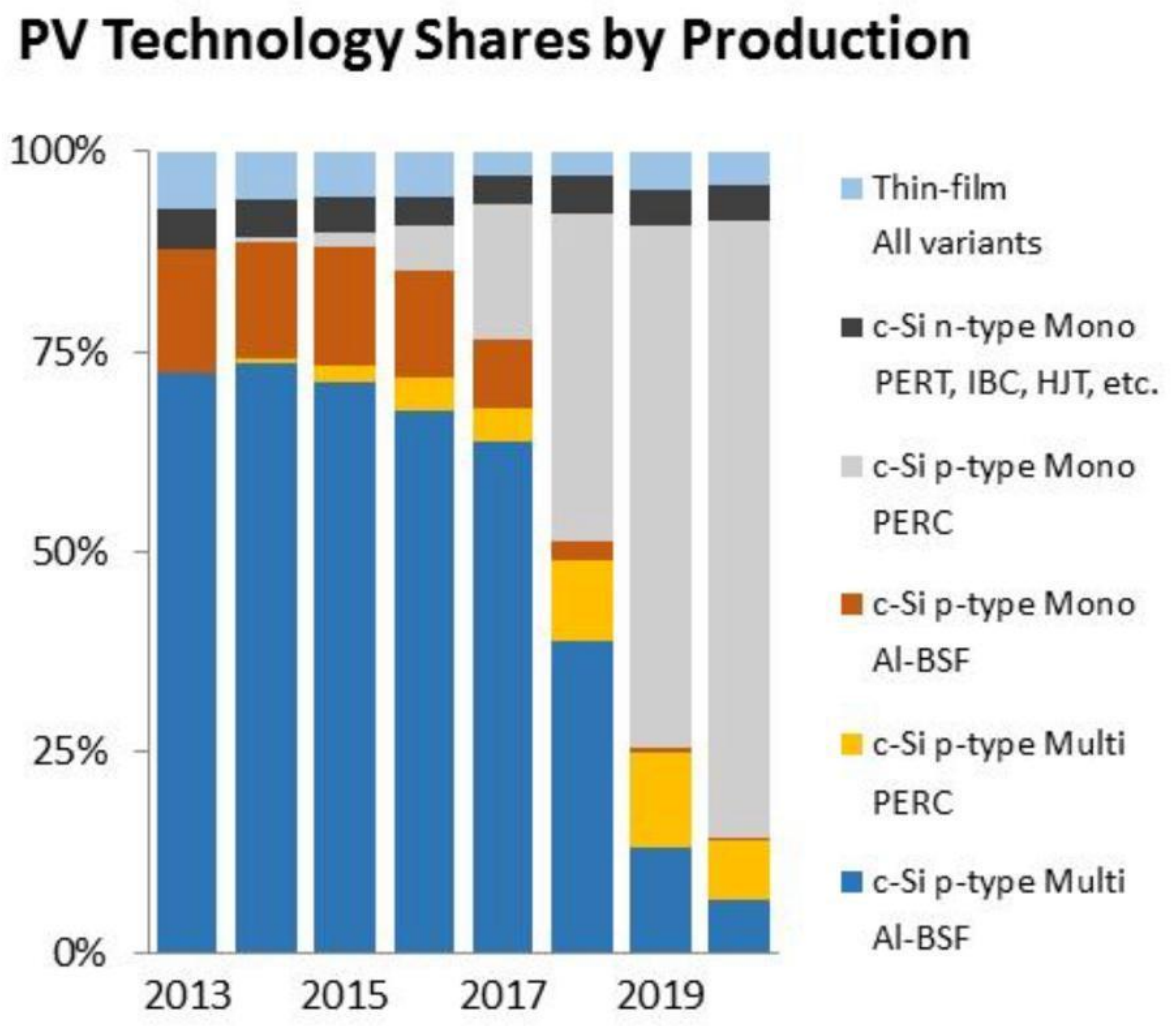
A drastic change in the PV industry lead by need for higher efficiency



- **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
- **IBC** up to 25% in production (Sunpower)

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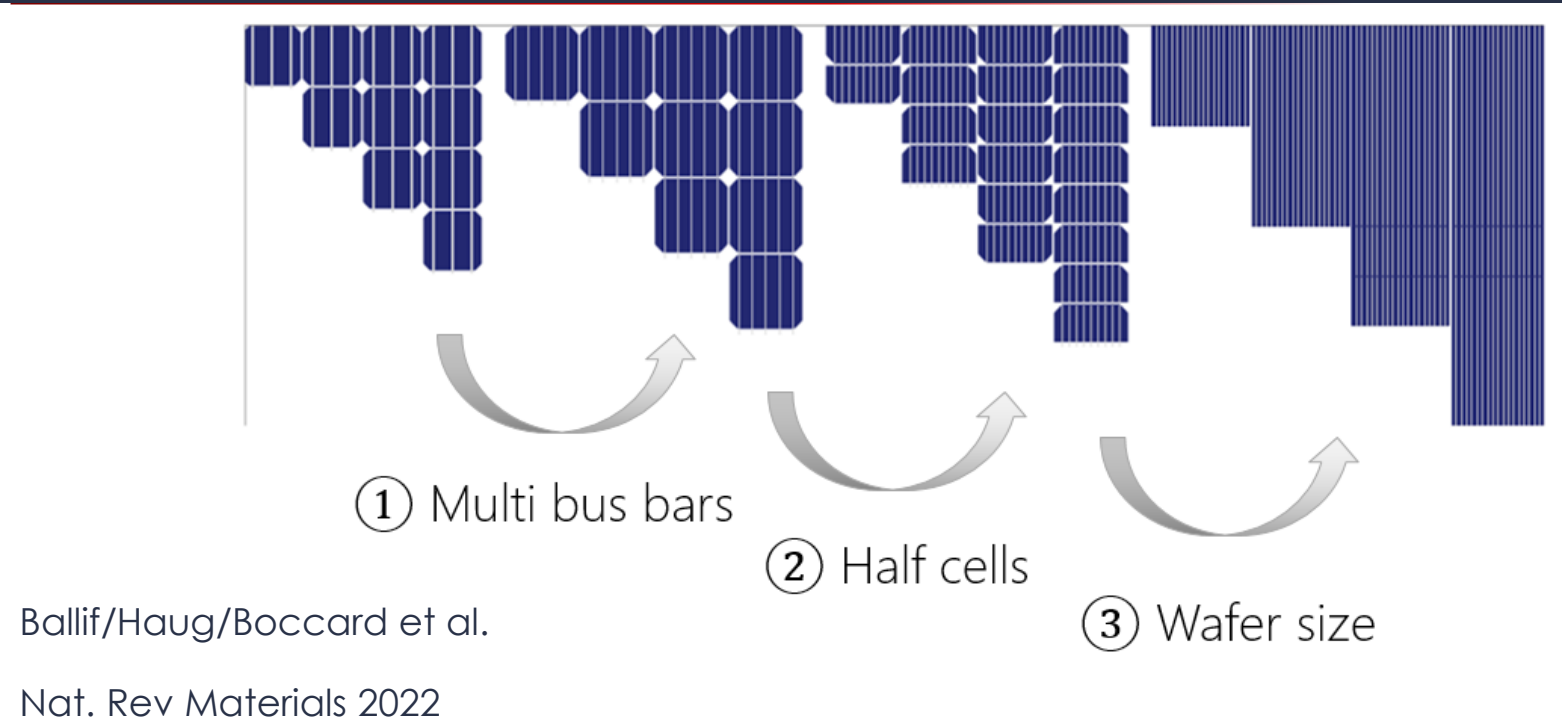
Source : PV tech

Why efficiency increase ?



Ballif/Haug/Boccard et al.

Nat. Rev Materials 2022

b) Module design change

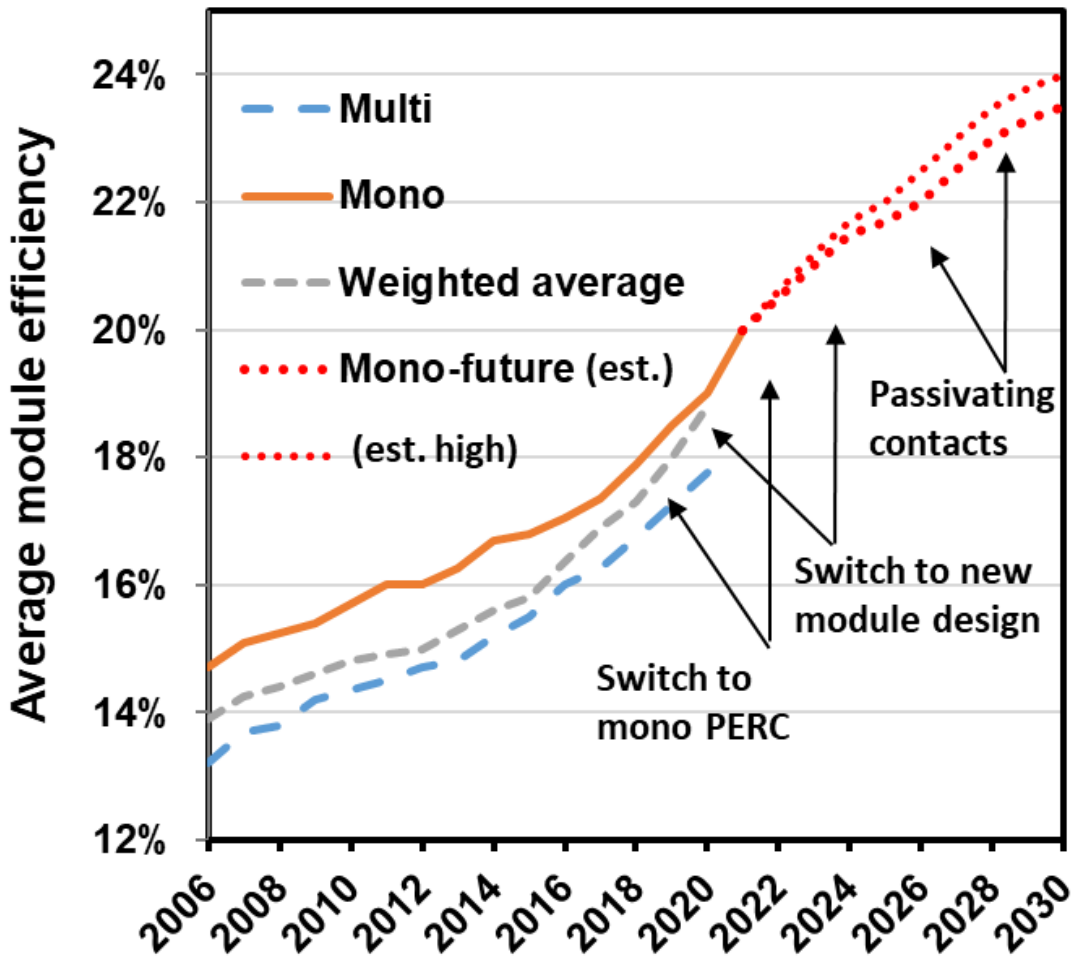
(0.5-1.5% absolute gain)

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)



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

Permanent increase in the module efficiency

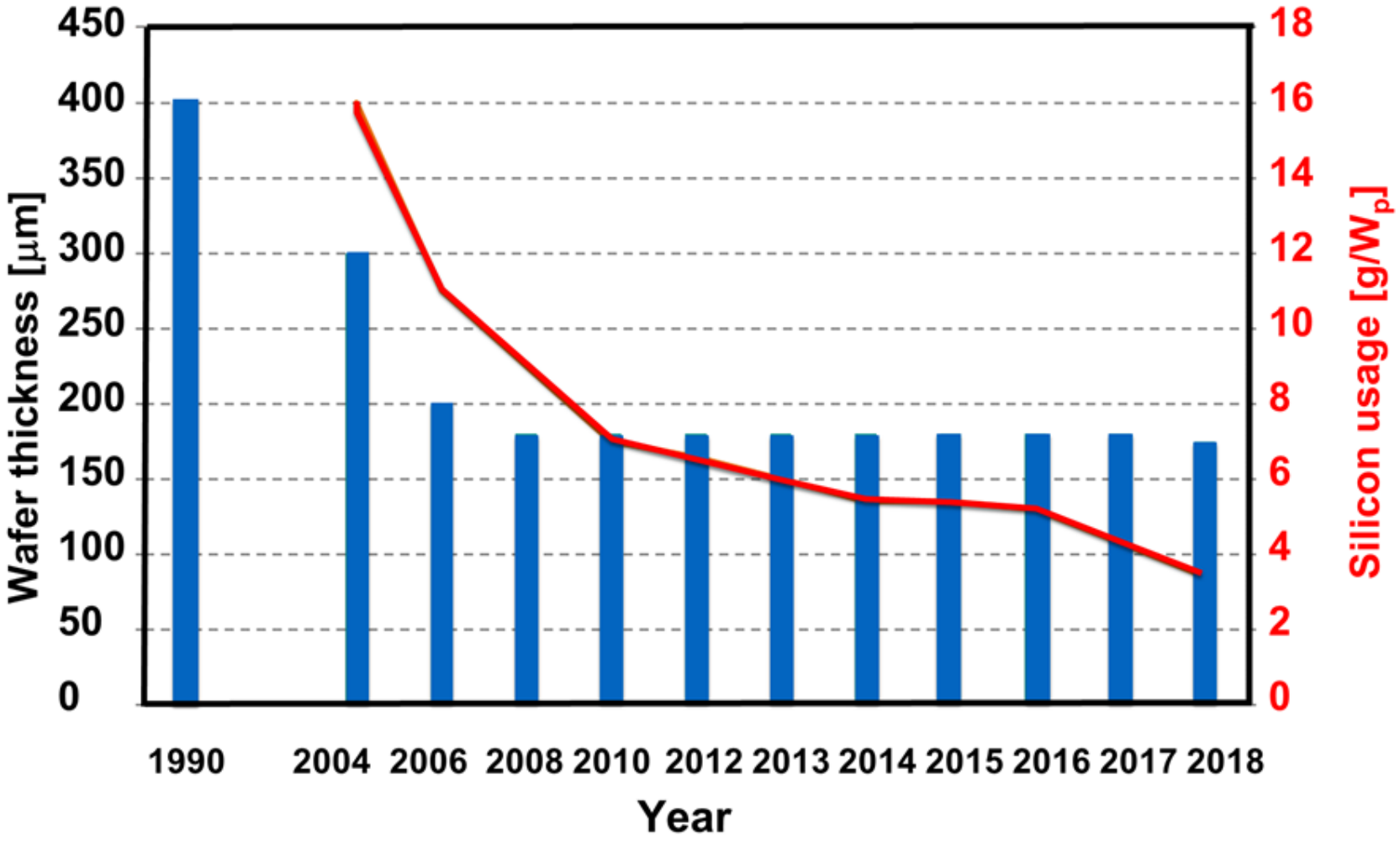
- 0.4-0.5% gain per year
- Efficiency of PV modules will further increase

(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

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

22

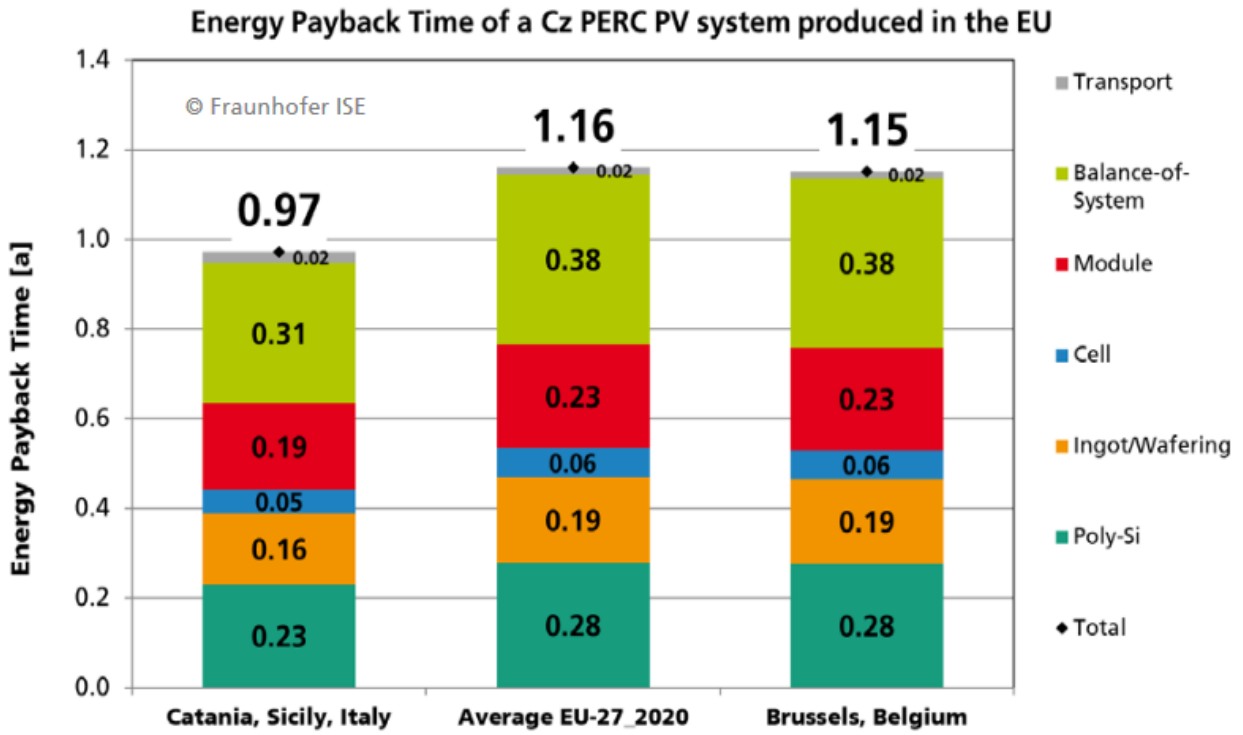
→From 17 to 3.5 g/W in 20 years,

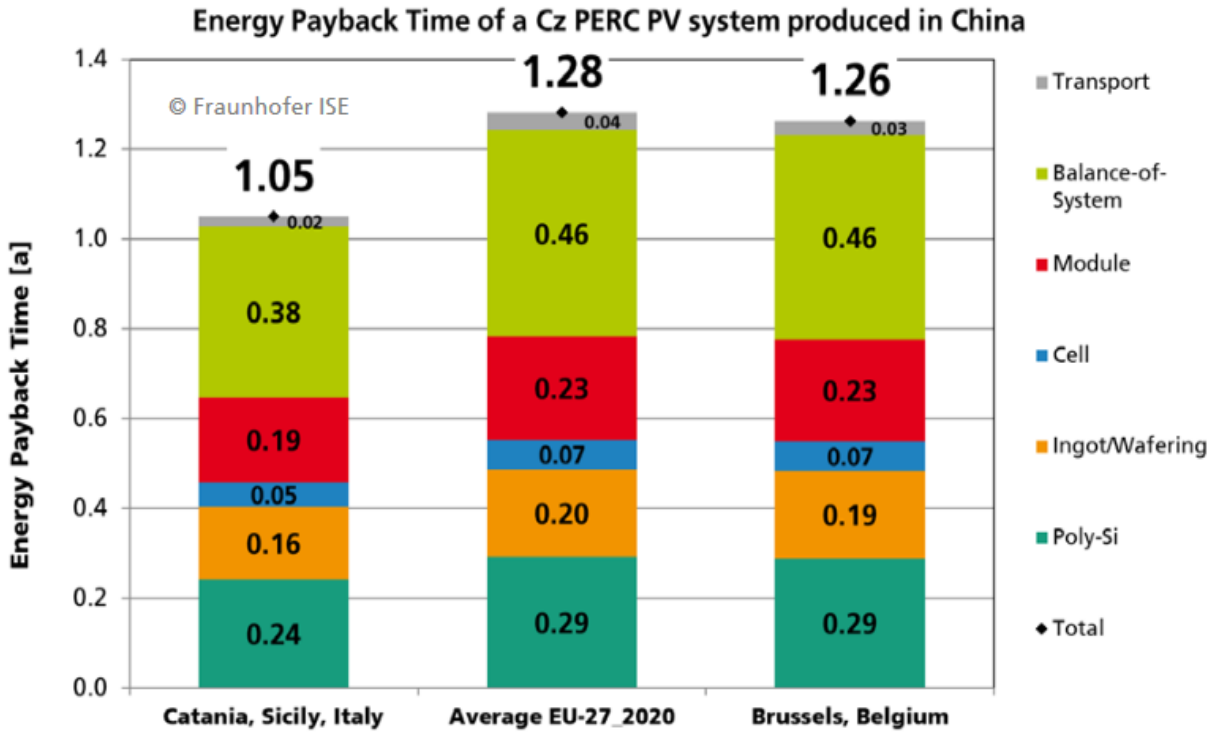
With low grey energy

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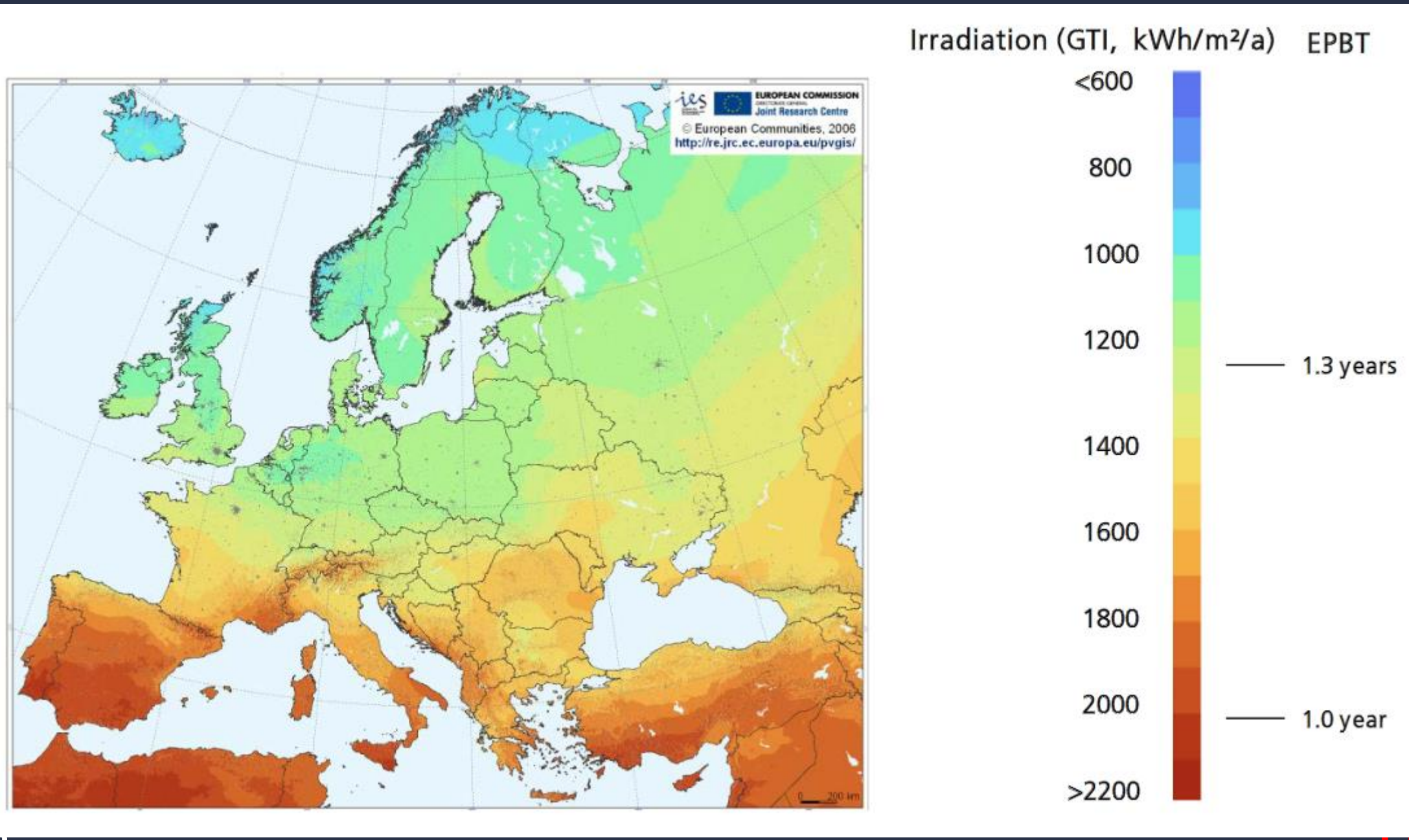
Energy Pay-Back Time of Silicon PV Rooftop Systems (2020)



Source: Fraunhofer report 2021

Module CO_2 footprint

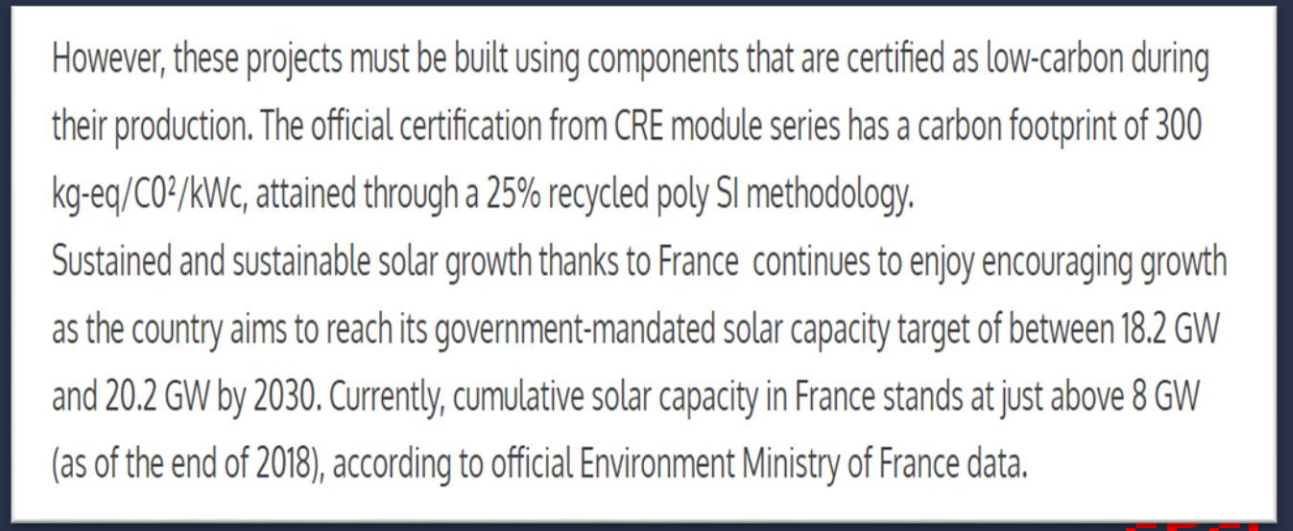
If ok electricity mix: 300 g/W of modules (coal electricity: ~700 g/W)
25 years of lifetime → 25 kWh

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

Comparison:

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)

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



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

Quizz: CO2 from PV panels

A quick calculation

- Assuming you need 40 TW of PV panels for decarbonising the world economy. How much CO_2 would be emitted for that assuming 300 g/W ?

- ……

- To compare with the current 46-50 GT billions tons CO_2 eq produced every year, and the remaining 1200 billions tons remaining for a +2°C scenario

- Note: the more you decarbonise, the better the CO2 contents of modules (and batteries and wind turbines).

Favor the renewal of a large PV industry in Europe ??

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…

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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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Microtracking pour l'agriPV: select light for plants or PV for Energy

Identified space for

- 5 GW just in Switzerland

First > 100 m2 prototypes under construction/tests

insolight

ROMANDE ENERGIE

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hiperion MAX SOLAR POWER

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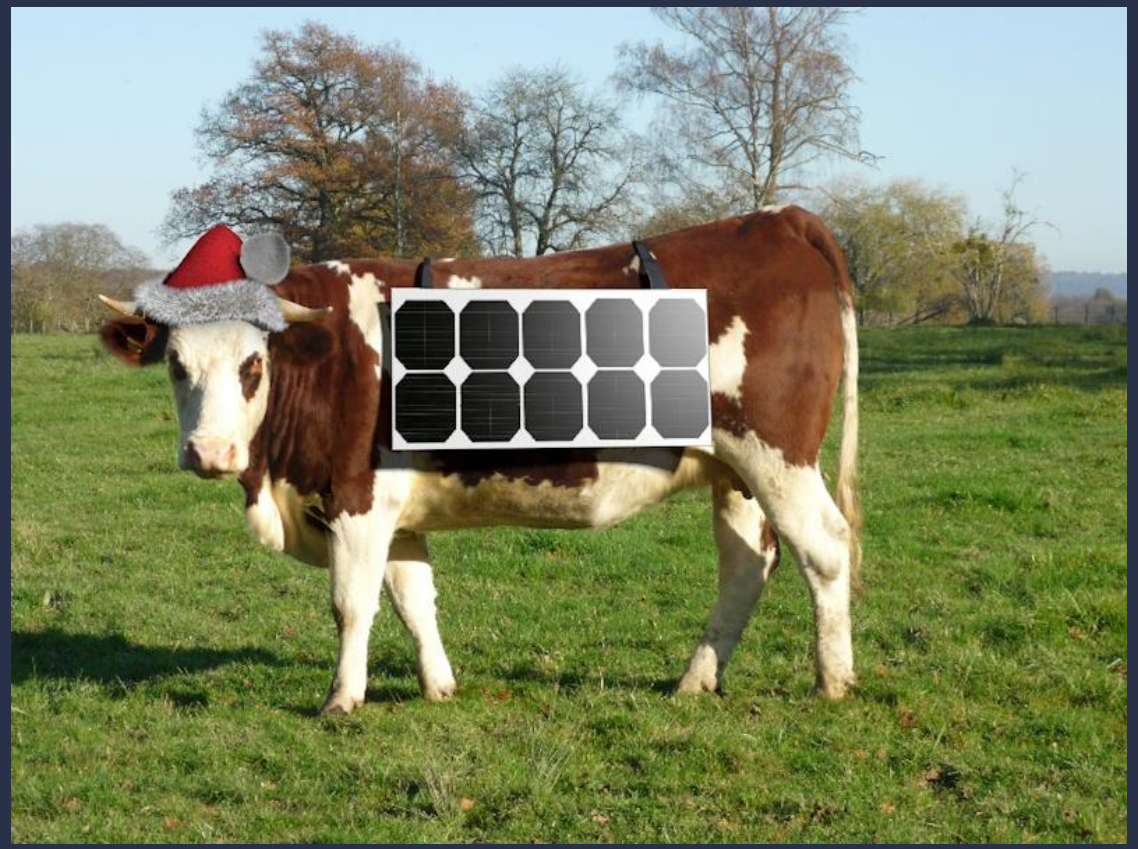
Massive solarisation of building

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

And not one out of 5 roof or 20% of a single roofs

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

Sensitive to aesthetics… increase acceptance and potential

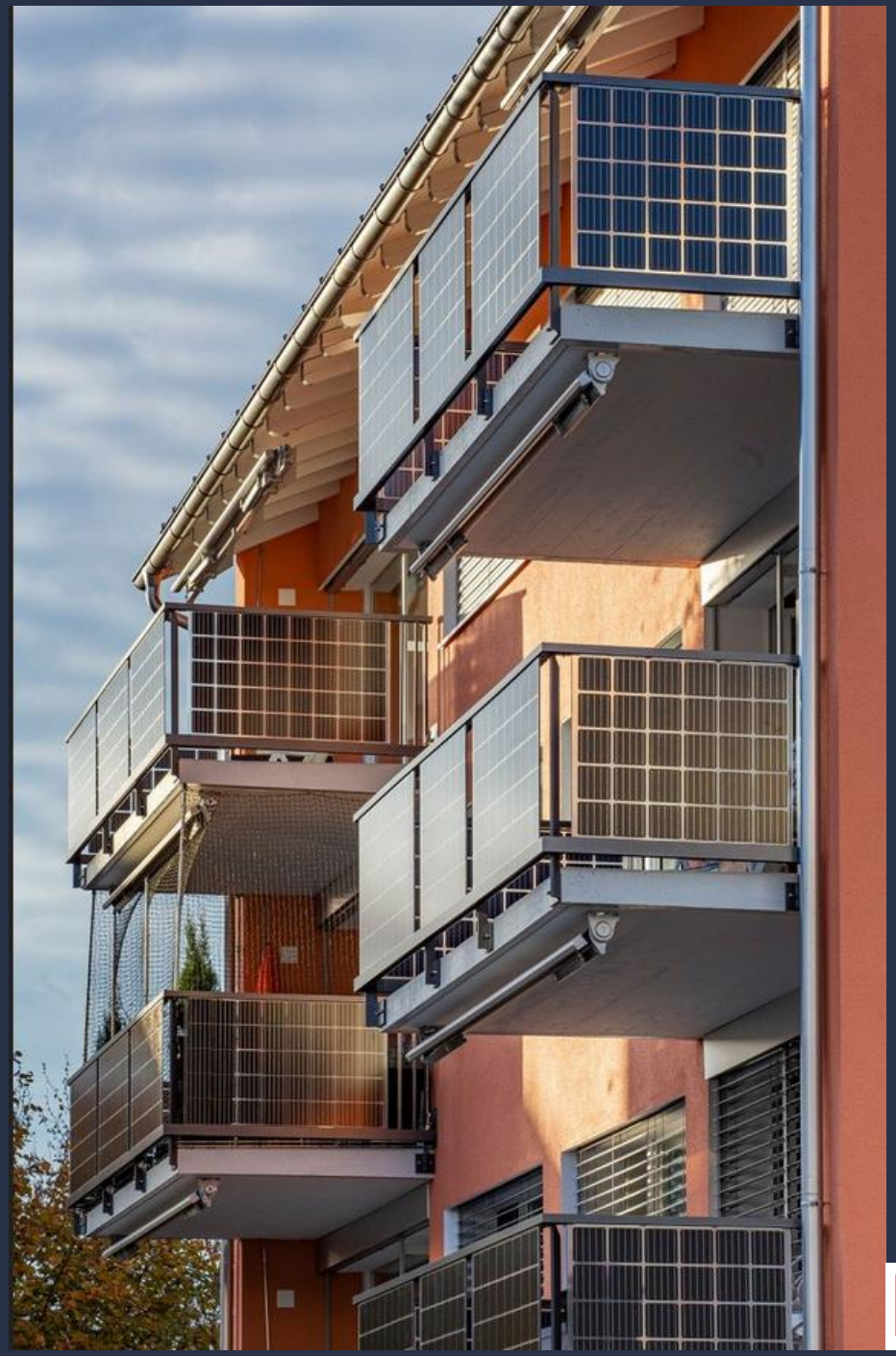


Some examples of Switzerland, a pioneer in transformative PV technologies

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

Prix solaire

Suisse 2015



Elegance and architecture

Transforming building and cities

- Based on CSEM polymer and module platform
- Technological support or transfert to companies

Manipulation of adhesion, temperature, creating color films, ….

White PV panels, together with Solaxess


RESTRICTED
AREA
DO NOT

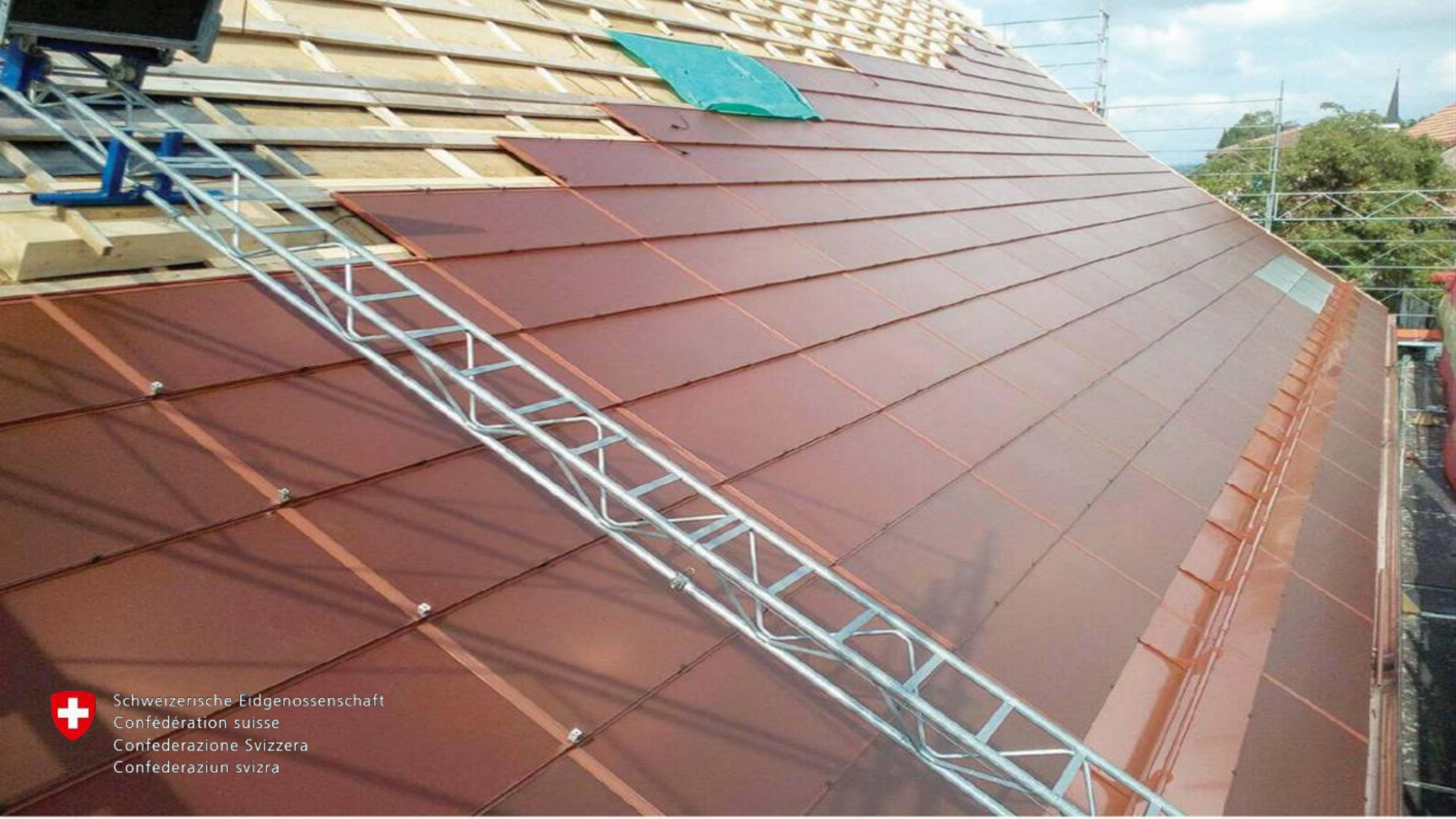

SOLAXESS
white solar technology

Using Solaxess «specialty foils»

SOLAXESS
white solar technology

Using Solaxess «specialty foils»

SOLAXESS
white 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

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SOLAXESS
white solar technology

3S Solar Plus

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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 !

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- **Conclusion**

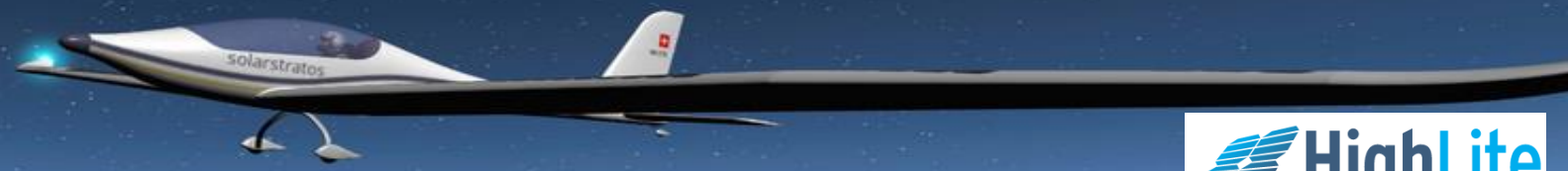
- Huge improvements in PV: greener, cheaper, verstatilty for construction.
- Foresee long term «curtailement» possibility to avoid grid overload. Brings much more smartness in system (flexilibity)
- Don't be afraid to have too much PV, there is never enough…
- A «free market» will certainly not be sufficient to ensure security of supply, so new regulations/incentives required
- Local manufacturing in Europe, in Austria, in Switzerland important… try and develop a local economy with special products, work with local manufacturers…
- Think of developping a more resilient system

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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