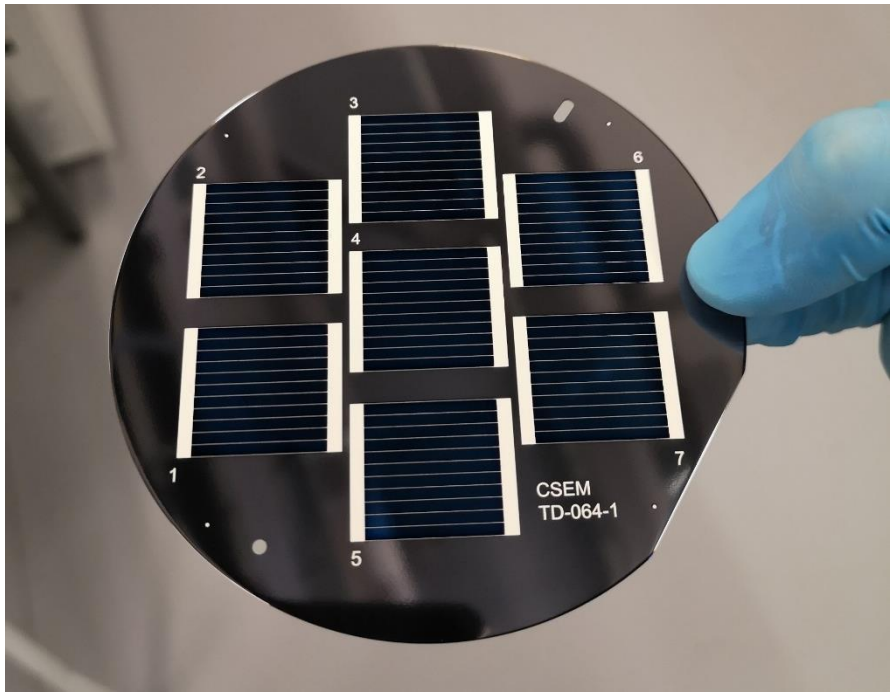
IV.
From sustainability to practice and research



Lecture 4

1. Is it sustainable ?

2. Some practical aspects of PV installations

Prof. Christophe Ballif

Sustainability of PV

Is photovoltaics sustainable ?

- No limit in raw material supply: Silicon, 2nd most abundant material in the earth crust (used both for cells and glass). Minor quantities compared to building industry
- No rare elements in c-Si modules (except Ag, enough extraction for > 2 TW/year, can be substituted by copper)
- Recycling can be organised (Sens eRecycling CH)

Energy payback and CO2 emissions associated to PV

20 years ago, 17g of silicon to make 1 g of PV modules

300 kWh/kg of energy to prepare silicon (5 kWh/W)

→ 5 years energy payback time in Switzerland

Sustainability 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

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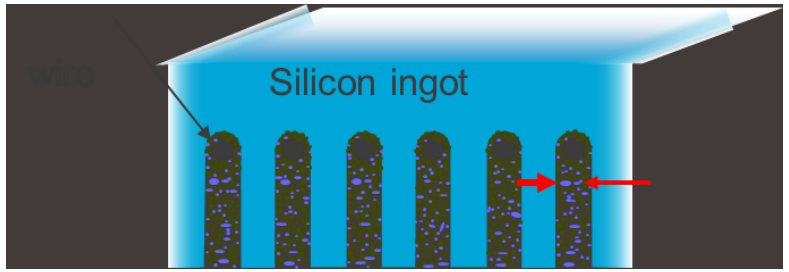
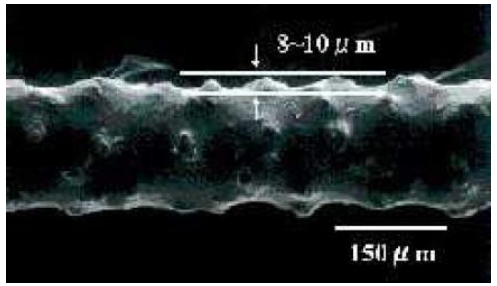
Sustainability of PV

2nd major improvement: Wafer sawing

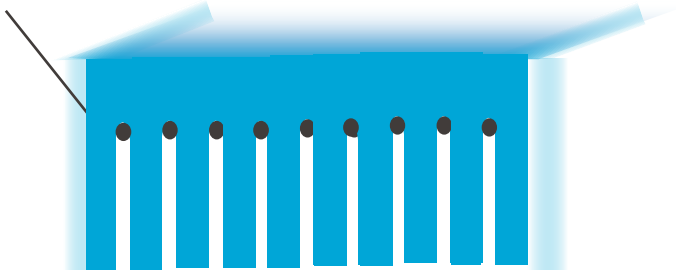


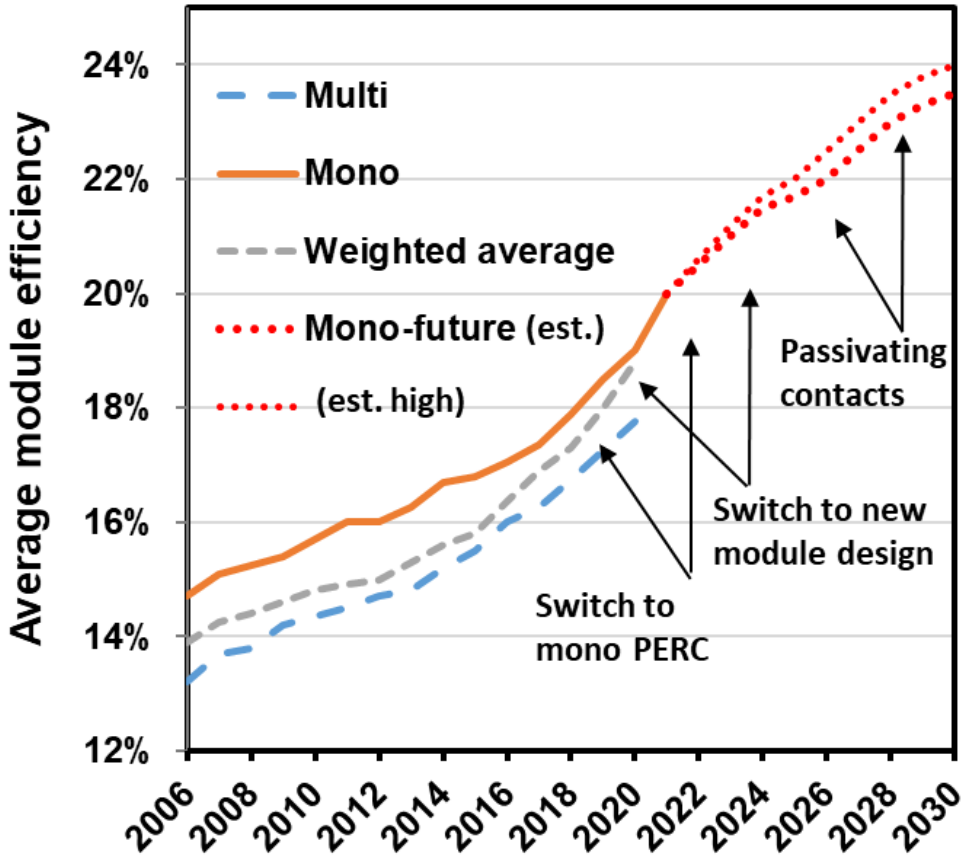
- Yesterday, multi-wire sawing, SiC particles loose 200 microns



Today, diamond wire for mono loose 50 microns and wafers are 30% thinner

→ 10 % more wafers than 5 years ago !



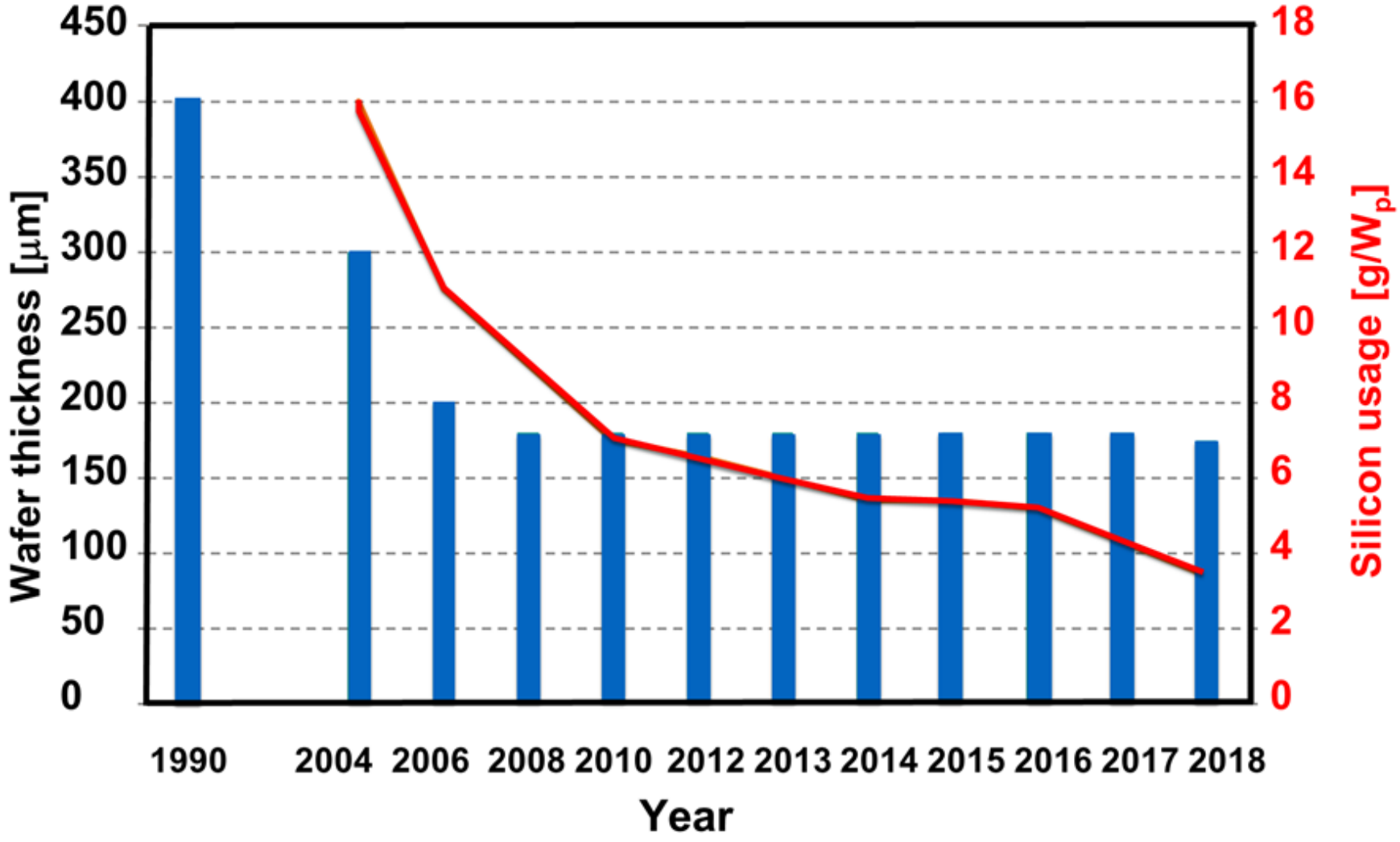


Ballif, Haug et al., *Nat Rev Mater* 7, 597–616 (2022).

Permanent increase in the module efficiency

Reduces all material usage per W !

Silicon usage



Efficient processes

Sawing

Efficiency

→

From 17, down to 3.5 g/W in 20 years

In 2023… 2.1 g/W

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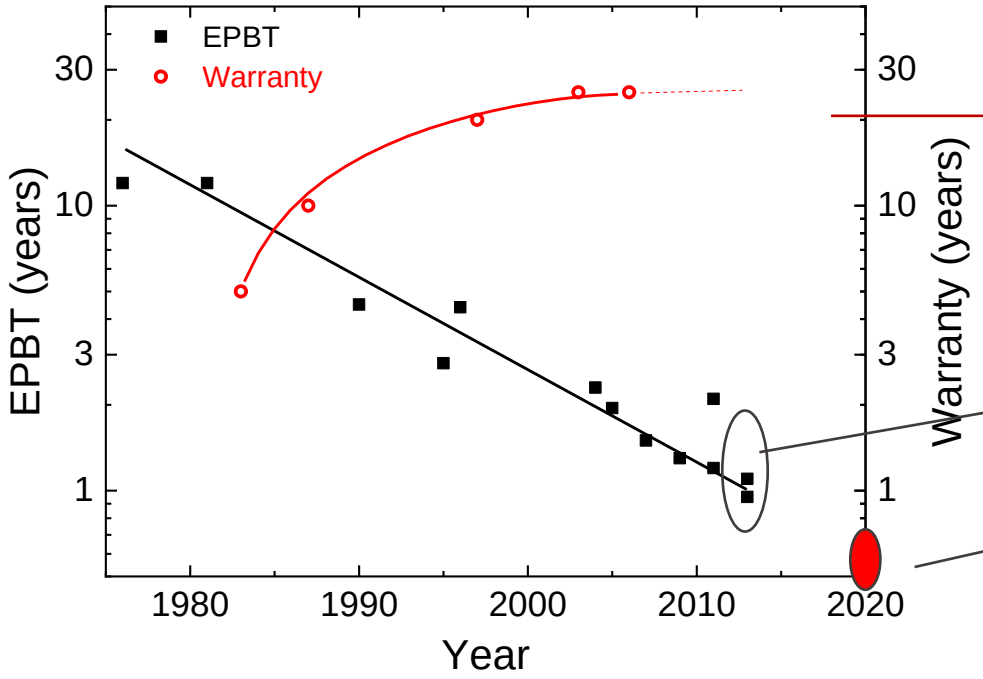
Sustainability

Prof. Christophe Ballif

Energy pay-back time (EPBT) of PV systems
Continuous decrease driven by leaner processing and increasing efficiencies



25 y warranty is today's industry standard

closer look on next page

Today EPBT, 6 months to 1 year

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

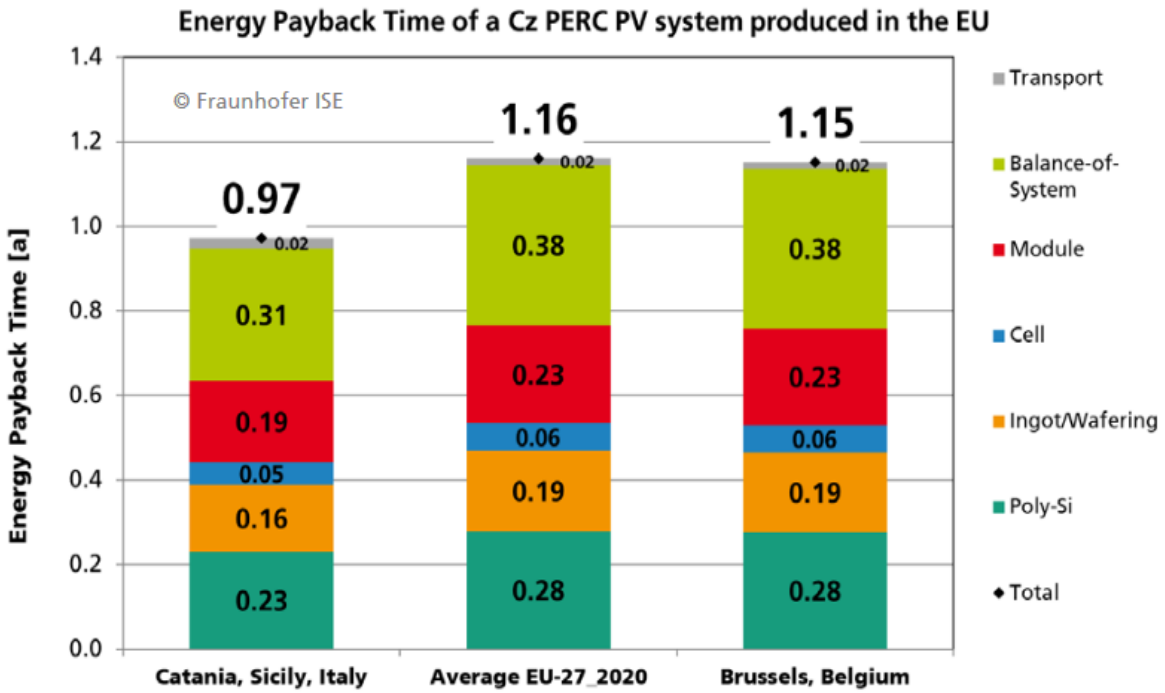
Long living myth: EPBT > module lifetime

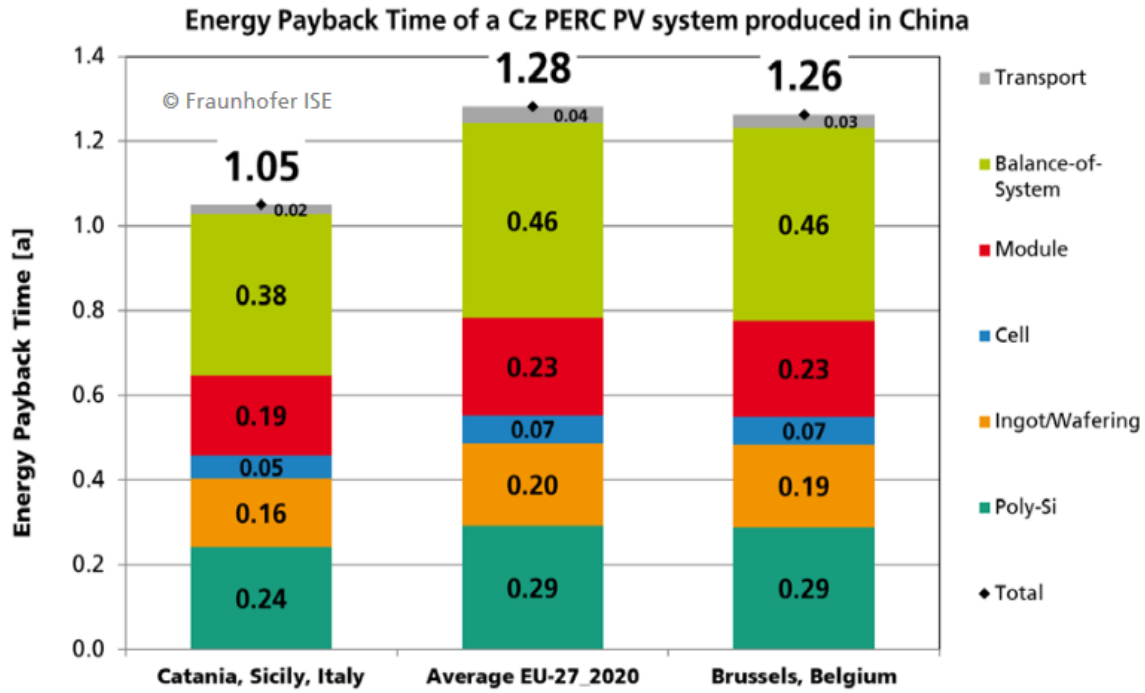
- was true in 1985 for warranty, NOT lifetime
- lifetime usually much longer than warranty

Wetzel, Prog. in PV (2014) Gallaher, Public Investments in Energy Technologies (2012)

Energy Pay-Back Time (EPBT) of Silicon PV Rooftop Systems (n.b. strongly improved since then)

Source: Fraunhofer report 2021





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

Full module (from sand to product) : **currently around 0.5-0.6 kWh/Wp** electricity required (5-6 cts/W at 10 cts/kWh local electricity).
Even if electricity prices increase by 5 cts/kWh impact on LCOE of solar electricity minimum (+2.7 cts CAPEX → 0.15 cts/kWh over 25 years at 3% cost of capital).

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Module CO_2 footprint

If EU electricity mix: 350 g/W of modules
With Chinese electricity mix 600g/W

25 years of lifetime → 25 kWh

→ modern processes of module fabrication → 10-20gCO_2/ kWh

Full System level typical emission (including inverter, installation…): 20-35 g CO_2/kWh

In summary: even with mono c-Si modules, system energy payback time ~ 1 year and CO_2 emission is acceptable (20 – 35g CO_2/kWh)

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

And the more you decarbonize your electricity system, the better it becomes

Reminder:

- Gas power plant 400g CO2 /kWh
- Coal power plant 900g CO2 /kWh

powered by Q.ANTUM DUO

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

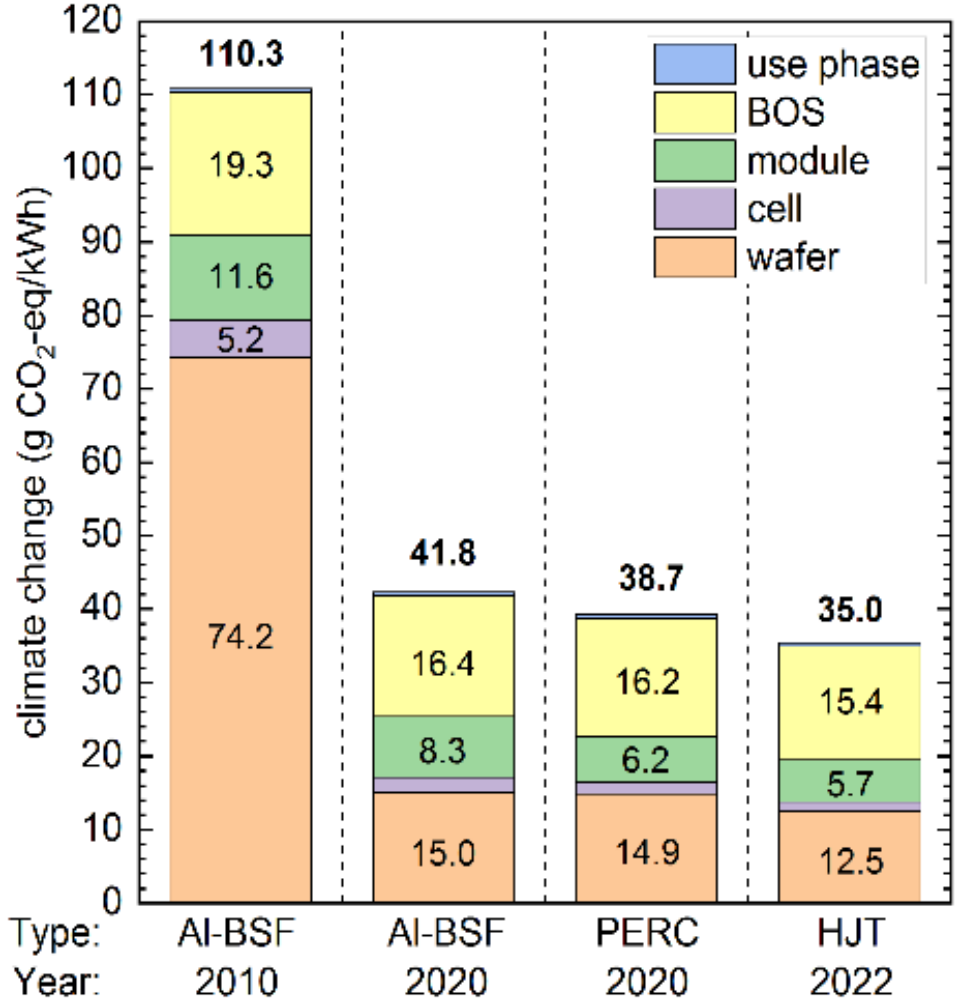
Hanwha Q CELLS GmbH, the German subsidiary of one of the largest solar cell and module manufacturers in the world, Hanwha Q CELLS Co., Ltd, has received on March 14 a Certisolis carbon footprint (CFP) certification of 300 kgeq/CO²/kWc in France for its high-efficiency Q.PEAK DUO module series.

APRIL 1. 2019 Q CELLS

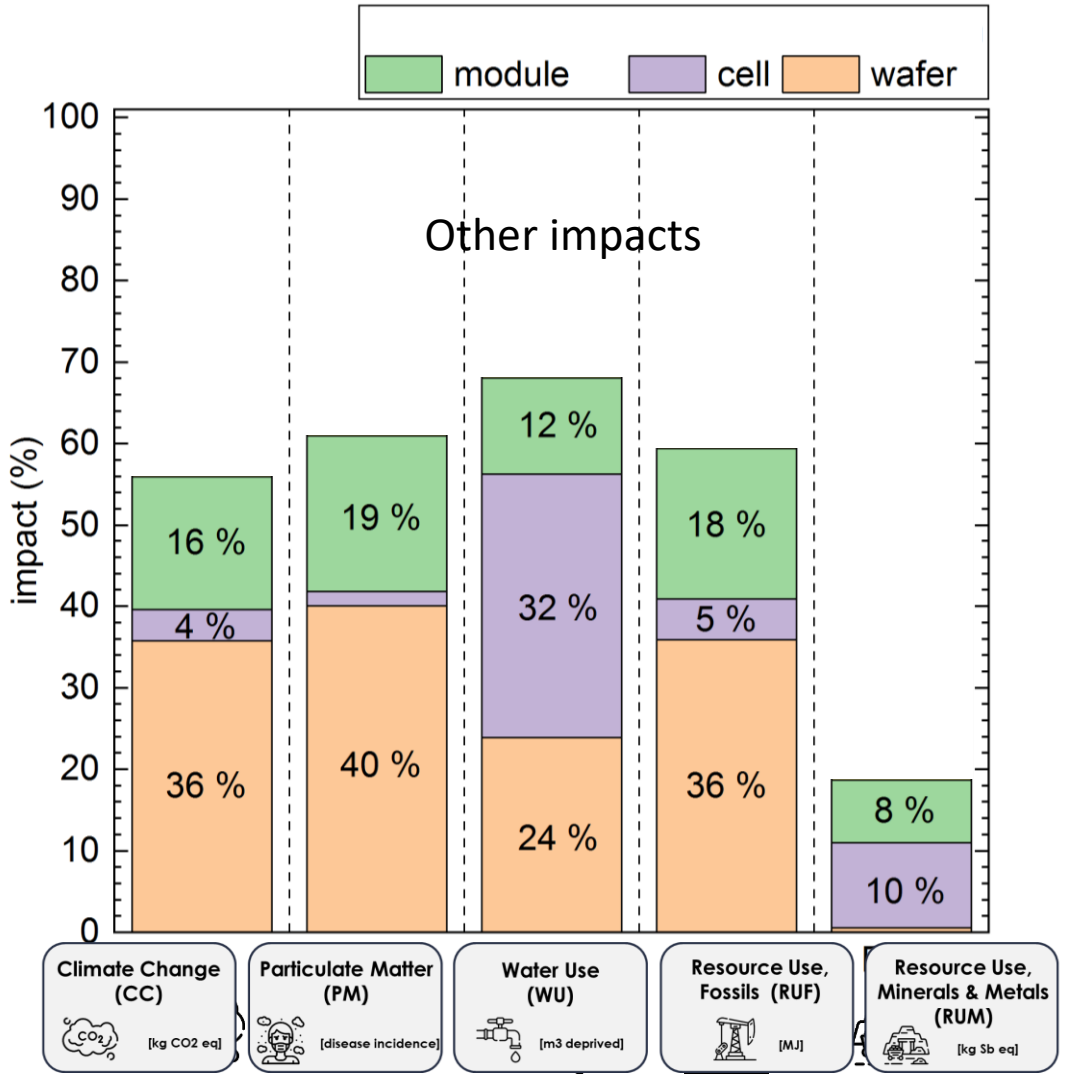
However, these projects must be built using components that are certified as low-carbon during their production. The official certification from CRE module series has a carbon footprint of 300 kg-eq/C0²/kWc, attained through a 25% recycled poly SI methodology.

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 (as of the end of 2018), according to official Environment Ministry of France data.

Sc-Si technologies: Carbon footprint – kWh FU



- Strong reduction of carbon footprint in 10 years for Al-BSF
- HJT carbon footprint is the lowest, mainly due higher module efficiency



Keeping a small fraction of our emissions for the energy transition

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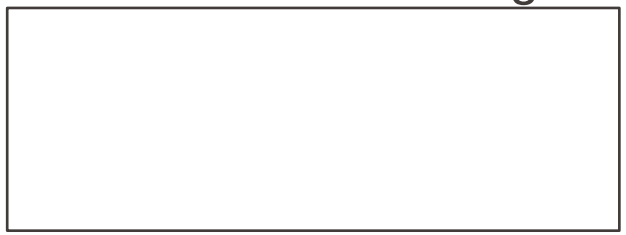
- Assuming you need 40 TW of PV panels for decarbonising the world economy. How much CO_2 would be emitted for that assuming 300 g/W ?
- ……

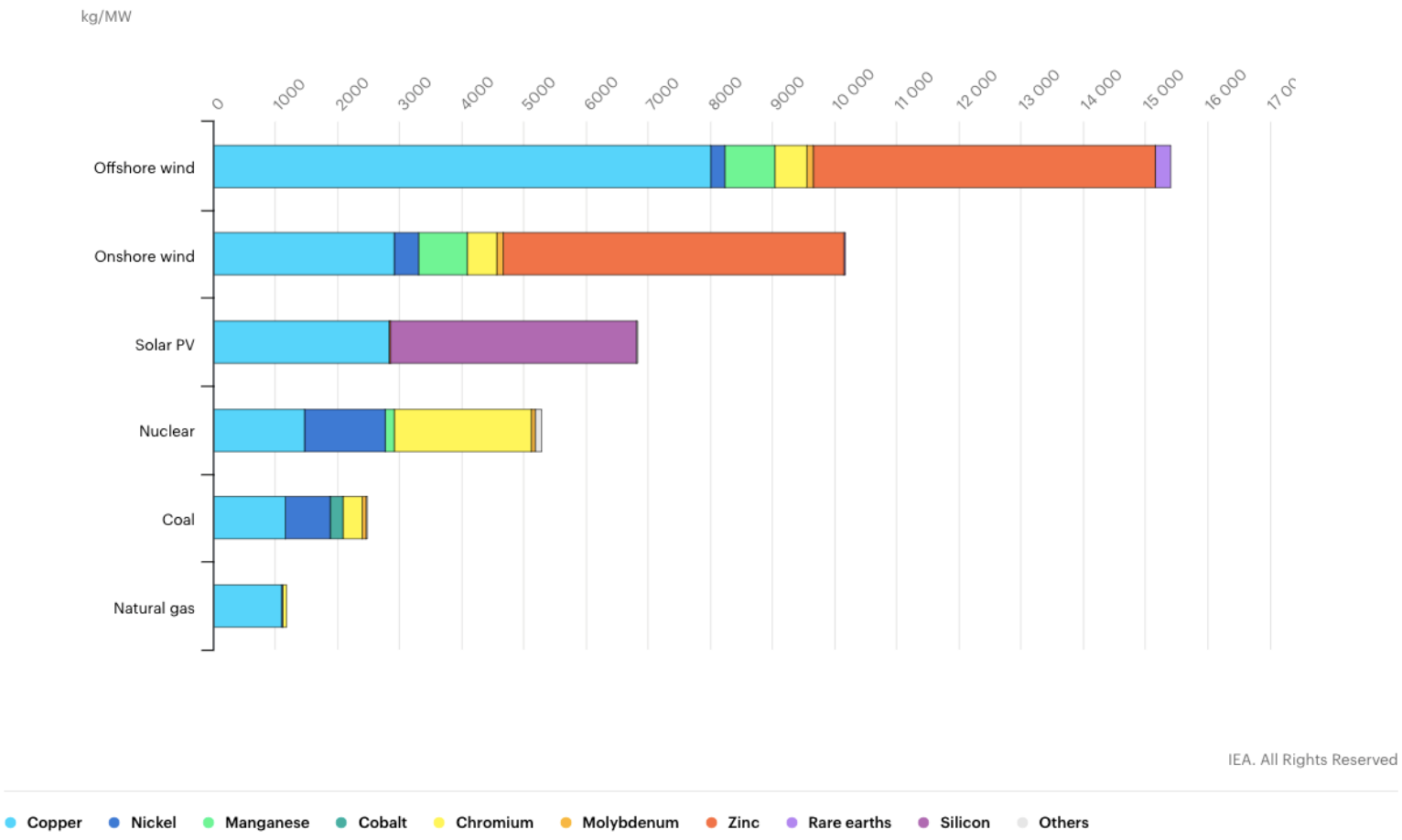


- 2 billions batteries of 50 kWh at 60 kg CO2/kWh → 6 GT
- 15 GW of Wind at 200 g CO2/W → 3 GT
- Systems, grid update…. → 6 GT

Estimated total (with current good practice) → 27 GT To compare with the current ~ 50 GT billions tons CO_2 eq produced every year, and the remaining 1000 GT remaining for a +2°C scenario

- **Using a few percent of our remaining carbon budget to make the object and infrastructure that will save on CO2 emission is the «less worse» use case for CO_2**
- And again, the more you decarbonise, the better the CO2 contents of modules similar orders of magnitudes for batteries and wind turbines).

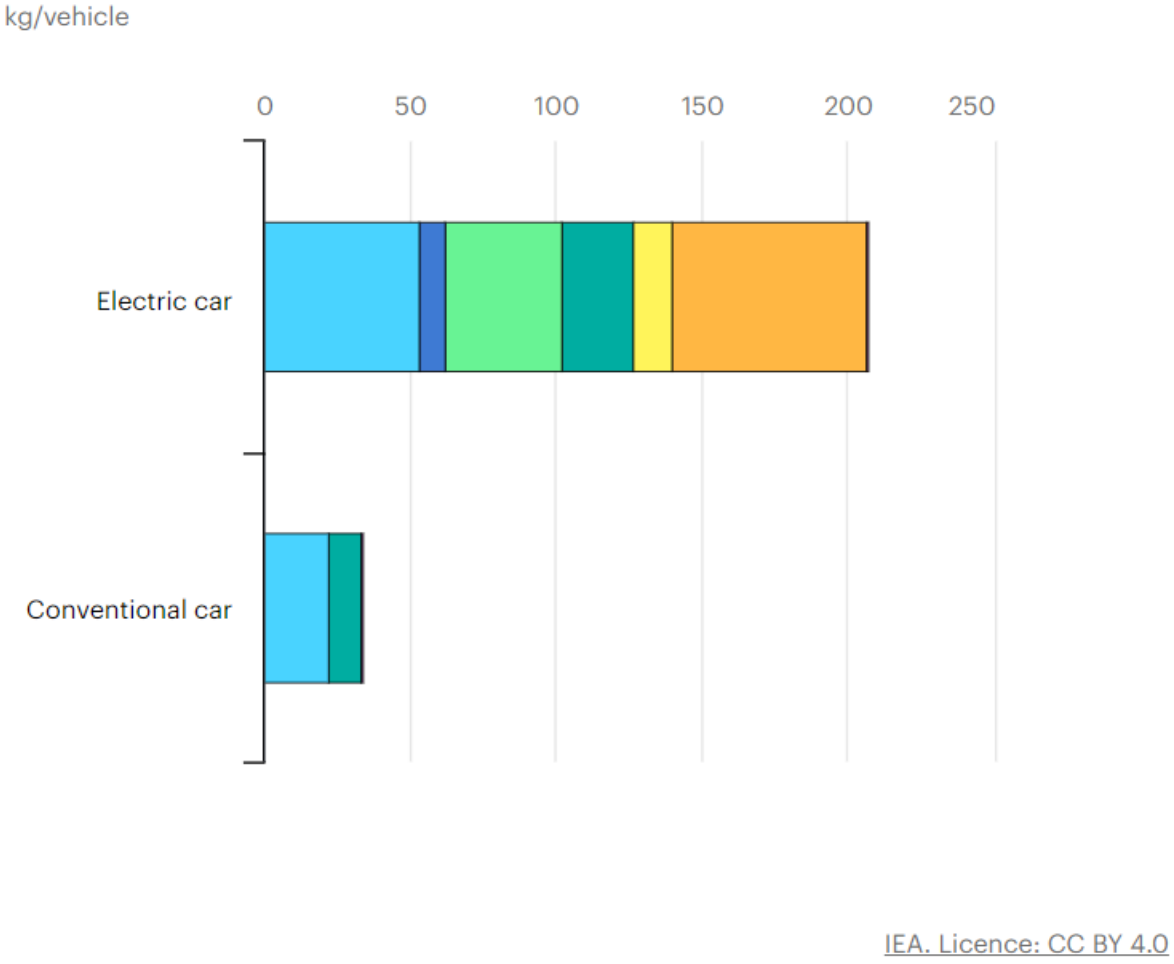
Material extraction



More Minerals needed for renewable electricity production

Prof. Christophe Ballif

Material usage for electrical NiCo lithium batteries



Note: many cars makers shift to Lithium Iron Phosphate batteries. Heavier but no Ni and Cobalt

Material usage: exemple Cupper

PV: 1 TW/year at 3 Cu Tons/MW → **3 MT /year**

Windturbines: 500 GW/year at 2 Tons/MW, with Al grid connection) → **1 MT/year**

Electric cars: 80 millions cars at 60 kg Cu, with charging station → **4.8 MT/year**

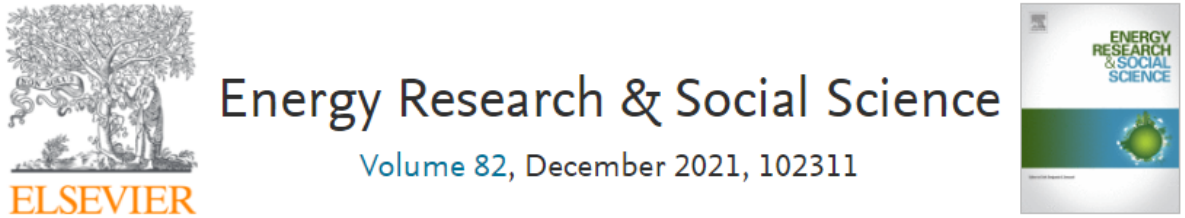
~ 8-9 MT out of 25 MT /year processed today

→ market pressure and possible bottlenecks, but not fundamental, and…

- Materials can be saved (improved designs), additional/improved mining and recycling. Or usage prioritised
- As for other less used materials alternative solutions always exist! e.g. rare earth for magnets of windturbines , Ag for photovoltaics, cobalt for batteries….
- **There is no succesfull product that every stopped being produced because of „not enough“**

Materials

There will be enough materials for the e-transition, but of course material usage should be contained everywhere. Solar is not limited even at 3000 GW/year



ELSEVIER

Energy Research & Social Science

Volume 82, December 2021, 102311

Perspective

More transitions, less risk: How renewable energy reduces risks from mining, trade and political dependence

Jim Krane, Robert Idel

More transitions, less risk: How renewable energy reduces risks from mining, trade and political dependence - ScienceDirect

"an emerging perspective in the US public discourse makes the opposite case, arguing that a buildout of renewable electricity would exacerbate supply risks, mining intensity, and import dependence. This paper's findings challenge such assertions."

Joule

CellPress

Volume 7, Issue 11, 15 November 2023, Pages 2408-2413

Commentary

Energy transition will require substantially less mining than the current fossil system

Joey Nijnens [1], Paul Behrens [2], Oscar Kraan [1], Benjamin Sprecher [3], René Kleijn [2]

Show more

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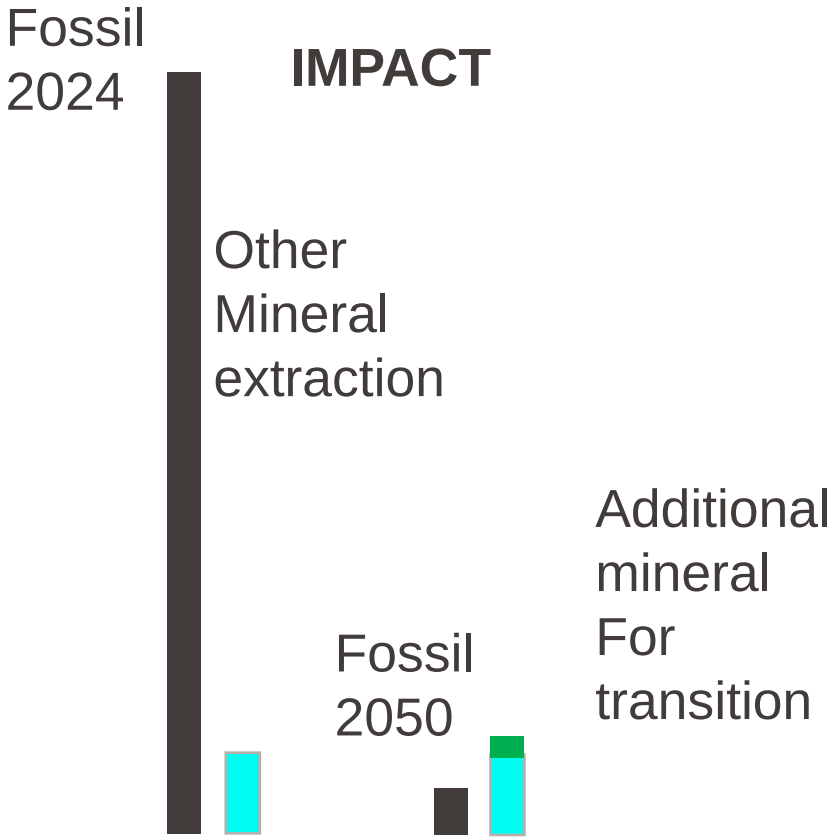
Fossil

- 5 trillions per year health costs
- 4-7 millions death
- Climate warming
- (and Putin)



Mainstream PV panels and a renewable world

Prof. Christophe Ballif

- No material resource issues (no scarce material, Ag could be become an issue, can be substituted by copper). Bottleneck and temporary price increase possible.
- Recycling possible (see PV cycle in EU and Sens eRecycling CH)
- For metals, mining, good practice required (as for any other product)
- Same for industrial production (as for any other product)
- Similarly enough materials, or substitution available for wind turbines and batteries
- Renewables: **chance to put more pressure on mining industry**
- To make products cheap, you need to save on resources and energy !!! This forces the material and energy learning curve!

- PV industry can have a minimum impact
- A small minor problem compared to global warming

2. Some practical aspects of PV installation

Not for the xam

- PV systems are mostly installed «grid» connected (at low or mid-voltage level). Usually do not provide «islanding» capabilities (in case of black-out). For islanding you need a special inverter and a battery (e.g. Studer in CH)
- Some inverters provide «battery ready» function, allowing loading/unloading of batteries
- Legal aspects will guide what you can do with your solar electricity:

e.g. in Switzerland
- self-consumption authorised and is not taxed, and there is minimum base feed-in tarif (with meters measuring in and out, not running reverse in «net-metering» mode).
-«self-consumption community» authorised (but one physical entrance point to the grid)
-One-time payement (typ 0.38 (rooftop)- 0.66 CHF/Watt (integrated > 70°) by Pronovo up to 30 kW

Tarificateur – Pronovo AG

Pronovo AG – Vollzugstelle für Förderprogramme Erneuerbare Energien

Nombre total des demandes

Le Diagramme 13 montre la puissance totale des nouvelles inscriptions mensuelles.

Outre les puissances des installations annoncées pour la PRU et la GRU, le diagramme contient également celles de la RUE, ainsi que les offres PV aux enchères avec adjudication et dépôt de garantie.

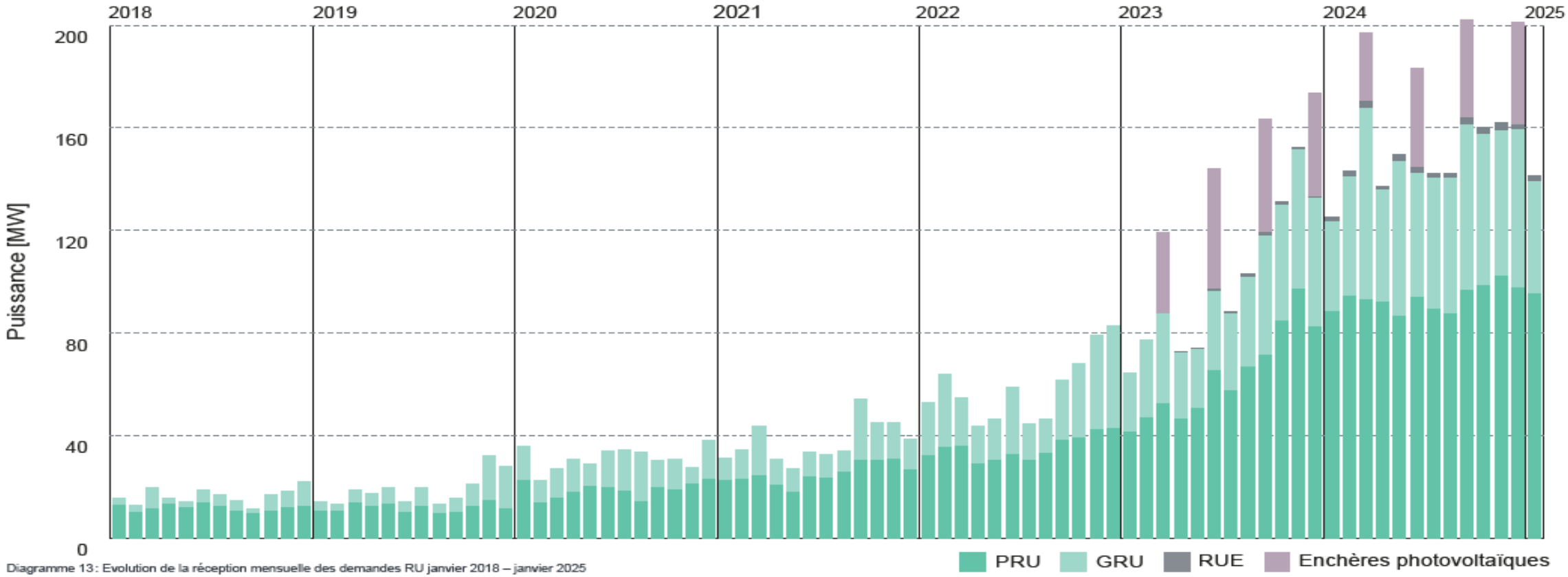
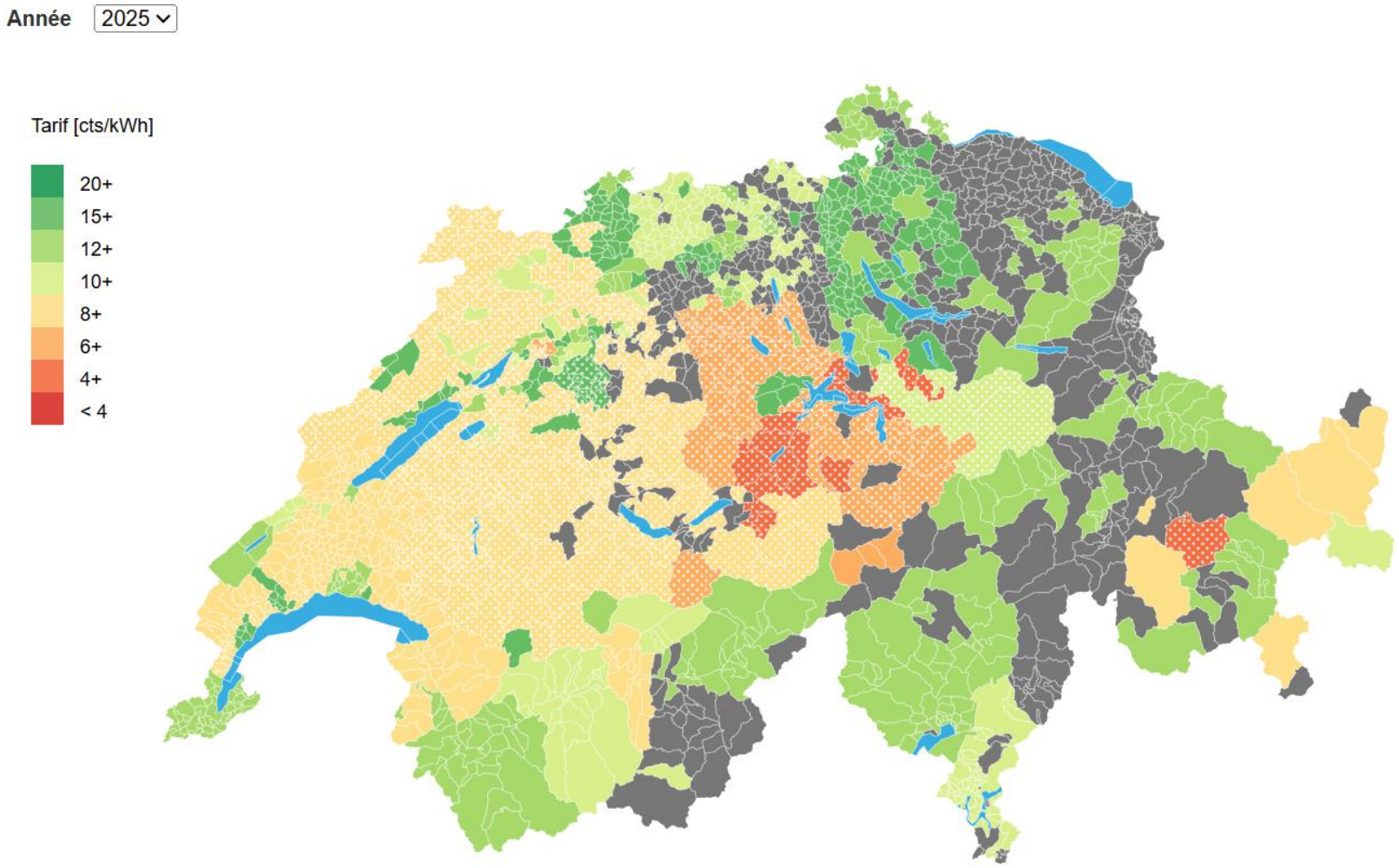


Diagramme 13: Evolution de la réception mensuelle des demandes RU janvier 2018 – janvier 2025

PV feed-in tarif

https://www.vese.ch/pvtarif/

Map 20245



Legal minimum in principle at least to market price
Depends on local distributor (but can change)
Strong variations in the last Years.

Soon (new electriciy law), minimum introduced at around 6.5 + «green origin», and quaterly basis price.

Too many installed systems tend to be undersized to favor self-consumption (whereas marginal cost of installation of more panels is not considered by many installers).

Installing the most would be the best in terms of energy transition

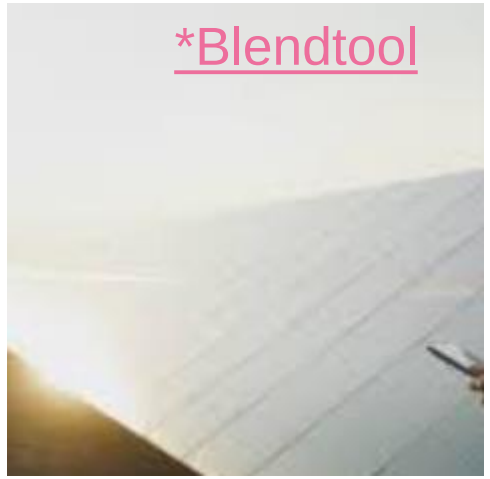
What you can easily do:

- Install a small system with a microinverter and plug-it in into your 220 V socket ! (very fast return on invest). No autorisation required in CH (max 600 W) .
- You can easily design your system, select the components and make all the engineering, including calculating the expected energy yield.
- Pay attention to ventilation/aeration, shading, roof waterproofness, and fireproof membrane, electrical circuit, and of course a good selection of components.
- If you have shadings, think of power-optimiser or microinverters (or Huawei solutions if a small fraction of modules risks be «shaded».
- But you'll have to take care of all norms and regulations, even more if you want to benefit from subsidies or incentives ! This depends a lot on the country.

Switzerland: you'll need to fill in 10 to 15 forms to get a system fully approved !

- Norms about components (e.g. 61730, … cables, connectors) (should be, but not always respected)
- Norms/ recommandation about construction permits, blinding risks*, building material norms (e.g. PV façade) (not always followed)
- Norms about AC and DC part of electrical systems (and annoucement to grid operator)
- Norms with respects to fire (depending on cantons),
- Requirements for getting local and/or national support

Association of PV professionals: **www.swissolar.ch**
Guide pratique des installations solaires
Guides pratiques et brochures (swissolar.ch)
See e.g. (in French unfortunately)
https://www.swissolar.ch/fileadmin/user_upload/Fachleute/Photovoltaik_Leitfaeden/200309_Leitfaden_RPG_Kurzfassung_FR.pdf



*Blendtool

Possibility for «auto-construction»

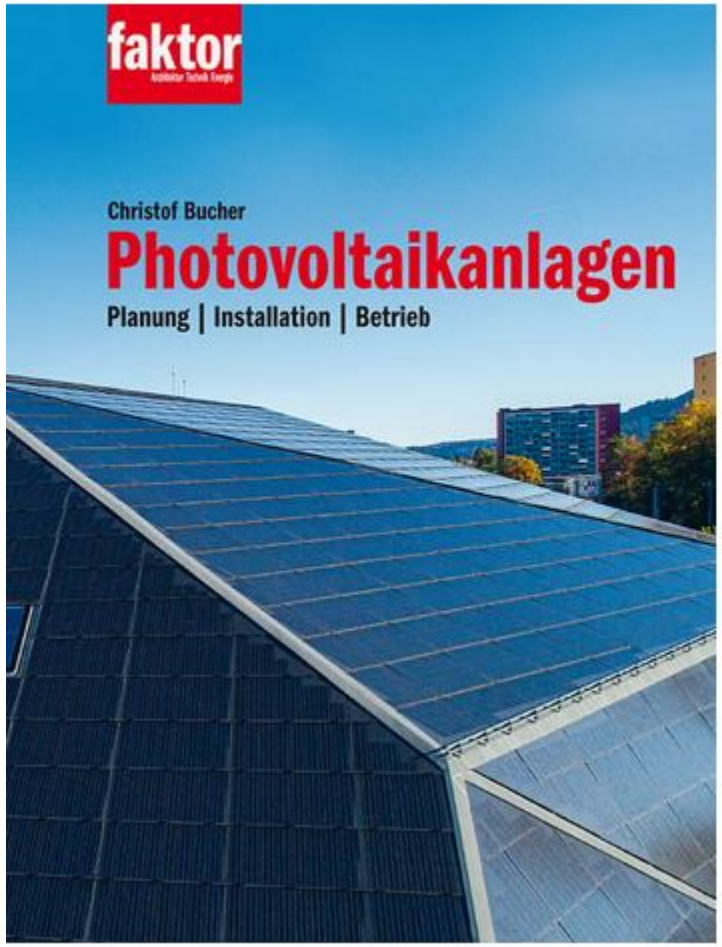
MANUEL POUR L'AUTOCONSTRUCTION (vese.ch) in French and German 2018

Possible to team up and install PV systems, 122 pages to learn it and respect the (changing)rules

Tâche / Etape	Planificateur, chef de chantier, coopérative	Maître de l'ouvrage	Co-constructeurs de la coopérative	Autres employés de la coopérative	Intervenants externes
Conseils, planif. globale, offre	5 heures	Participation			
Autorisations, demandes de subventions	3 heures	Participation			
Planification de détail, commande du matériel	3 heures				
Planification du chantier et coordination	4 heures				
Echafaudage	Contrôle	Commande			Spécialiste
Montage: structure, modules, passages de câbles, onduleurs	Directives 8 heures	16 heures	48 h		
Raccordements électriques DC	Coord.			Si autoris. art. 14 OIBT	Electricien
Raccordements électriques AC	Coord.				Electricien
Mise en service, remise, documentation	2 heures				
Total	**25 heures**	**16 heures**	**48 h**		

Fig. 7. Etapes de réalisation d'une installation photovoltaïque. Les heures indiquées sont approximatives et se réfèrent à une installation de 10 kW_c sur toiture de tuiles, sans complications.

A complete book about PV in Switzerland (2021, new edition 2025)



PHOTOVOLTAIKANLAGEN (BUCH + E-BOOK)

Christof Bucher

Kartonierter Einband, 440 Seiten

★★★★★ (0)

Erste Bewertung abgeben

Im neuen Standardwerk zur Photovoltaik hat Autor Christof Bucher viel Wissen für Planung, Bau und Betrieb von PV-Anlagen zusammeng... Weiterlesen ›

French edition in preparation

Stand-alone, islanding or microgrid systems, or «easy compatibility»: Swiss technology

- https://www.studer-innotec.com/en/

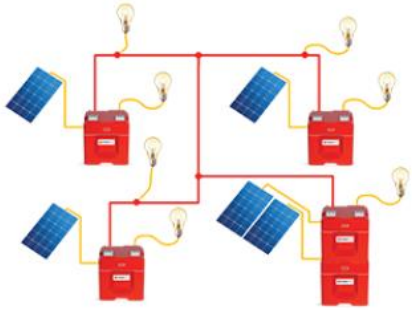
With a battery possibility to use the system during a black-out

https://power-blox.com/products

Self-assembly of battery
+ PV components

Stand-alone: Power of 200 Watt

Stacking: Power of up to 1.8 Kilowatt



Swarmgrid: Power of up to 10 Kilowatt

Wrap-up PV: A possible scenario

- The solar market, thanks to the high acceptance of solar, low cost and ease of installation, will grow quickly to 800-1000 GW/year by 2030 (some scenarios sees > 2TW/year). Low cost batteries will help !
- Many other aspects of energy transition (wind, electrification, grid) will be more implemented in many countries (but not all), likely always a factor 2 to 2.5, too slow to stay within the 2° scenario («don't look up» and Trump kind off effect)
- Solar chain has to ensure good practice (low CO2 emission, no forced labor, fair mining, no chemical pollutions), panel recycling. This is globally on good tracks.
- Long term solar electricity LCOE can further go down (thanks to cost decrease and mostly efficiency increases), but today price are already extremely low (oversupply)
- Integration of renewables (solar, wind, flexibilitity and batteries) will become a key (but interesting and workable) challenge. The more batteries, the less grid adaptation required
- With more and more climate events and energy security issues, droughts and fires, the push to develop renewables will continue
- Technology development in solar will continue to take place !
- Lot of opportunities for specialised companies, including in Europe along the value chain. But mass manufacturing will require support, as one can't beat China.

EPFL

PV-lab
IMT NEUCHATEL

What is your scenario ?