INTEGRATED-PV IN BUILDINGS & INFRASTRUCTURES: A CARBON FOOTPRINT PERSPECTIVE

Integrated Photovoltaic Conference

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Milan (IT)

Neuchâtel (CH)

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MOTIVATION

1. 5 to 10 TW_p of PV to be installed in Europe by 2050 to meet climate targets
2. **Conflicts** of PV with other land uses (agriculture, forestry, etc.) are frequently reported
3. Installation in the **built environment** (***buildings/infrastructures***) to be favoured

4. **Why PV in facades (90°-tilt) or other sub-optimal orientations?**

-the availability of optimal-oriented surfaces may be limited (shading!)

- S-facing façade: more stable production throughout the year, maximize production in winter & minimize effects of curtailements in summer

- **E/W-facing façades**: PV generation peak shaving/shifting

OUTLOOK

a. We are not taking an economical perspective

See e.g. *Gholami & Rostvik, Energy 2020* (in some countries N-facing facades may be "profitable" on a 20-30 yrs horizon;

b. Focus on the **carbon intensity (CI) of PV** (gCO2/kWh) deployed at different orientations/locations;

b. Comparison to the **CI of electricity consumption** in all European countries:

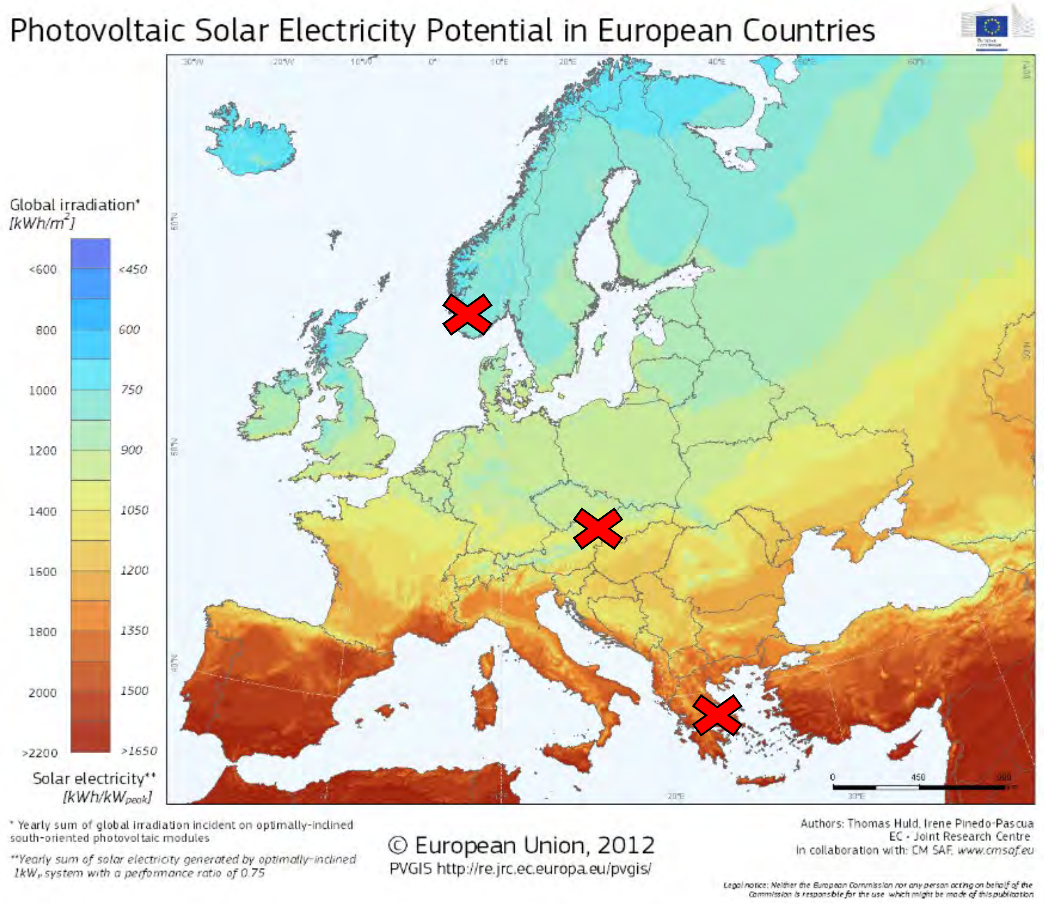
>>asses if **PV is acting as a net *CO_2 sink* or *source*** (compared to local el. mix);

CARBON INTENSITY (CI) OF SOLAR PV

a. Most lifecycle CO_2 emission are attributed to HW manufacturing
b. Little to transport, nearly no other emissions over lifetime
c. Breakdown of emissions: largest contributions cells/modules (~63%)

d. **CI intensity of a PV system** [kgCO_2-eq/kW_p] is fixed
e. **CI intensity of solar electricity** [gCO_2-eq/kWh] largely depends on siting and orientation

(factor of ~2 between Athens & Oslo)



Data:
PV-GIS JRC-EC

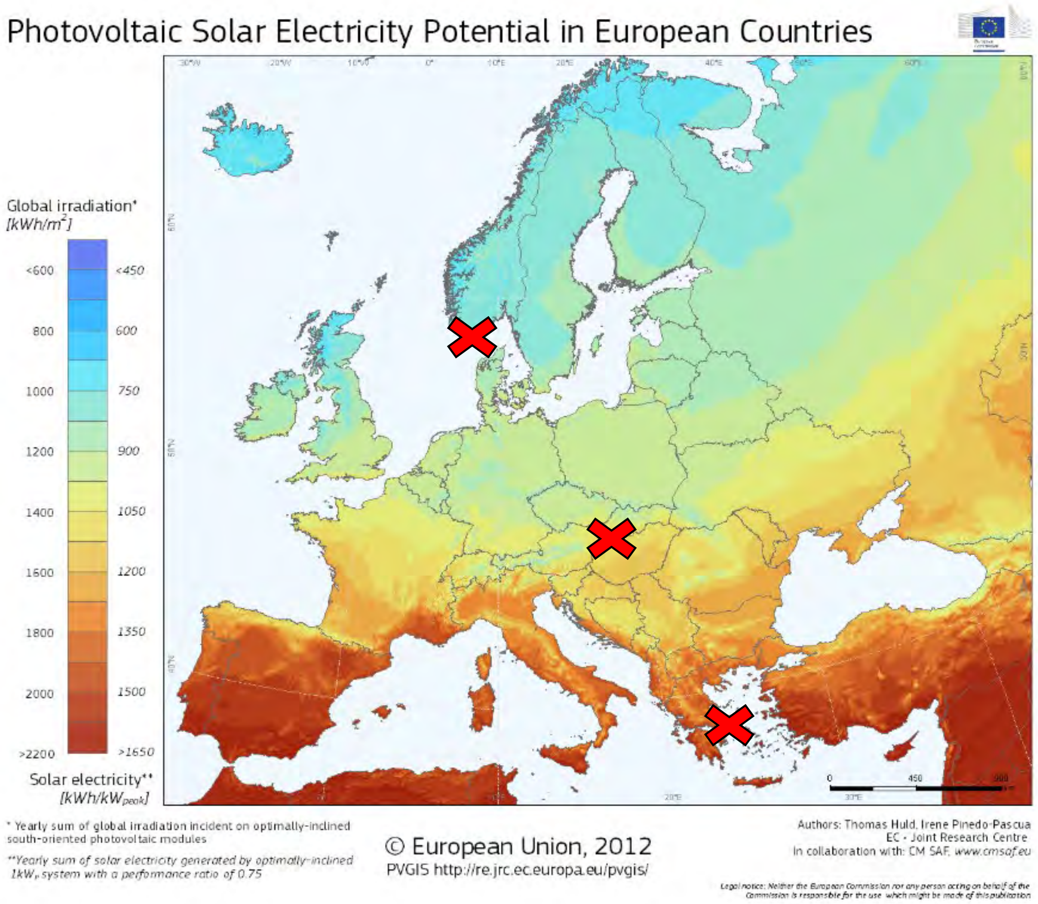
ENERGY YIELD [KWH/KW$_P$] / INSOLATION [KWH/M^2*Y] FOR DIFFERENT ORIENTATIONS/LOCATIONS IN EU

Orientation/tilt

For a given location, the energy yield of a PV systems corresponds:

- **S-facing facade**: ~72% of S-opta
- **E/W-facing facades** ~50% of S-opta
- **N-facing façades**: ~16% of S-opta

S-opta = S-facing at optimal tilt (opta)



Data:

PV-GIS JRC-EC

WHAT IS THE CARBON INTENSITY (CI) OF PV?

- Published figures are often **old/outdated**
- Majority of **PV module production in China** (high CI of electricity generation *-not consumption-* mix ~1000 gCO2/kWh in 2019, 65% of electricity comes from coal)
- Few recent works (2021-2022):

  - R. Frischknecht: IEA-PVPS 2022 factsheet

  - V. Fthenakis, *Progress in Photovoltaics* 2021 (lower CI numbers)

  - et al.

- IEA-PVPS 2022 factsheet : **PV 42.5 gCO2/kWh.**

  Assumptions: **3 kWp rooftop PV**, 975 kWh/kW$_p$ (83% of optimal tilt in Bern, CH 46°N), lifetime 30 yrs, degradation rate -0.7%/y

- In this work:

CI of PV corrected for energy yield (site/orientation) (lifetime 30 yrs, -0.7%/y)

CARBON INTENSITY (CI) OF COUNTRY ELECTRICITY MIXES?

PV electricity in urban environments is generated close to the final user and is mostly injected in low voltage (LV) grids.

To allow a fairer comparison, we use **CI (gCO_2eq/kWh) of electricity consumed** at LV grid with upstream compensation (Well-to-Wheel approach **W2W**).

Corrected for:

- electricity imports/exports between countries;
- transmission and distribution losses;
- upstream emissions caused by the extraction, refining and transport of the fuels to the power plants

Source: *Scarlet et al. Applied Energy 305 (2022)*

See as well: *Tranberg et al., En. Strategy Review 2019 & Gholami et al. Energy, 2020*

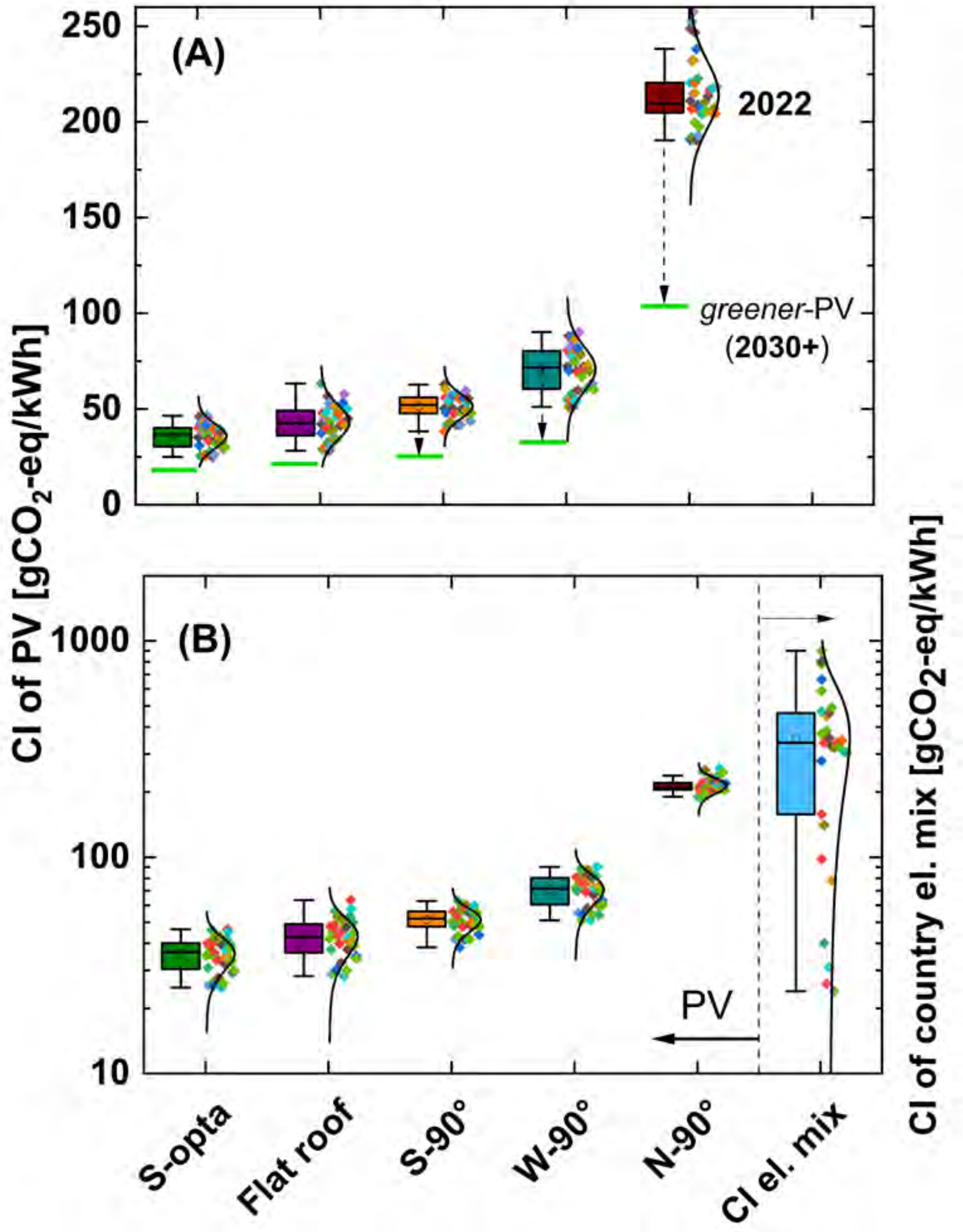
CI OF PV VS CI OF COUNTRY ELECTRICITY MIXES (3) – ALL EUROPE

- Results for capital cities
- Probability distribution of the CI of PV (all European countries, top &bottom)

  - CI of PV 2022

  - CI of PV 2030+ (*greener PV scenario*)

- Probability distribution of the CI electricity mix (all European countries, bottom)



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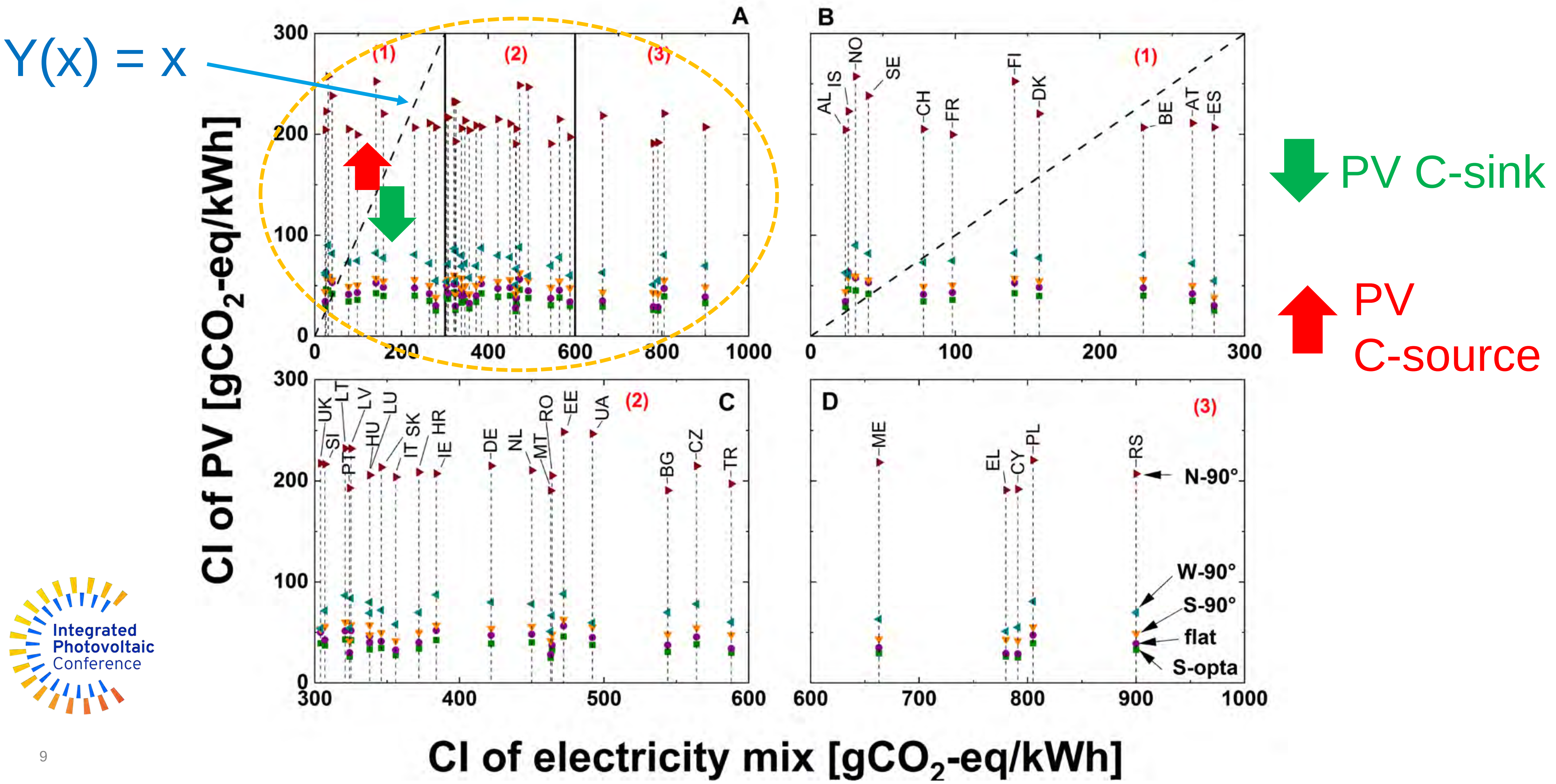
CI OF PV VS CI OF COUNTRY ELECTRICITY MIXES (4)



WELCOME TO FIRENZE !!!

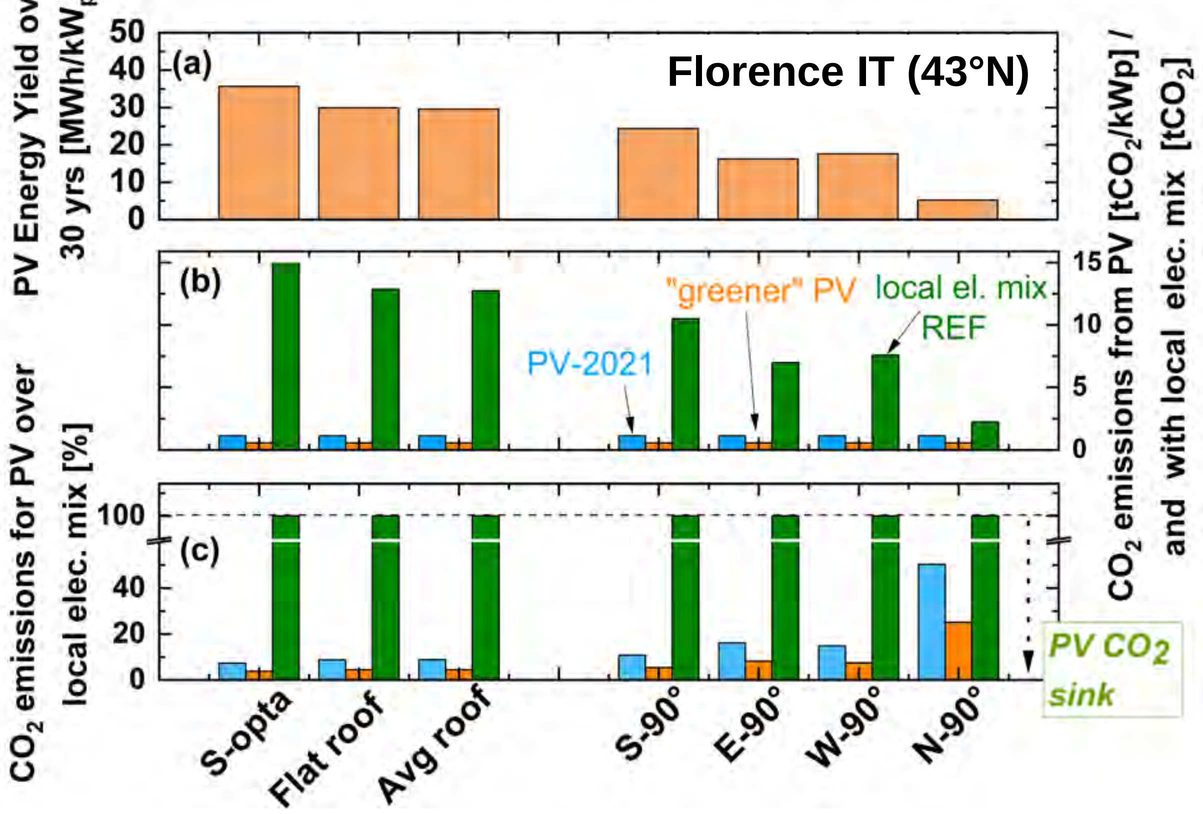
CI OF PV (OVER 30 YRS) VS CI OF COUNTRY ELECTRICITY MIX (CONSUMPTION)

Florence - IT

CI electricity mix (IT): 356 gCO2eq/kWh

(EU avg is 375 gCO2eq/kWh)

CI *PV-2022*:
42.5 gCO2eq/kWh



CI «greener PV» (2030-3035):
21.2 gCO2eq/kWh

Technological progress + production in countries with lower CI of el. mix (Europe?)

Lifetime CO_2 emissions of PV vs local electricity mix:
S- facing facade: 11% , W/E- facing: 16%, N-facing: 57%

>> PV is acting as a net CO_2 sink even in N-facing facades!

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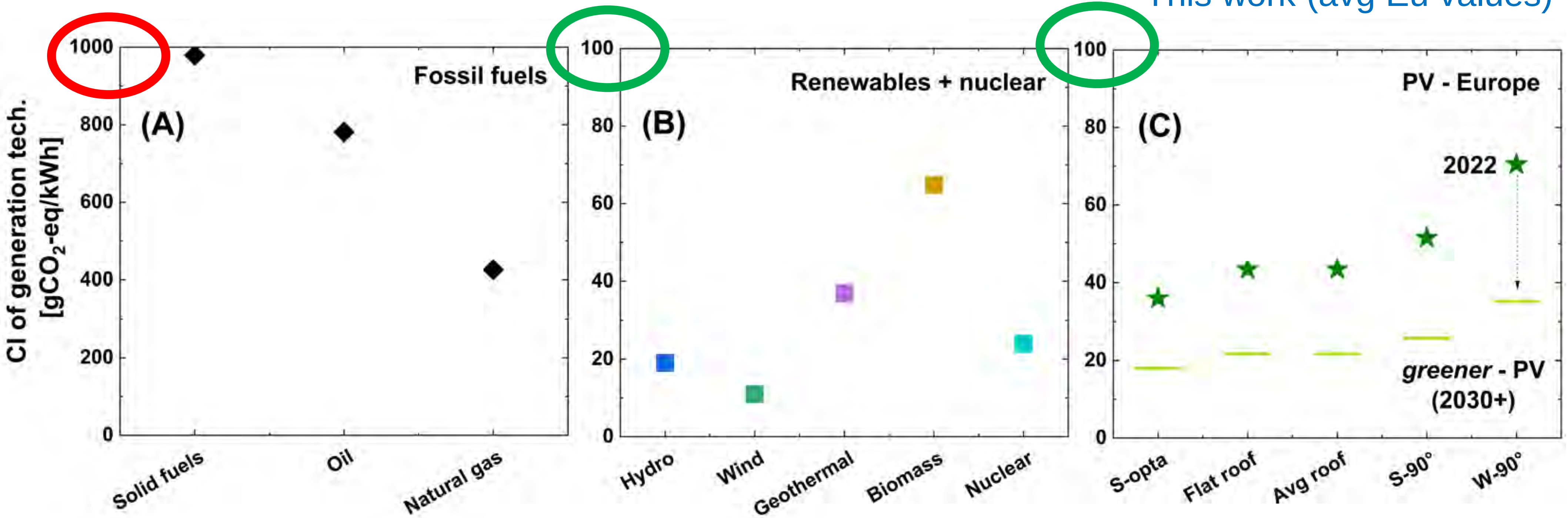
HOW DOES PV COMPARE TO OTHER GENERATION TECHNOLOGIES?

This work (avg Eu values)



- Fossil & other renewables
- PV: this work (mean European value)
- Both case: large variability

Source: *Scarlet et al. Applied Energy 305 (2022),*
NREL factsheet Report 2021

CONCLUSIONS

1. PV in urban/built environments - even at sub-optimal orientations – is a key-enabling decarbonization technology
2. CI considerations tell us that today PV is justifiable in most EU countries and most orientations (including – in several cases – N-facing facades)
3. In a «greener-PV» scenario (42.5 >> 21.2 gCO_2eq/kWh) this threshold is further reduced
4. CI of PV vs CI of local el. mix may serve as a first (but not unique) discriminant. We also need to decarbonize transport and heating sectors!!!

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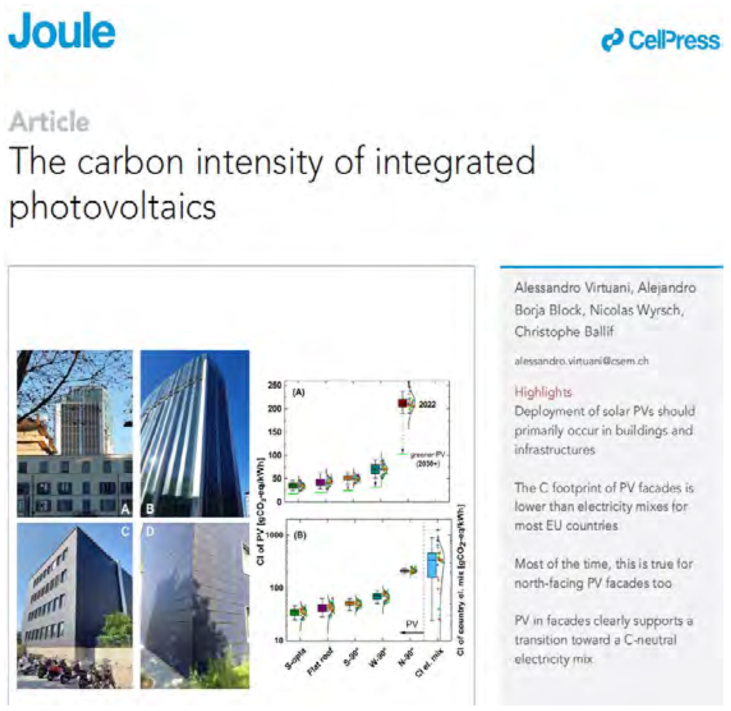
Interested in learning more?!?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Article
The carbon intensity of integrated photovoltaics
Alessandro Virtuani, Alejandro Borja Block, Nicolas Wyrsch, Christophe Ballif
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Highlights
Deployment of solar PVs should primarily occur in buildings and infrastructures
The C footprint of PV facades is lower than electricity mixes for most EU countries
Most of the time, this is true for north-facing PV facades too
PV in facades clearly supports a transition toward a C-neutral electricity mix

Virtuani et al., Joule 2023

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AGAINST …MINIMAL PV REQUIREMENTS (AS THEY ARE SET)

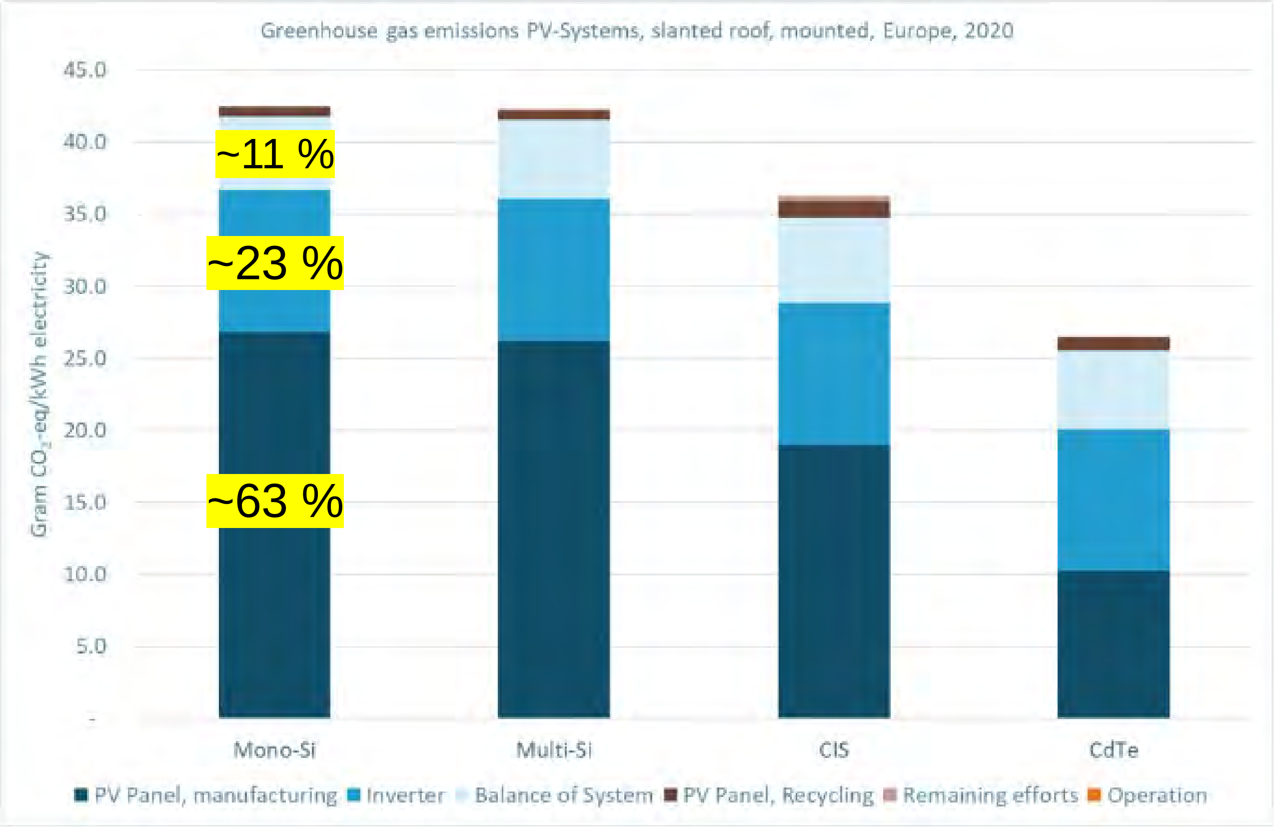
Source: Thomas Södestrom (csem)

Legislations demanding minimal PV requirements lead sometimes to the **«absurd» situations** where only 10 m^2 of PV is installed on single family houses, when 100+ m^2 (of well oriented PV) could be installed.

The situation of such roofs will likely be locked-up for the next 30 years.

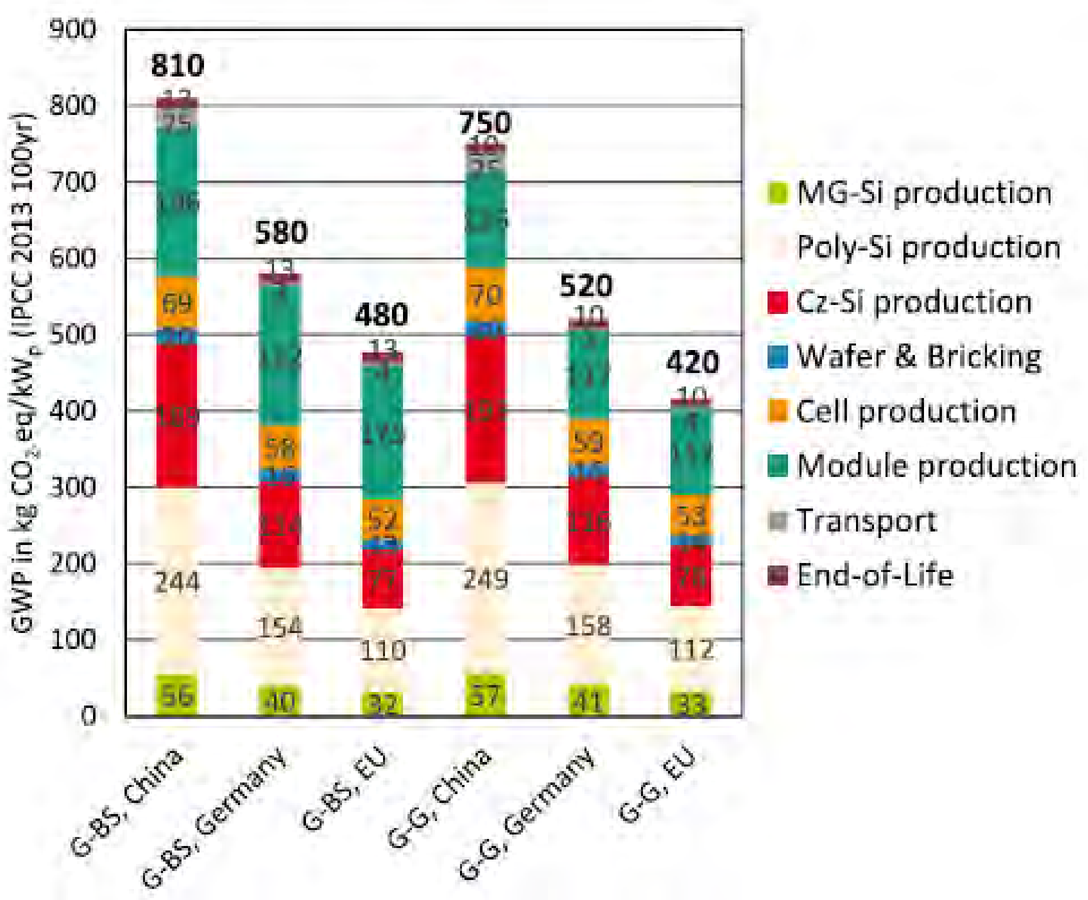
E.g. new residential project in Switzerland

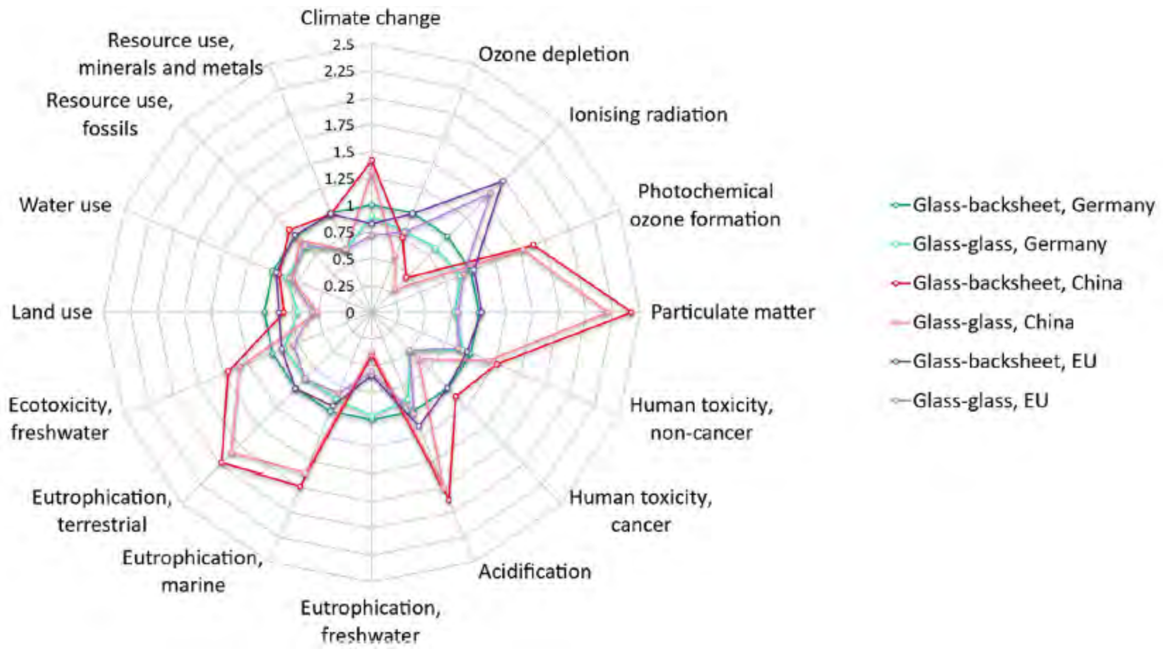
CI OF PV: BREAKDOWN OF SYSTEM CONTRIBUTIONS



IEA-PVPS Factsheet (2021)

GLOBAL WARMING POTENTIAL & ENVIRONMENTAL IMPACT





Müller et al. SolEnMatSolCel-2021

CAVEATS

1. Both CI of PV and of national electricity mixes are «**moving targets**»

>> **the sooner PV is installed, the greater the value (decarbonization potential)**!!!

2. We do not differentitate between BAPV (building-added) vs BIPV (building-integrated)

3. We do not offset the CO_2 footprint of BIPV/I-PV modules when they are replacing other construction elements;

4. We do not take into account lower pv generation due to:

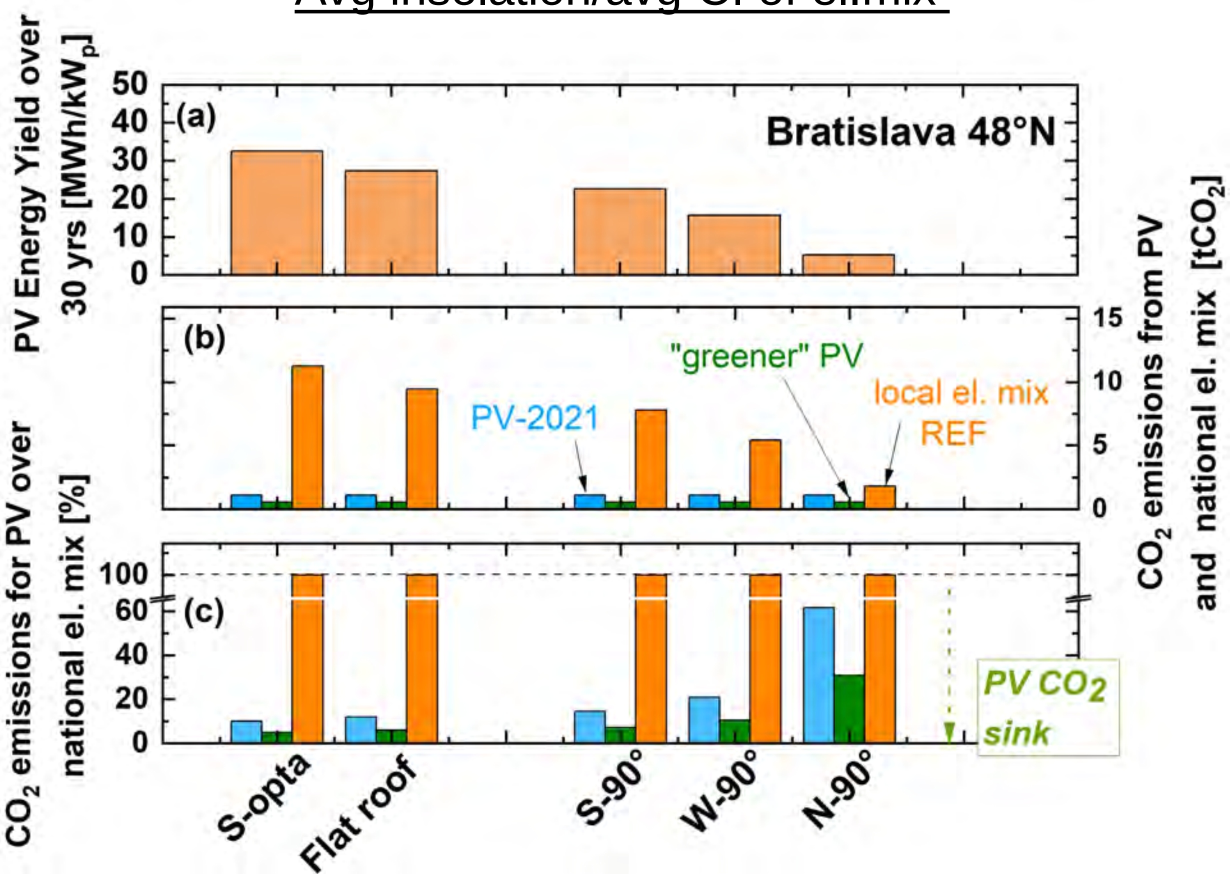
- Full integration (BIPV), i.e. higher operating temperatures

-Use of Colored-PV or more-transparent PV (lower efficiency)

CI OF PV (OVER 30 YRS) VS CI OF COUNTRY CONSUMPTION ELECTRICITY MIX (1)

CI el. mix (SK): 346 gCO2eq/kWh (EU avg is 375 gCO2eq/kWh)
Avg insolation/avg CI of el.mix

CI *PV-2022*:
42.5 gCO2eq/kWh



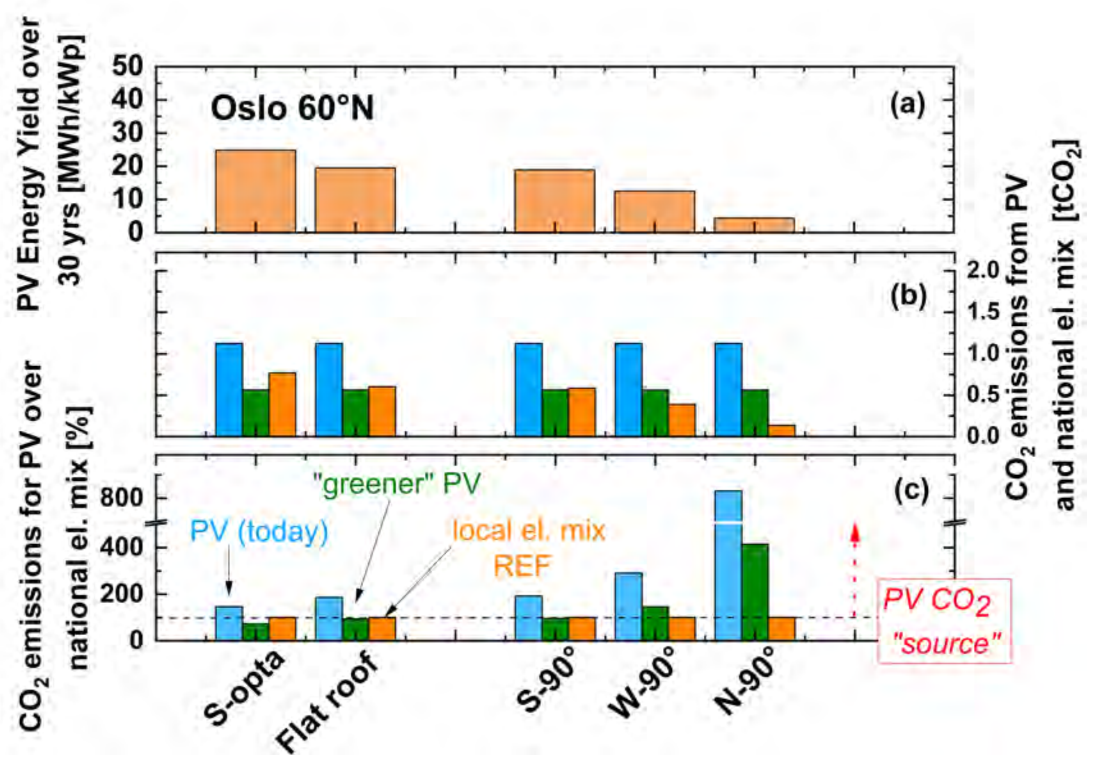
CI «greener PV» (2030-3035):
21.2 gCO2eq/kWh

Technological progress
+ production in countries
with lower CI of el. mix
(Europe?)

CO_2 emissions of PV vs local electricity mix:
S- facing facade: 18% , W/E- facing: 23%, N-facing: 71%
>> PV is acting as a net CO_2 sink even in N-facing facades!

CI OF PV VS CI OF COUNTRY ELECTRICITY MIX (2)

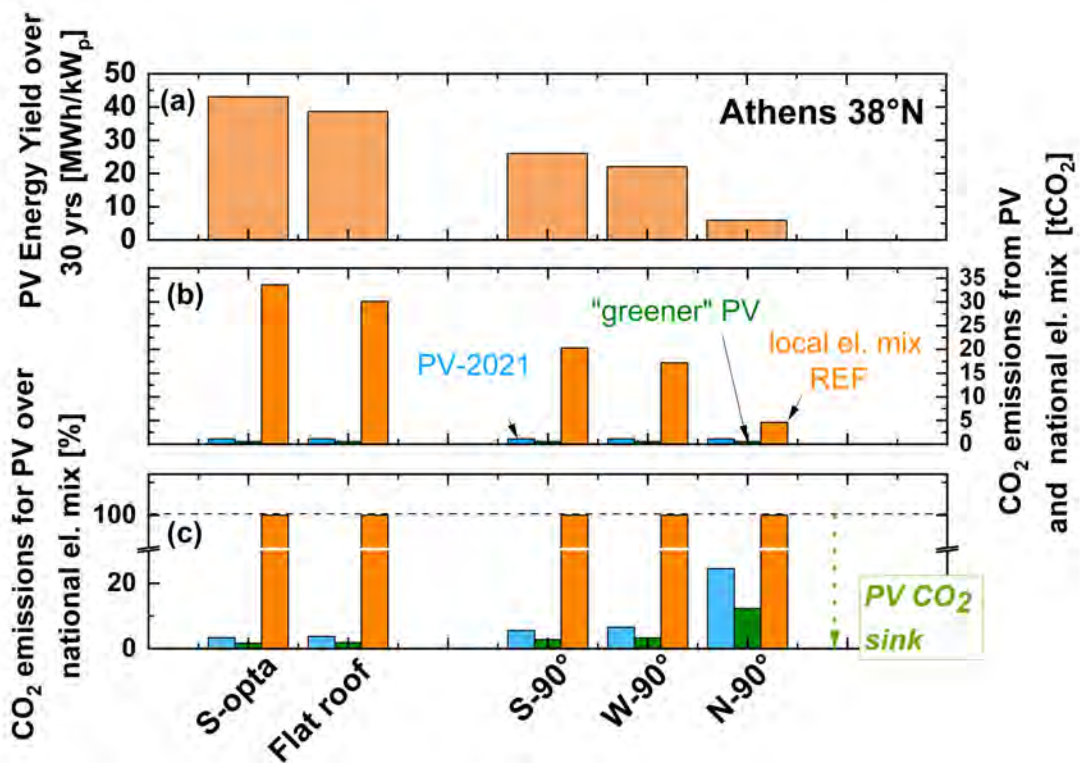
CI el. mix (NO): 31 gCO2eq/kWh
low insolation / low CI-el. mix



NO: today PV, not at the first place!

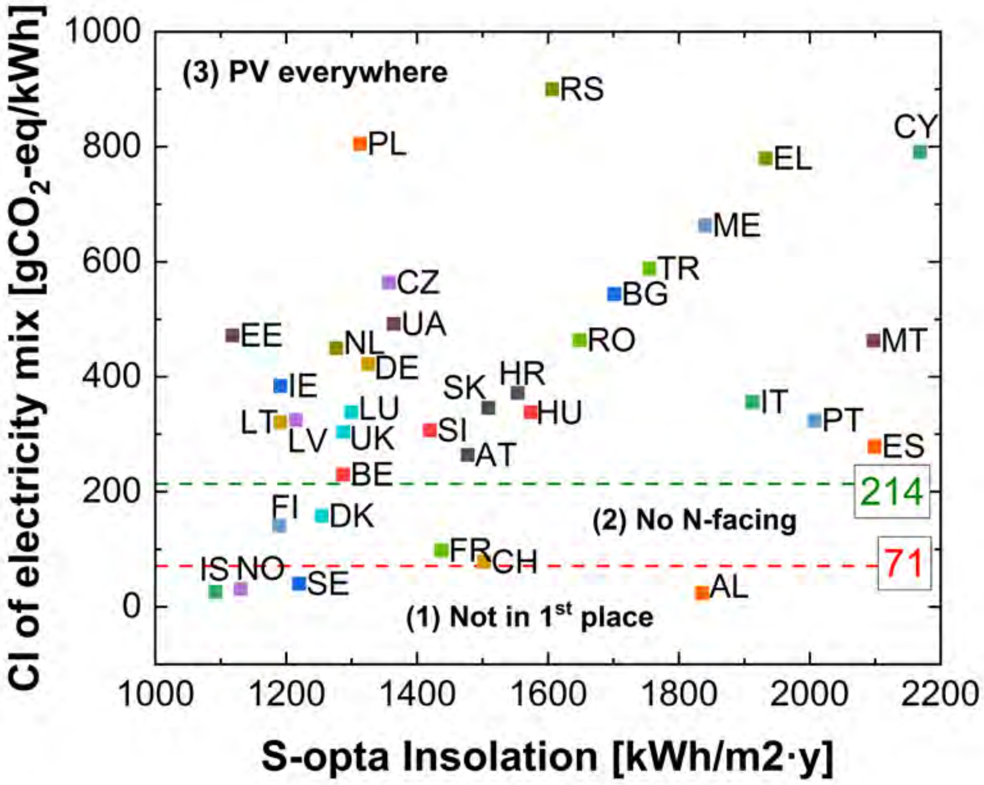
NO: with «greener»-PV, possibly «somewhere».

CI el. mix (NO): 780 gCO2eq/kWh
High insolation /high CI-el- mix



GR: today PV makes sense everywhere!

WHERE DOES PV GO FIRST?



CI of national electriciy mix vs S-opta Insolation (capital city)

LCA DATABASES ARE OFTEN OUTDATED

A. Müller et al. *Solar Energy Materials and Solar Cells 230 (2021) 111277*

Table 4
Overview of most important parameters and assumptions of the LCIs compared in the sensitivity analysis: Ecoinvent v.3.7 [22], IEA PVPS 2015 [3] and this study for glass-backsheet module production in the EU.

	Unit	Ecoinvent v3.7 [22]	IEA PVPS 2015 [3]	This study [30]
Reference year of LCI		2005	2011	2020[a]
Module power	W_p	224	224	366
Module efficiency	%	14	14	19.8
Wafer thickness	µm	270	270	170
Kerfloss	µm	191	145	80
Wafer sawing method		Slurry based	Slurry based	Diamond wire sawing
Electricity consumption		MG-Si: Norwegian electricity, poly-Si: 60% hydroelectricity, Rest: EU medium voltage grid mix (year 2017)	MG-Si: Norwegian electricity, poly-Si: 60% hydroelectricity, Rest: EU medium voltage grid mix (year 2017)	Only EU medium voltage grid mix (year 2017)
MG-Si	kWh/kg	11	11	11
Poly-Si	kWh/kg	110	110	72
Cz-Si	kWh/kg	85.6	68.2	38.4
Wafering	kWh/m²	8	25.7	2.35
Cell	kWh/m²	30.2	14.4	6.24
Module	kWh/m²	4.71	3.73	3.32
Silicon consumption				
MG-Si	kg Si Sand/kg MG Si	2.7	2.7	2.7
Poly-Si	kg MG Si/kg Poly-Si	1.13	1.13	1.13
Cz-Si	kg Poly-Si/kg Cz Si	1.07	0.781[b]	0.639[b]
Wafering	kg Cz Si/m² wafer	1.07	1.58	1.03
Cell	m² wafer/m² cell	1.06	1.03	1.02
Module	m² cell/m² module	0.932	0.935	0.898
Poly-Si composition		Mix of electronics grade (14,6%) and solar grade (85,4%) silicon	Mix of electronic grade (14.6%), solar grade (80.2%) and off-grade (5.2%) Si.	Only solar grade silicon
Aluminium	kg/m² module	2.63	2.13	1.51
Glass	kg/m² module	10.1	8.81	8.00

[a] Reference year for foreground LCI is 2020 [30], while background processes from Ecoinvent have older reference years [22].
[b] Input of recycled Cz-crystal (corners from cutting round ingot in square slabs) not included in Cz-process but in Wafering process.

Müller et al. SolEnMatSolCel-2021

AVAILABILITY OF SOLAR RESOURCES