Future material demand for global silicon-based PV modules under net-zero emissions target until 2050

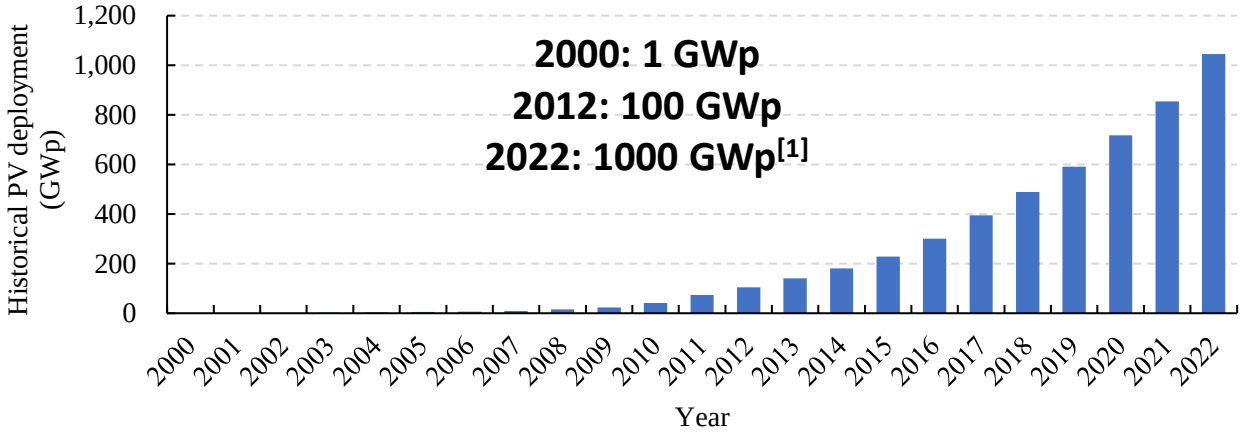
Chengjian Xu, Olindo Isabella, Malte R. Vogt

27th of September 2024
5EP.1.1, 41st EU PVSEC, Wien, Austria

PVMD
Delft University of Technology

TU Delft

Exponential growth in photovoltaics



Past decade:

- Average annual growth rate: 25%
- Price: -91%

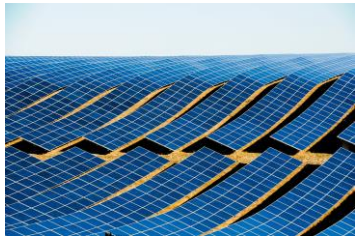
Today:

- 1 TWp cumulative global installed PV capacity
- PV is cheapest form of electricity in most countries

Solar cell
~5-10 Wp

PV module
~300-500 Wp

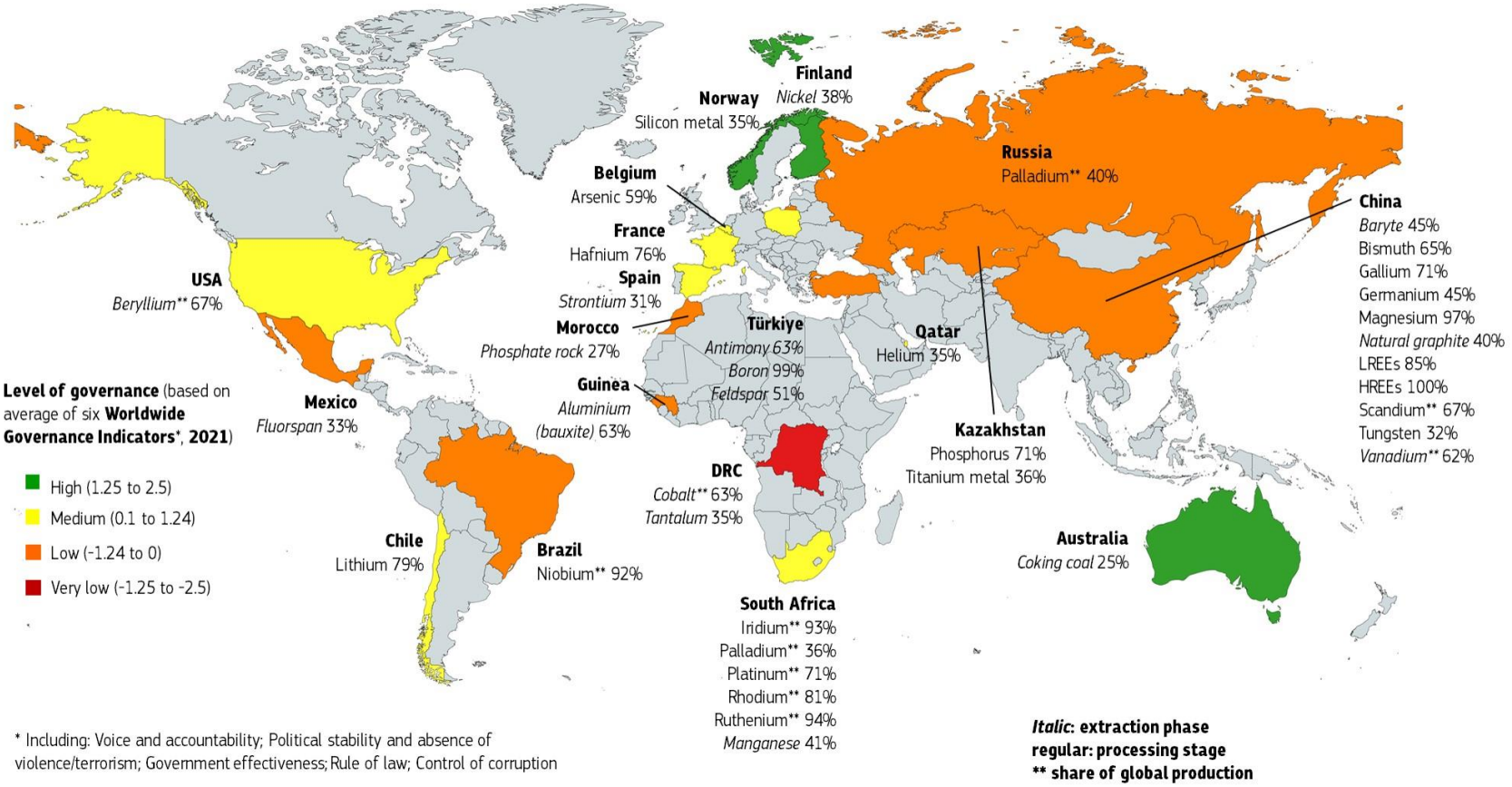
Rooftop system
~2-10 kWp



Solar farm
~1 MWp-8.4 GWp

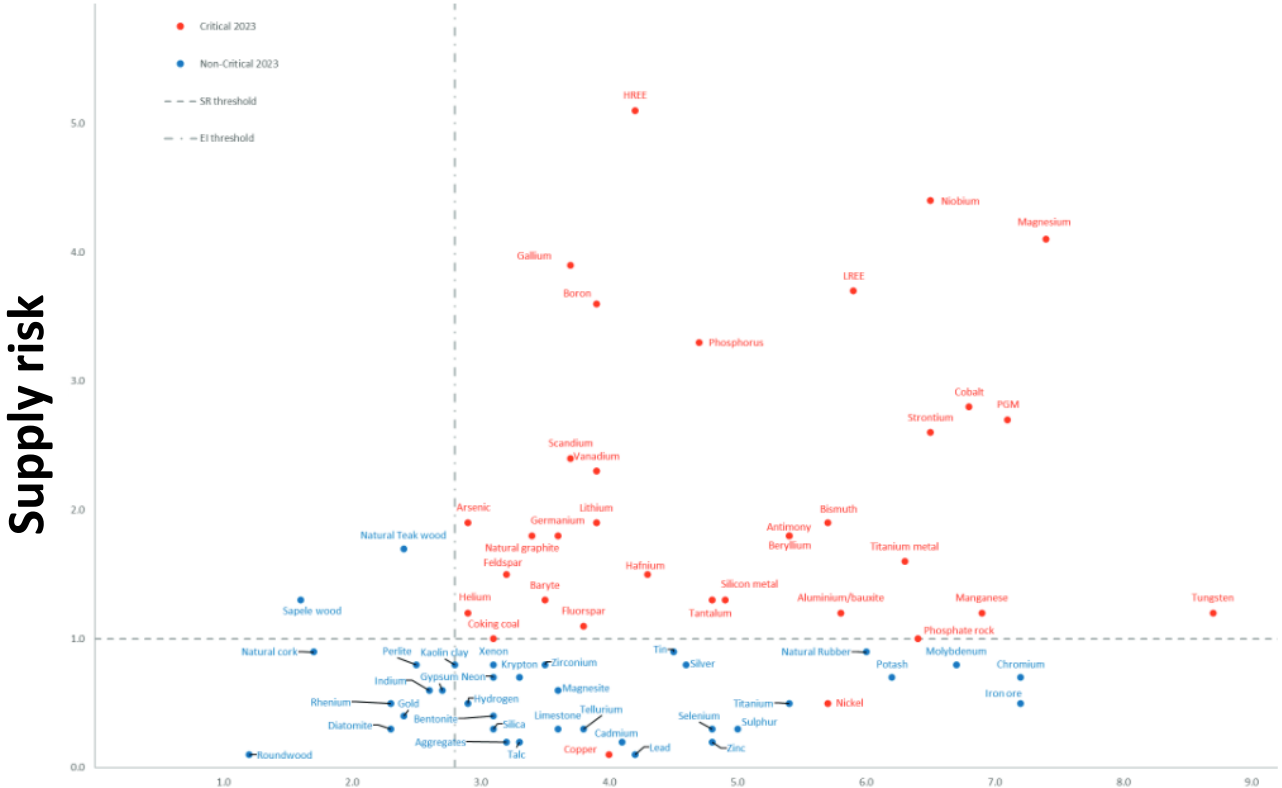
[1] Adapted from IRENA RENEWABLE CAPACITY STATISTICS (2023)

Do we have enough critical raw materials for PV?



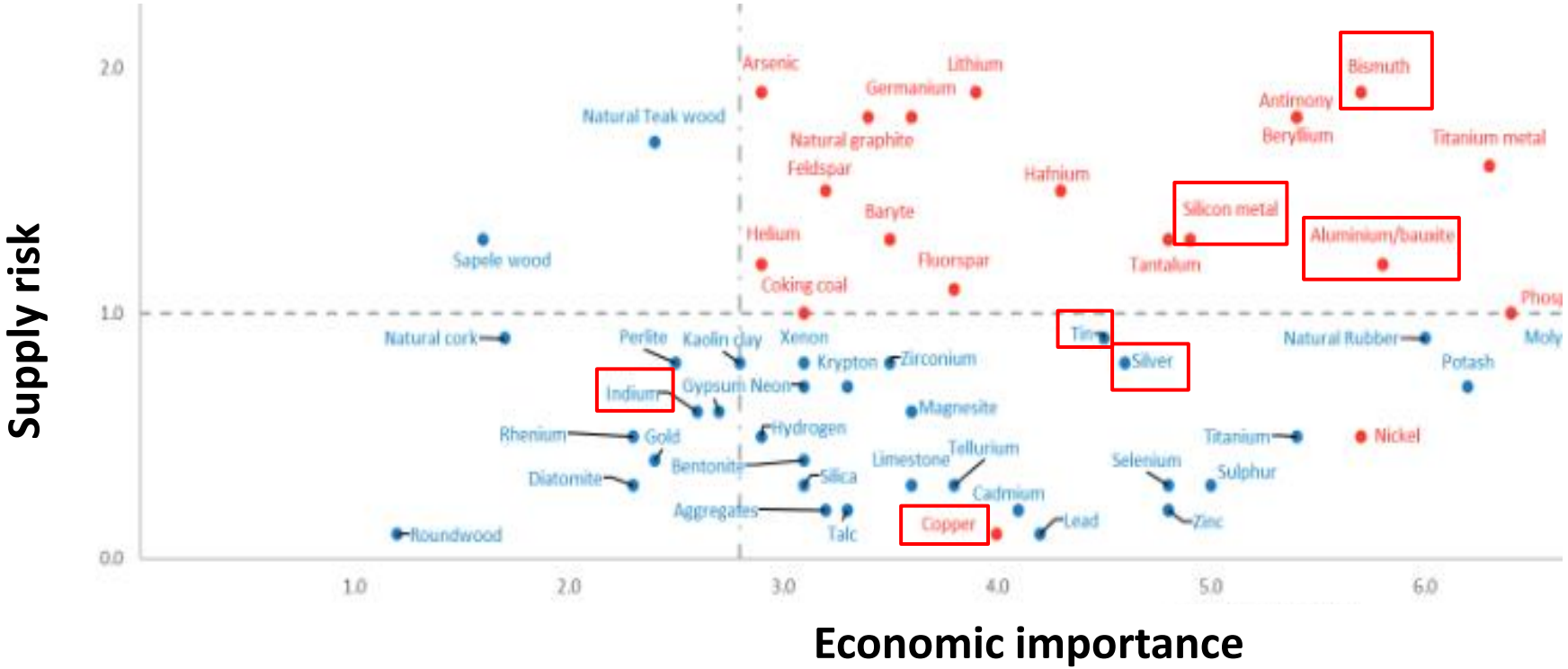
https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials

Critical raw materials



Source: European Commission, Study on the Critical Raw Materials for the EU(2023)

Critical raw materials



Source: European Commission, Study on the Critical Raw Materials for the EU(2023)

Critical raw materials ACT

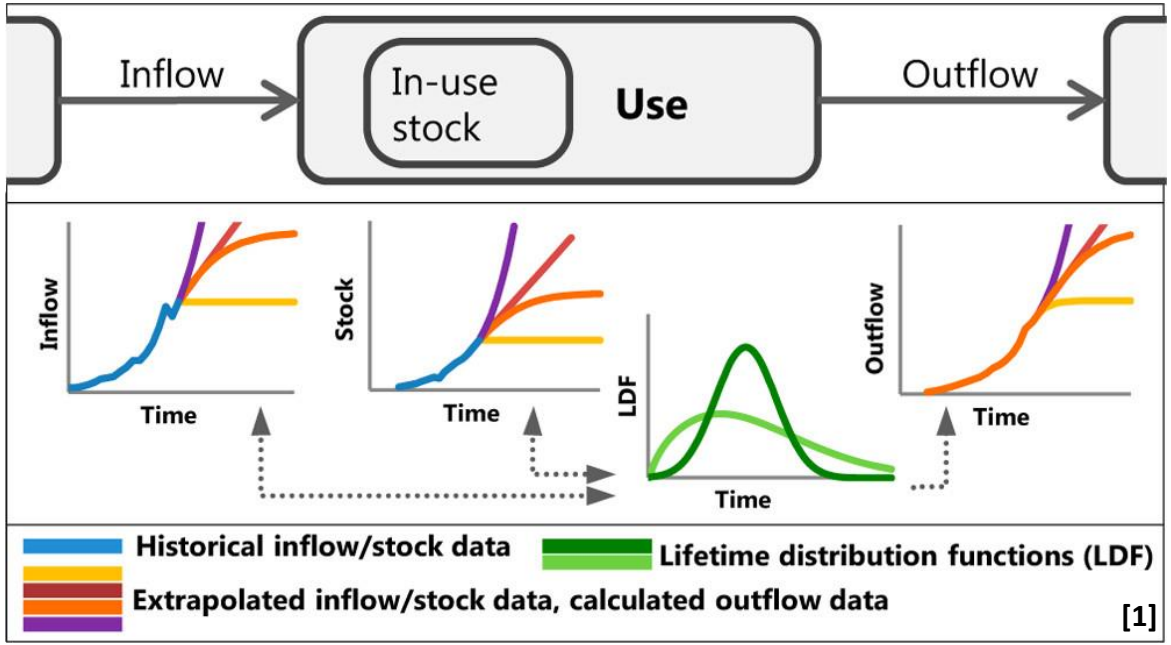
European Commission

EU Critical raw materials ACT

- **2030 domestic capability benchmarks for strategic raw materials:**
  - **>10%** of the EU's annual consumption for **extraction**
  - **>40%** of the EU's annual consumption for **processing**
  - **>25%** of the EU's annual consumption for **recycling**
  - **<65%** of the EU's annual consumption from a **single third country**

Source: European Commission, Study on the Critical Raw Materials for the EU(2023)

Dynamic material flow analysis model

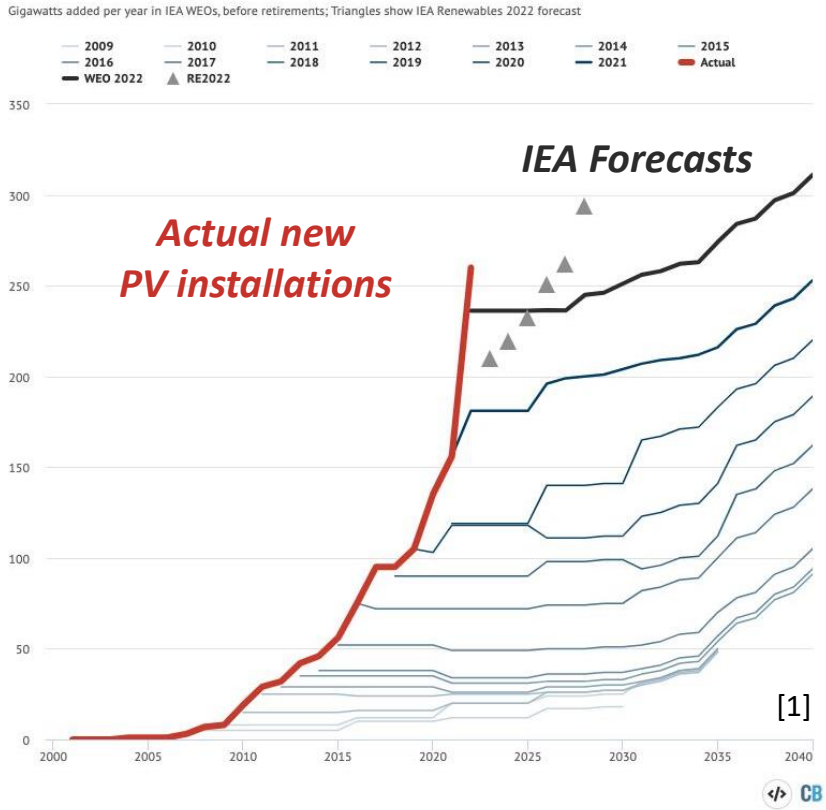


- **Stock driven**
- **Global PV deployment[2,3,4]**
- **PV technology changes**
- **PV lifetime[5]**
  - Utility PV systems: Average lifespan of 26 years
  - Residential PV systems: around 18 years, considering economic motivations
  - Weilbull distribution

[1] E. Müller, et al., *Environ. Sci. Technol*. **48**, 2102-2113 (2014)
[2] International Technology Roadmap for Photovoltaic (ITRPV), 13th Edi., (2022)
[3] International Energy Agency (IEA), Net Zero by 2050, (2021)
[4] IEA, https://www.iea.org/reports/solar-pv, (2022)
[5] V. Tan et al., *Sustainability*. **14**, 5336 (2022)

PV capacity growth projections past

Gigawatts (GWp) of PV added globally per year

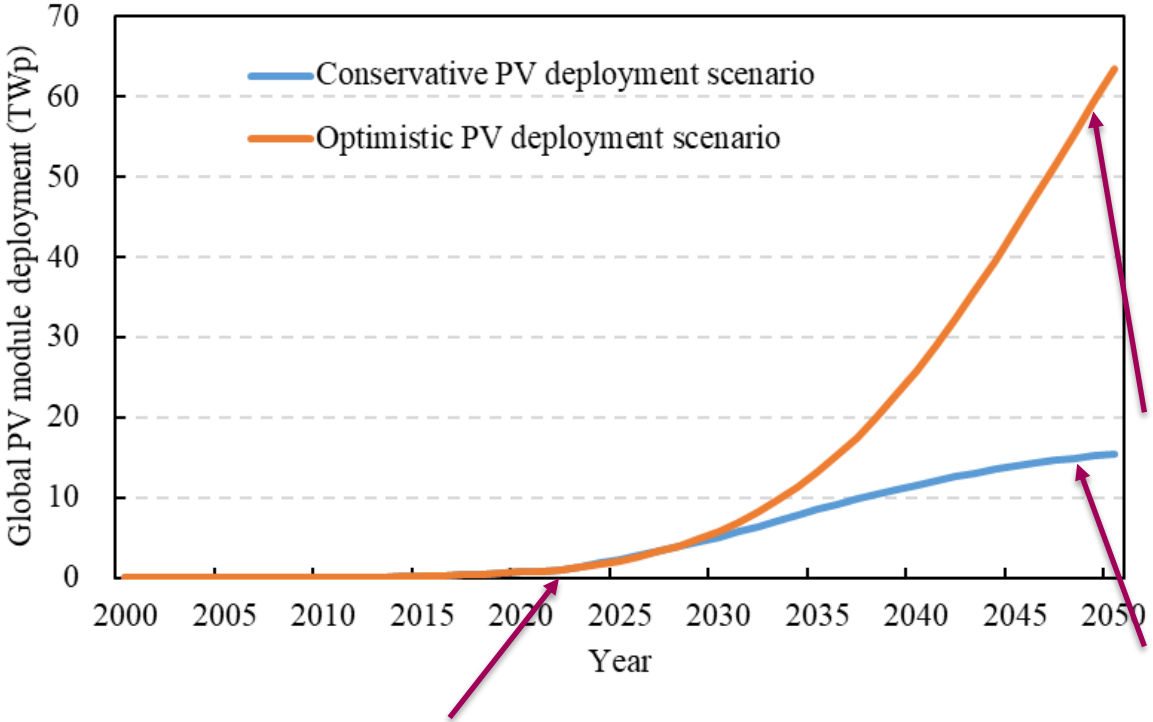


[1]

- **Growth scenarios can be wrong!**
- **IEA is conservative on PV growth**

[1] https://twitter.com/AukeHoekstra (2023) based on IEA projections

Global PV deployment size



- **Net zero emissions goal by 2050**

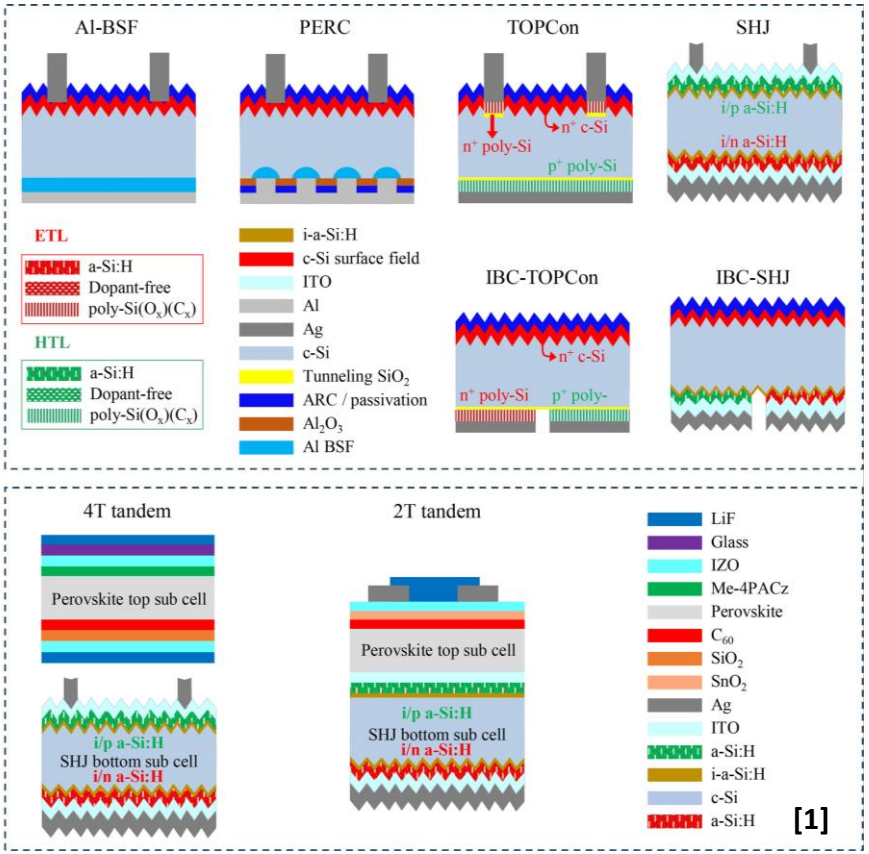
Broad electrification scenario [2] as High scenario:
63.4 TWp by 2050, supplying 69% of 150 PWh global electricity demand

IEA scenario[1] as Low scenario:
15.5 TWp by 2050, supplying 35% of 70 PWh global electricity demand

1 TWp in 2022, supplying 4.5% of 29 PWh global electricity demand

[1] IEA, *World energy outlook(WEO)*, (2021)
[2] D. Bogdanov et al., *Energy* **227**, 120467 (2021)

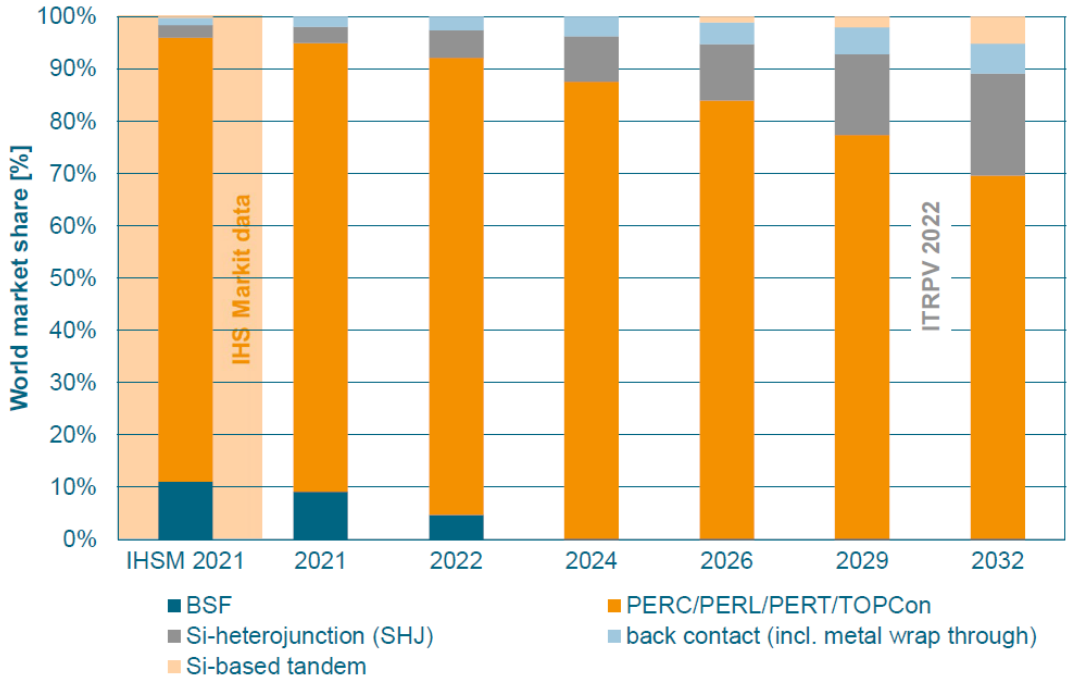
PV technology composition



- **Eight cell architectures**
- **ITRPV[2] for material use (Wafer thickness, Silver, Glass, Aluminum, etc.)**
- **Including module level (G-G, bifacial, frames, etc.)**

[1] Chengjian Xu et al., *RCR* **210**, 107824 (2024)
[2] International Technology Roadmap for Photovoltaic (ITRPV), 13th Edi., (2022)

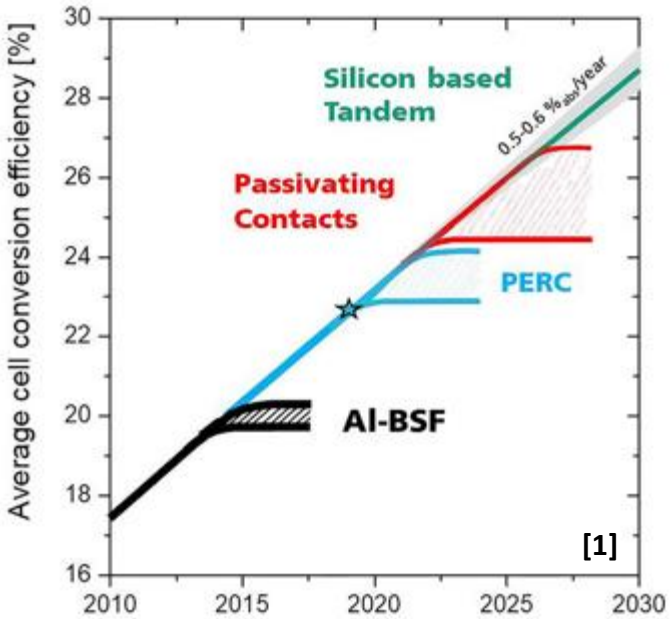
PV technology trends

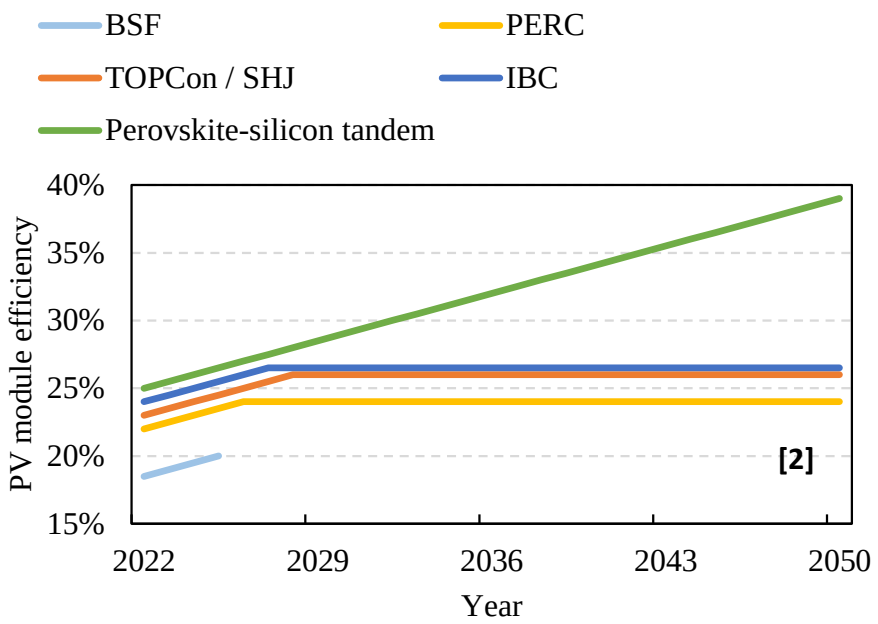


- **Market share of PV technologies[1]**
- **Learning rates[1]**
  - **Silver consumption**
  - **Cell dimension**
  - **Glass consumption**
  - **Many more ….**

[1] International Technology Roadmap for Photovoltaic (ITRPV), 13th Edi., (2022)

PV efficiency projection

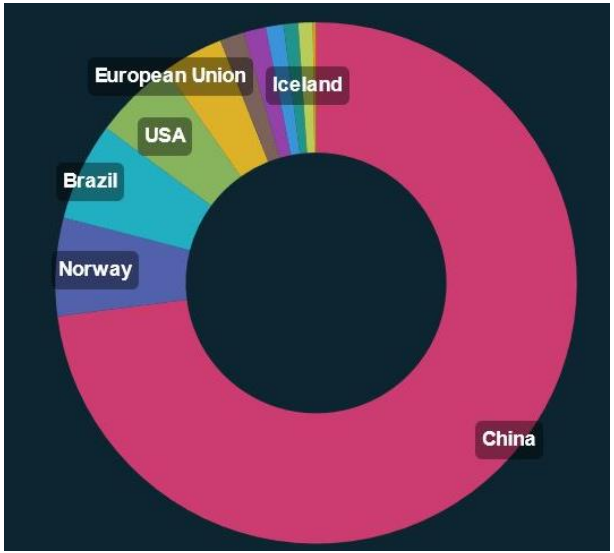




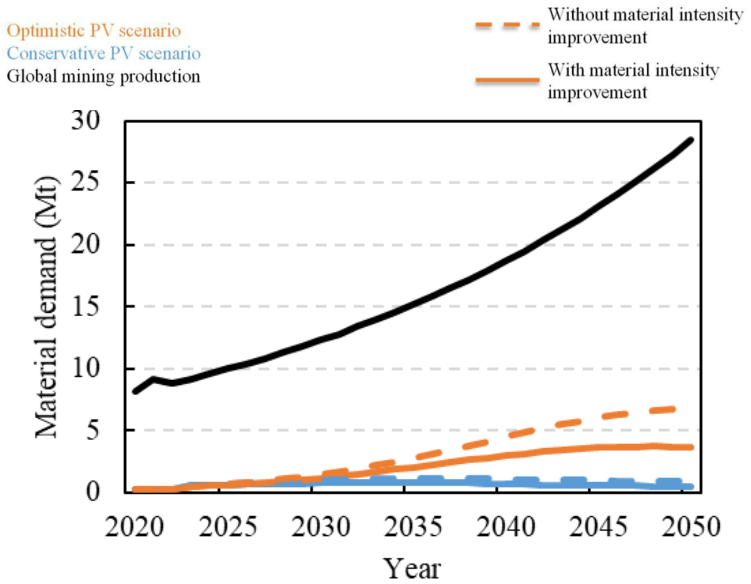
[1] M. Hermle et al., *Appl Phys Rev.* **7**, 021305 (2020)
[2] Chengjian Xu et al., *RCR* **210**, 107824 (2024)

Silicon metal demand PV 2022->2050

World's refined silicon metal producers[1]



- **Critical raw material[1]**
- **4% of world's production in EU(France)[1]**

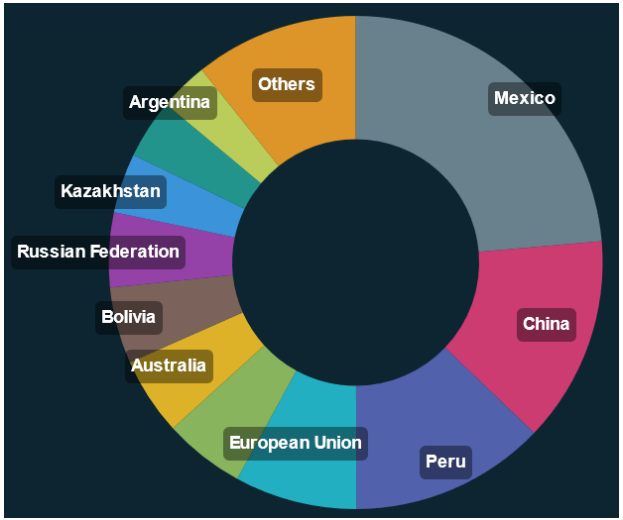


- **46 % reduction due to material intensity improvement[2]**

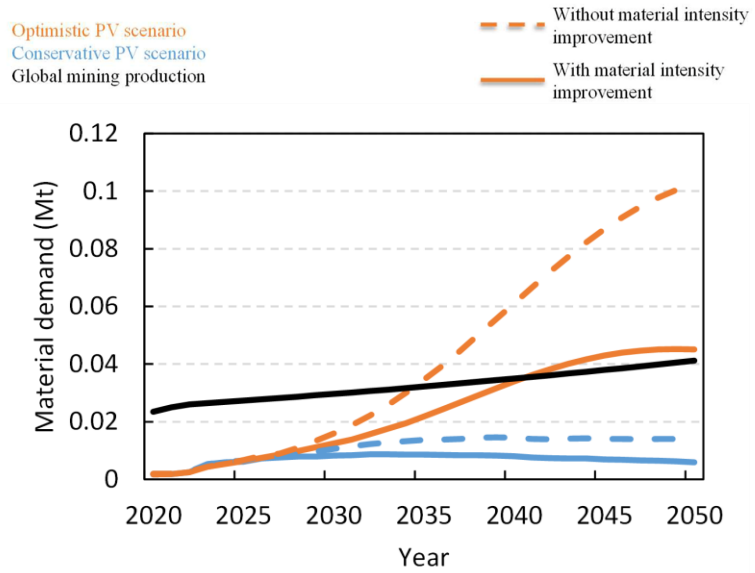
[1] https://rmis.jrc.ec.europa.eu/
[2] Chengjian Xu et al., *RCR* **210**, 107824 (2024)

Silver demand PV 2022->2050

World's primary Ag producers[1]



- Supply risk too low[1]
  - 82% of EU demand self-supplied
- 8% of world's production in EU(Poland)[1]



- 56 % reduction due to material intensity improvement[2]

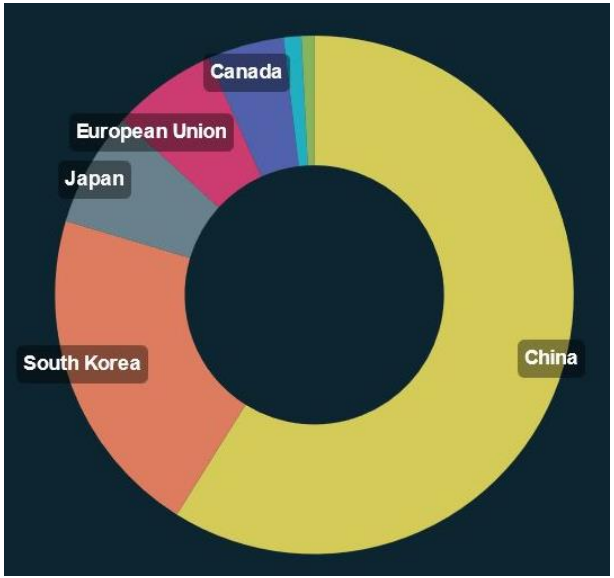
[1] https://rmis.jrc.ec.europa.eu/

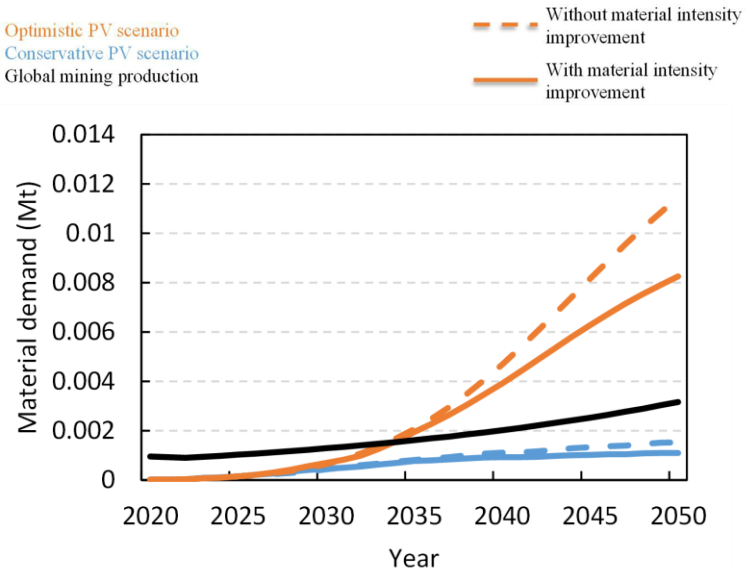
[2] Chengjian Xu et al., *RCR* **210**, 107824 (2024)

Update based on: International Technology Roadmap for Photovoltaic (ITRPV), 15th Edi., (2024)

Indium demand PV 2022->2050

World's refined In producers[1]





- Supply risk & economic importance too low[1]
  - 63% of EU demand self-supplied
- 6.5% of world's production in EU(France)[1]
- 28% reduction due to material intensity improvement[2]

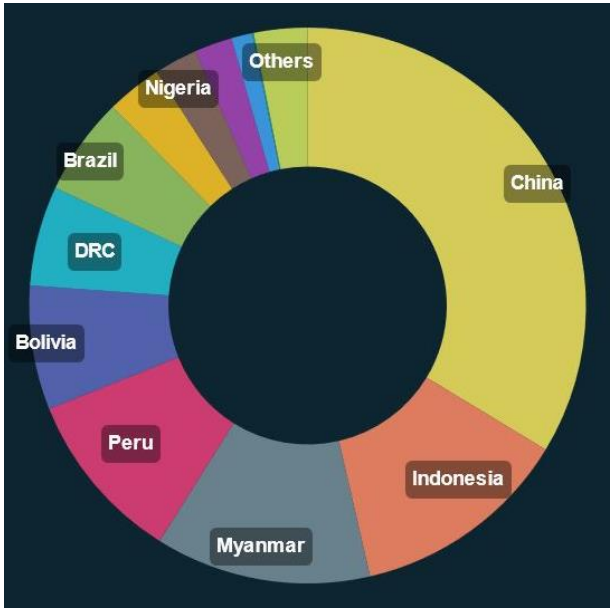
[1] https://rmis.jrc.ec.europa.eu/

[2] Chengjian Xu et al., *RCR* **210**, 107824 (2024)

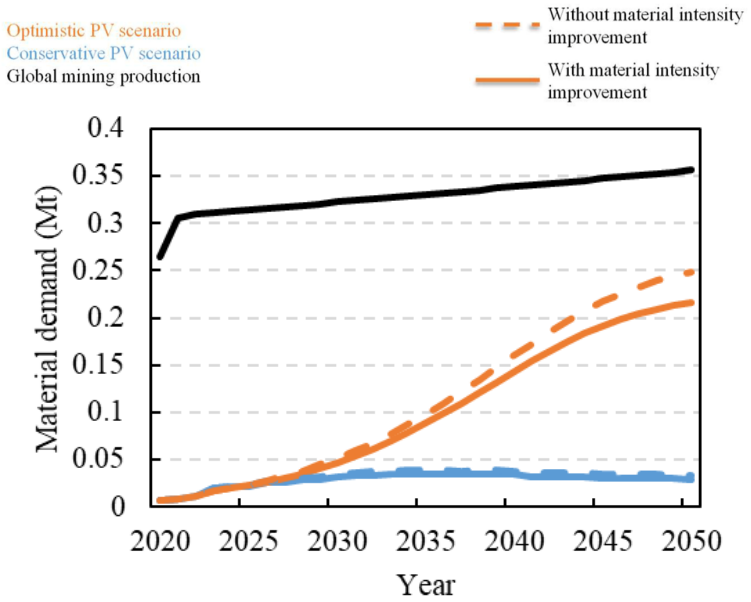
Update based on: International Technology Roadmap for Photovoltaic (ITRPV), 15th Edi., (2024)

Tin demand PV 2022->2050

World's primary Tin producers[1]



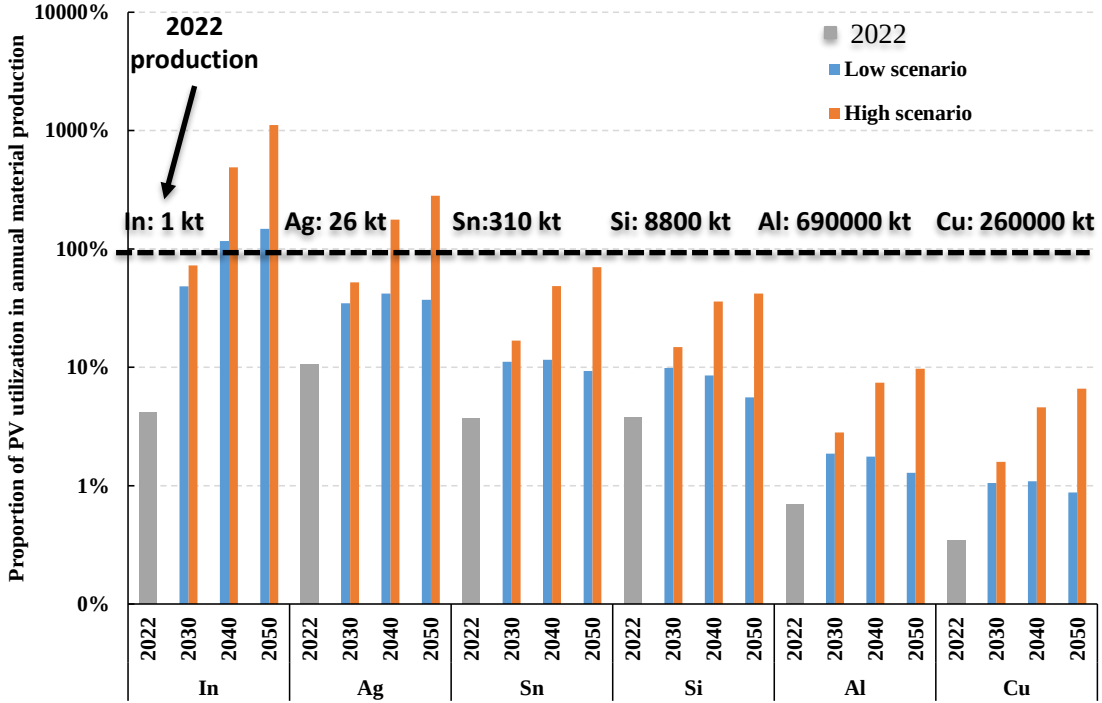
- Supply risk too low[1]
- 4% of world's production in EU (Spain)[1]



- 70% of global production by 2050

[1] https://rmis.jrc.ec.europa.eu/
[2] Chengjian Xu et al., *RCR* **210**, 107824 (2024)

PV module material demand vs current production



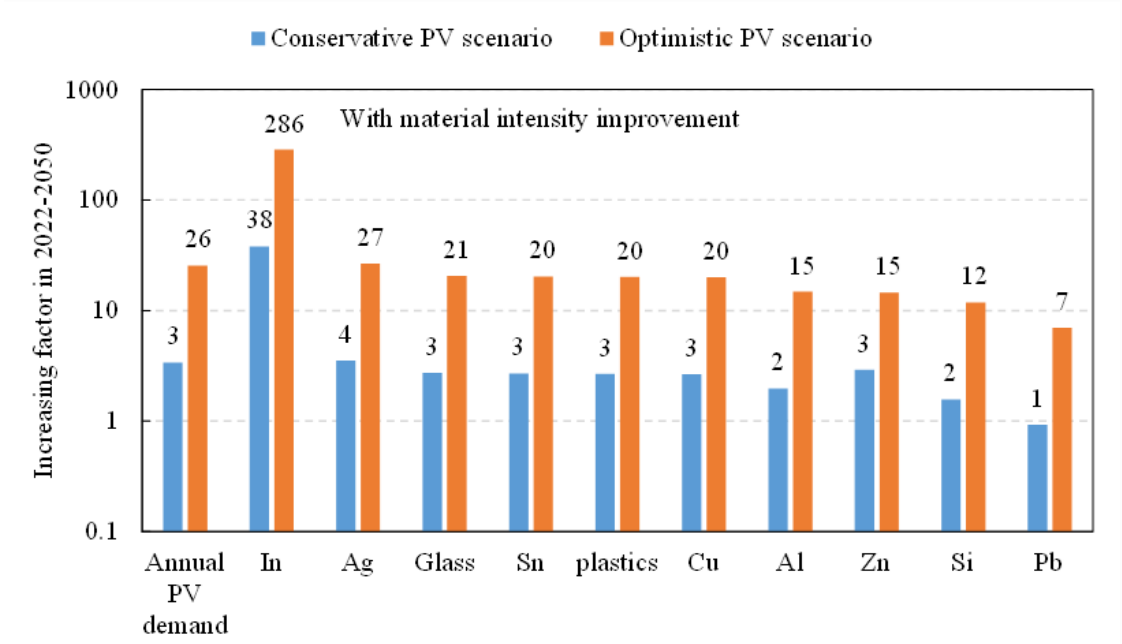
- PV demand challenge: In>Ag>Sn>Si

Al & Cu

- Module level: Al & Cu <10%
- System level: See 5DV.2.44
  - Mounting <-> Al
  - Cables <-> Cu

Chengjian Xu et al., *RCR* **210**, 107824 (2024)

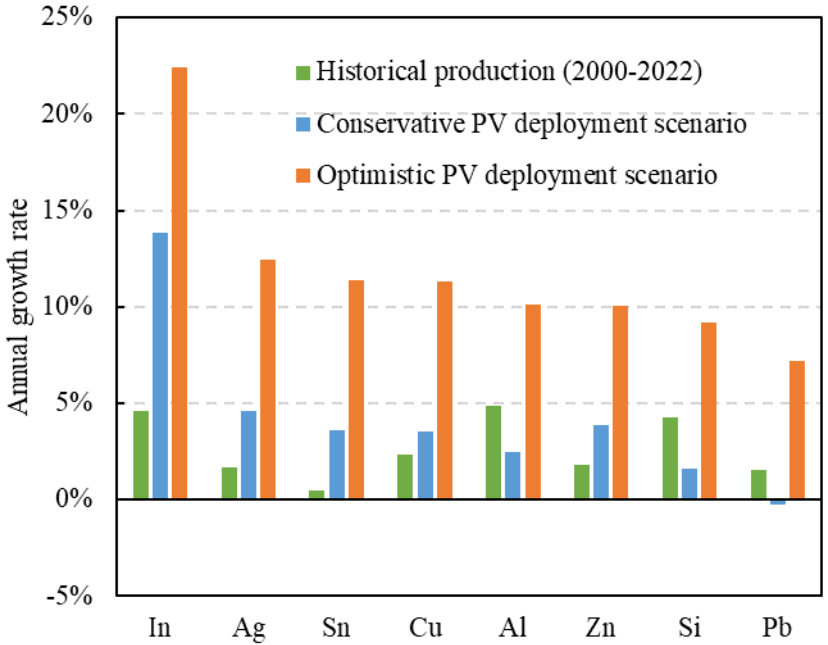
PV material demand growth 2022->2050



- **In and Ag growth factor higher than PV demand**
- **Relative decoupling for other materials**

Chengjian Xu et al., *RCR Advances* **210**, 107824 (2024)

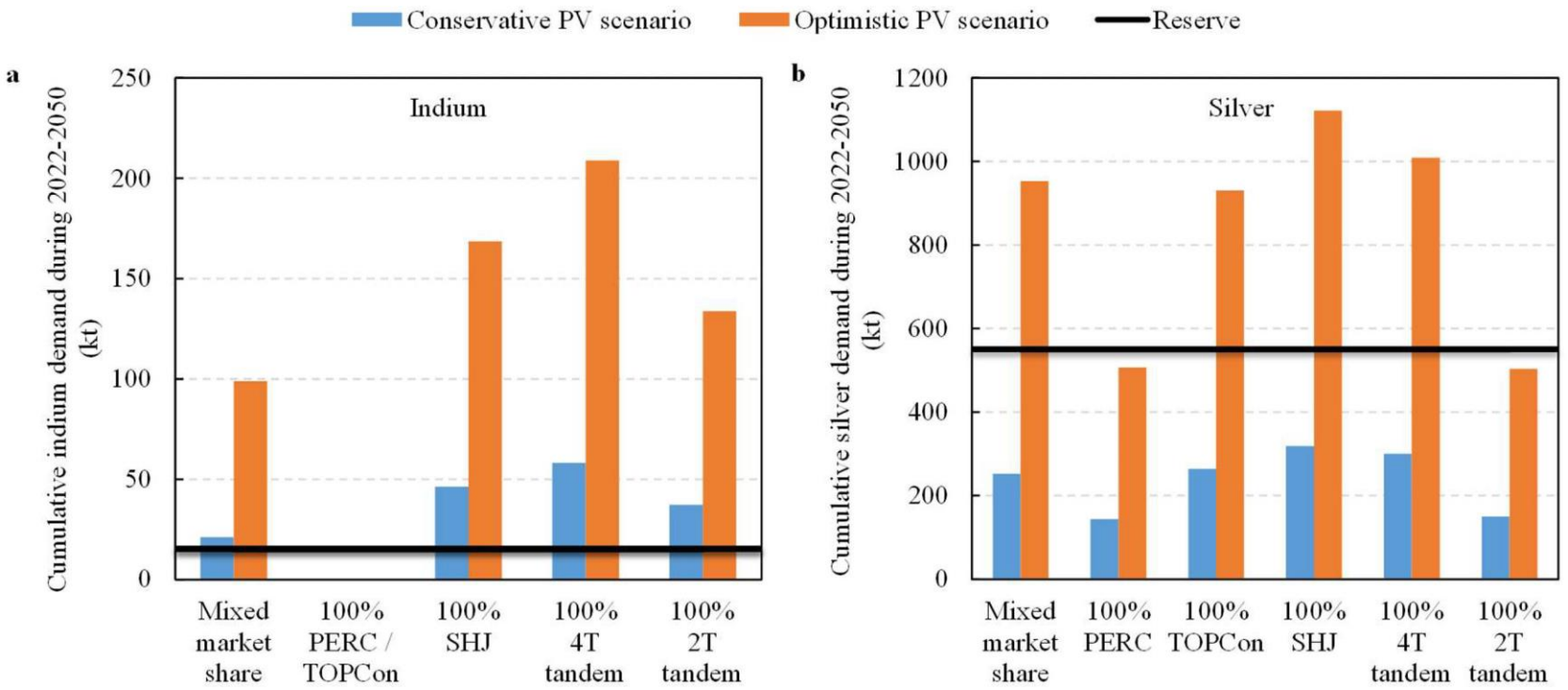
Comparison historical production growth



- **Historical material production increase <5% annually**
- **20 years to open a mine**

Chengjian Xu et al., *RCR Advances* **210**, 107824 (2024)

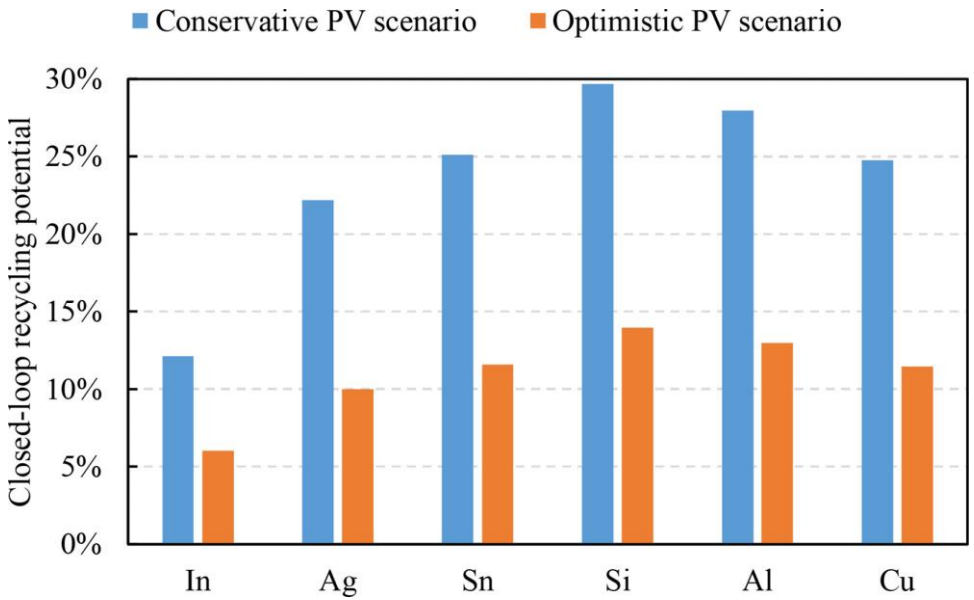
Effect of PV technology



- **PERC and TOPCon best for Indium**
- **PERC and 2T tandem best for silver**

Chengjian Xu et al., *RCR* **210**, 107824 (2024)

Recycling potential



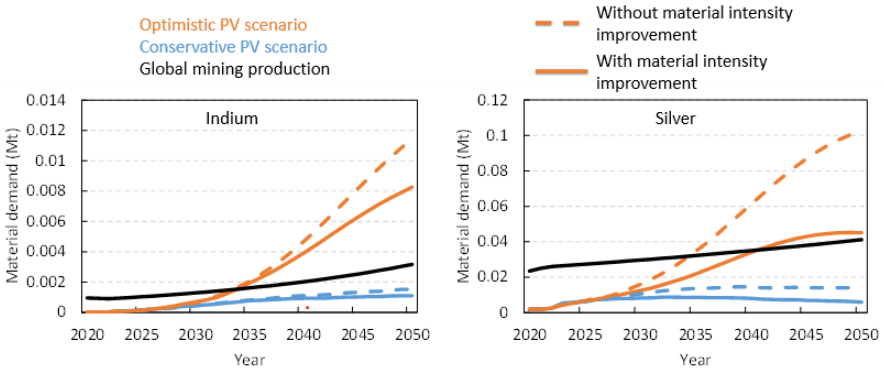
2050:

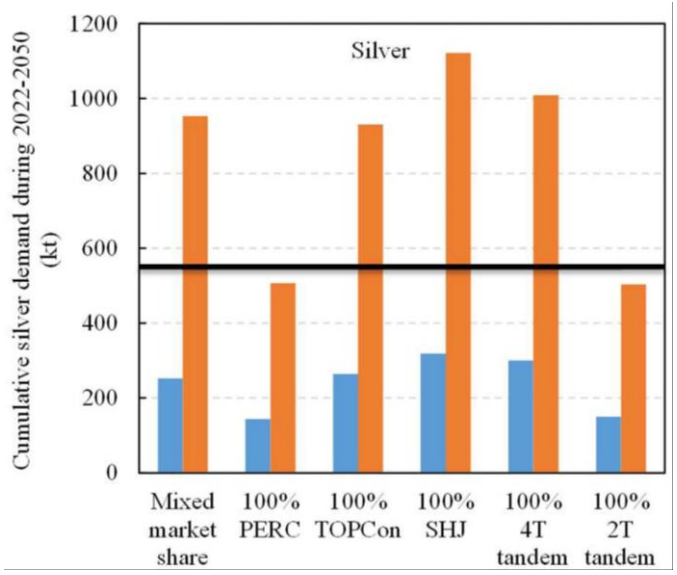
- **Up 30% of Si and Al PV material demand from End-of-Life modules**
- **Conservative growth gives higher closed loop recycling potential**

[1] Chengjian Xu et al., *RCR Advances* **210**, 107824 (2024)

Conclusions: Material demand

- **Stock driven dynamic material flow analysis model has been developed**
- **Improvements in material intensity can reduce the annual demand for PV:**
  - **46 % for silicon**
  - **56 % for silver**
- **PV technology choices significantly influence indium and silver demand**
- **Potential for up to 30% of PV material demand from End-of-Life modules by 2050**





Thank you for your attention!

TU Delft Institutes

Urban Energy

e-Refinery

AgTech

TU Delft Climate Action Programme

Funded by the European Union

PVMD funding

Rijksdienst voor Ondernemend Nederland

URBAN EUROPE

HORIZON 2020

cet Partnership

Horizon Europe

NWO

HyET Solar
Flexible light weight solar modules

Contact

m.r.vogt@tudelft.nl

Hiring now!

Open PhD and Postdoc positions!