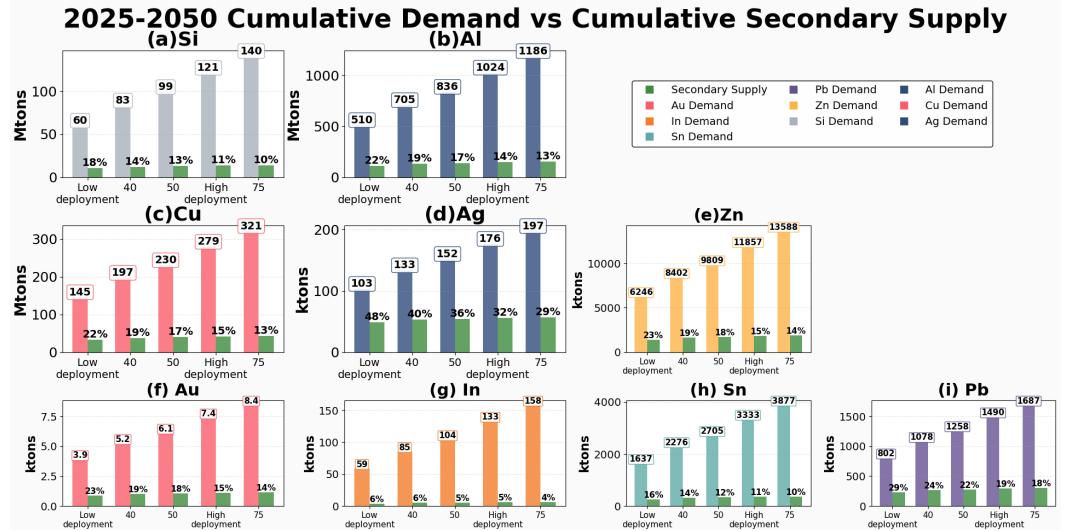




Primary and Secondary Material Flows for the Future Global Deployment of Silicon-based Photovoltaic Systems

Mohammad Abdelbaky, Chengjian Xu, Olindo Isabella, Malte R. Vogt

Resource constraints make forward-looking material demand planning essential



World ▾ Business ▾ Markets ▾ Sustainability ▾ Legal ▾ More ▾

Silver faces sixth year of deficit with stock drawdown raising squeeze risks, research shows

CHINA

China tightens indium phosphide checks as AI demand climbs

A niche compound essential to AI data-centre optics has become Beijing's newest point of leverage over the buildout.

June 19, 2026 - 8:22 am

Copper Hits All-Time High Amid Tariff Turmoil, Mine Struggles

By Bloomberg News

September 7, 2026 at 5:08 PM GMT+2

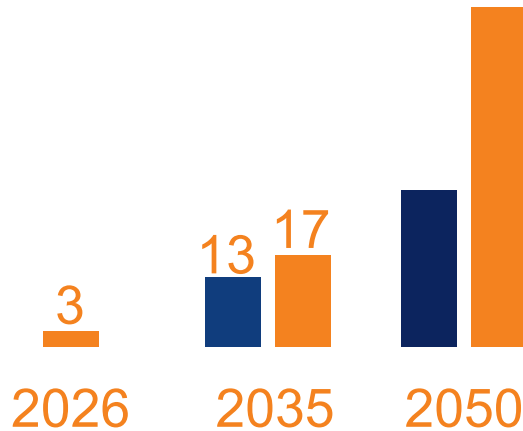
Updated on September 7, 2026 at 7:54 PM GMT+2

Material Flow Analysis (MFA) model

Deployment scenarios



Installed capacity by 2050



Low, 29 TW

IEA Net Zero Emissions ^[1]

High, 63 TW

1.5°C without carbon removal ^[2]

Sensitivity scenarios of 40, 50 and 75 TW

[1] IEA, World Energy Outlook 2025, IEA, Paris (2025)

[2] D. Bogdanov. et al., Energy **227**, 120467 (2021)

TECHNOLOGY DEVELOPMENTS

Extrapolating 2025-2035 trends

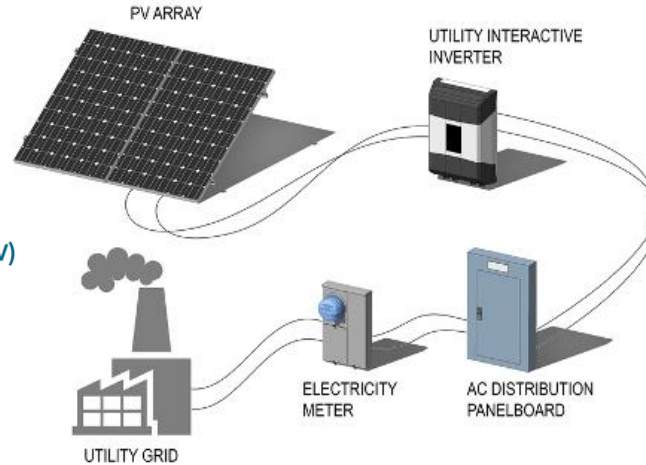


Inverter

BoS

- Cell technology (TOPCon, SHJ,...)
- M10 or G12 cell format
- Silver & Copper metallization
- Silicon wafer thickness
- Kerf loss
- Cell efficiency
- Module efficiency
- Bi-facial modules
- Lead-free solder alloys
- Front and back glass thickness
- Frame material

International Technology
Roadmap for Photovoltaics (ITRPV)



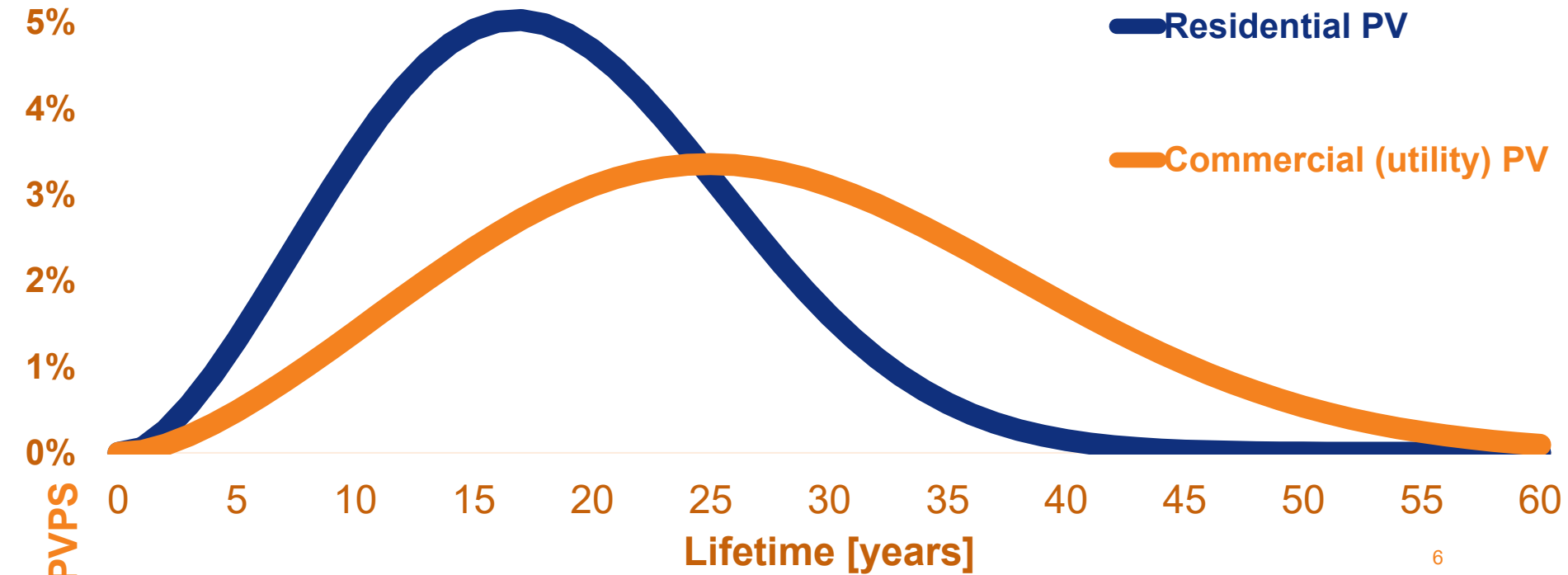
- Cabling
- Mounting structures

Lifetime modelling



Weibull probability distributions^[1]

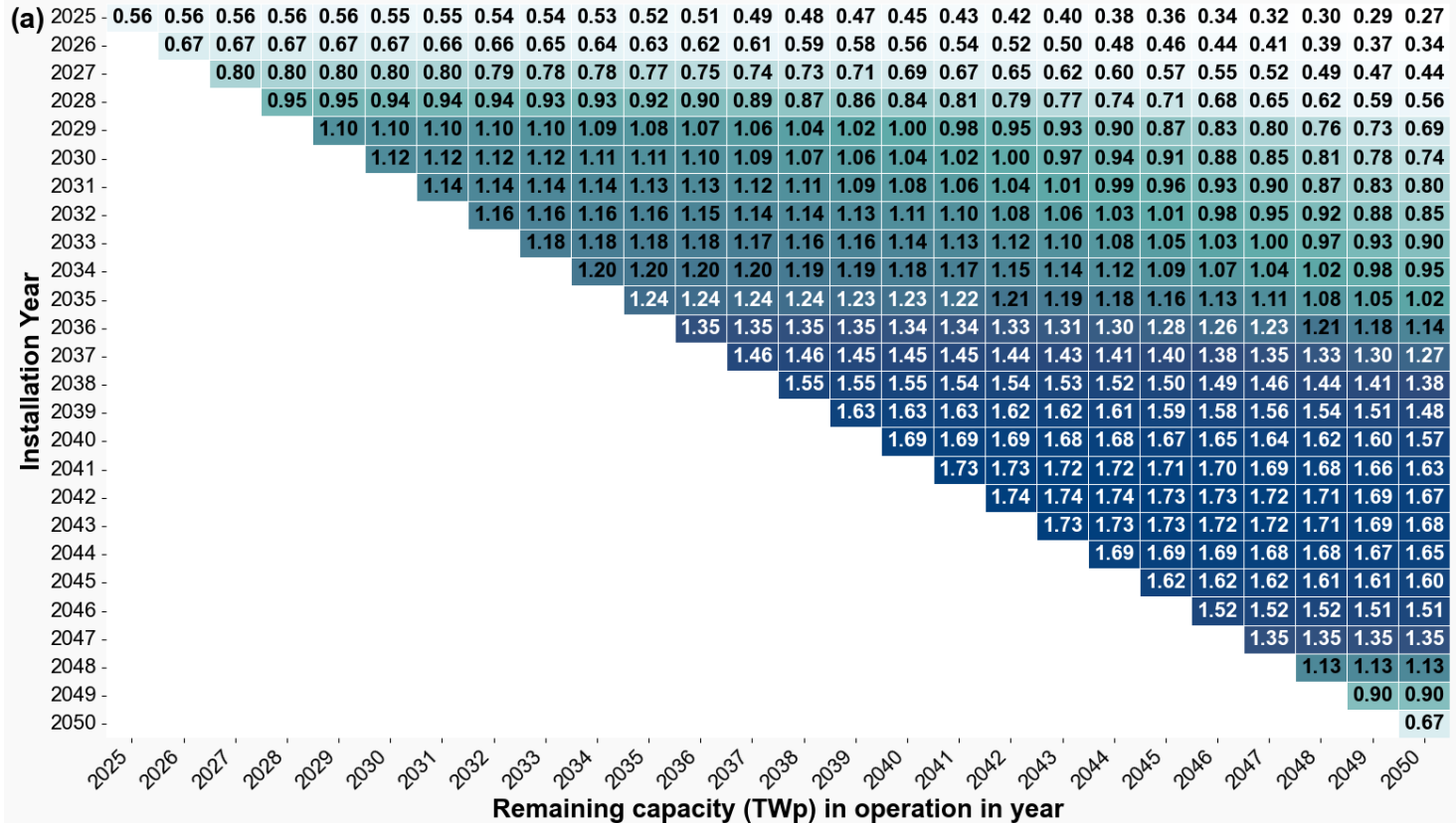
Density



Lifetime modelling



Stock-driven model

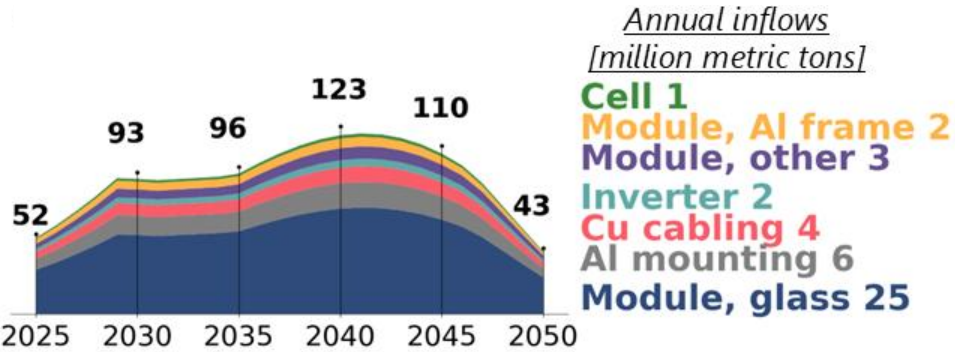


Results

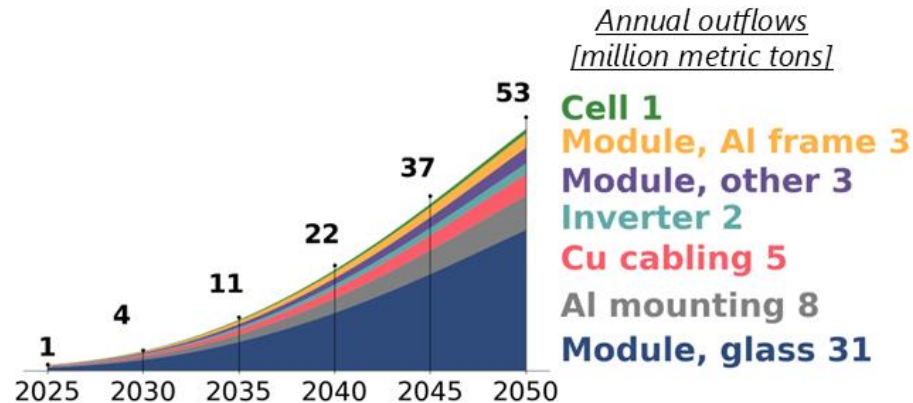
General results



New annual installations



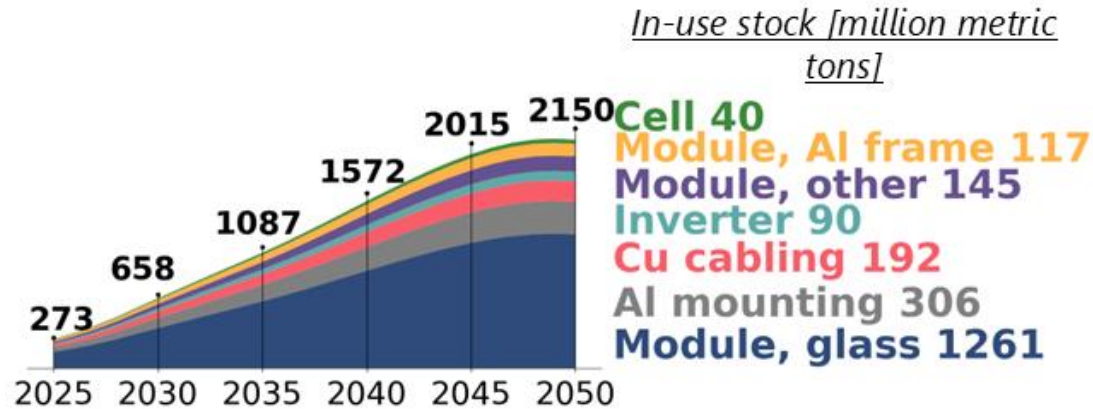
End-of-life systems



General results



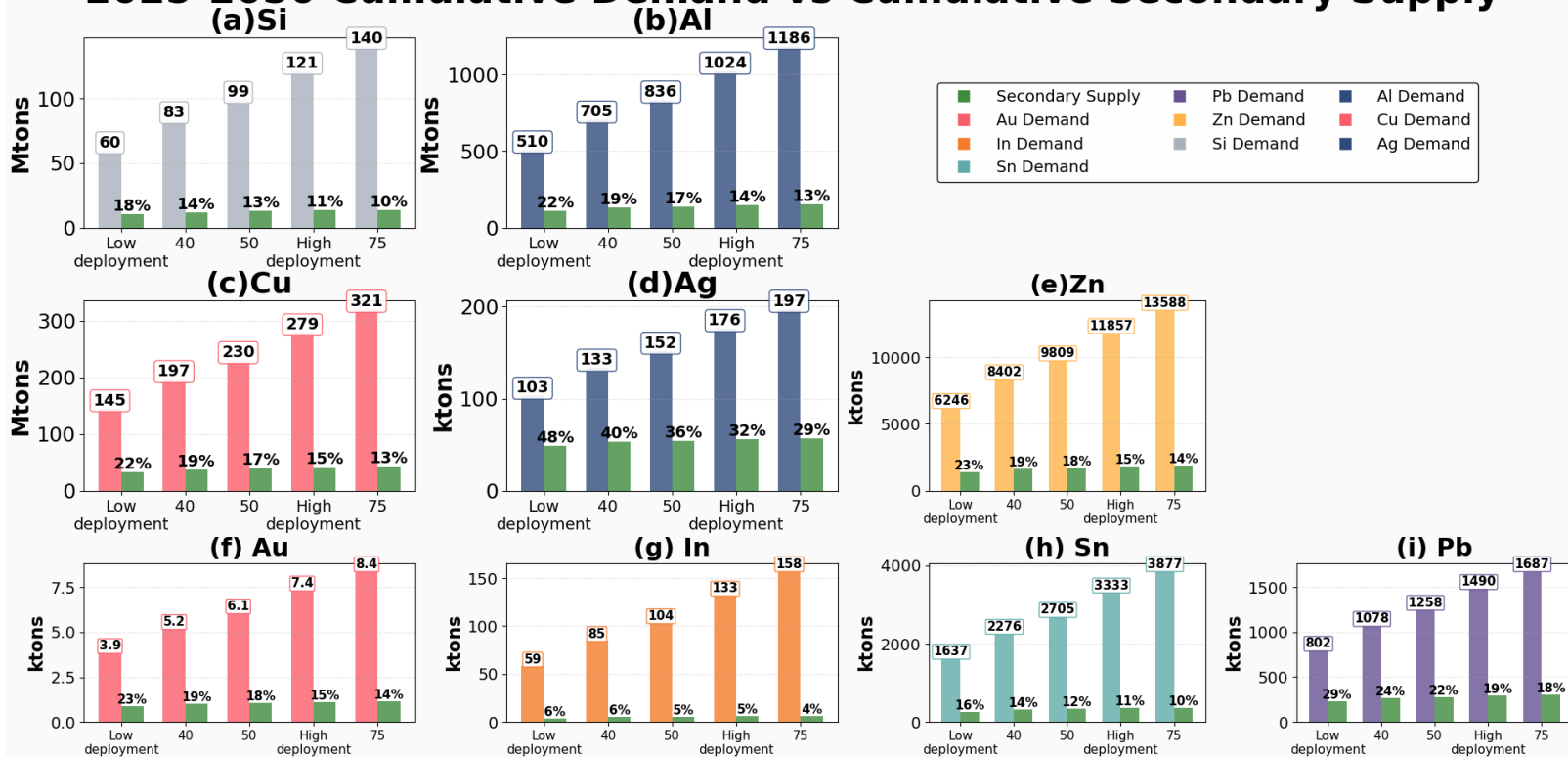
In-use stock



General results



2025-2050 Cumulative Demand vs Cumulative Secondary Supply





15-20%



Future PV waste

Cumulative demand

CUMULATIVE DEMAND 2025-2050

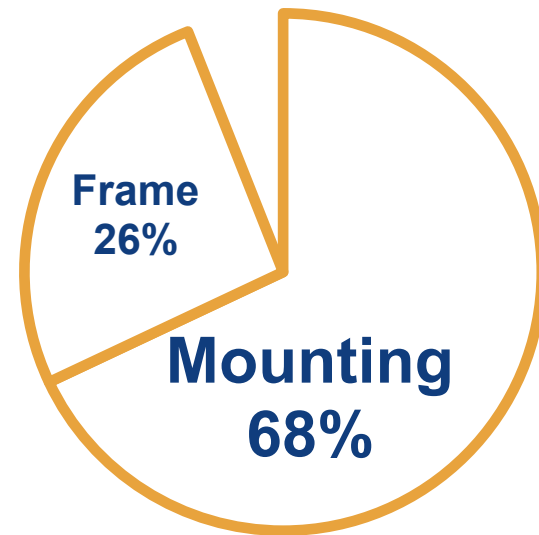


BULK MATERIALS

Aluminum	510-1 100 Mt
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Copper	145-280 Mt
--------	------------

Solar-grade silicon	60-120 Mt
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CUMULATIVE DEMAND 2025-2050

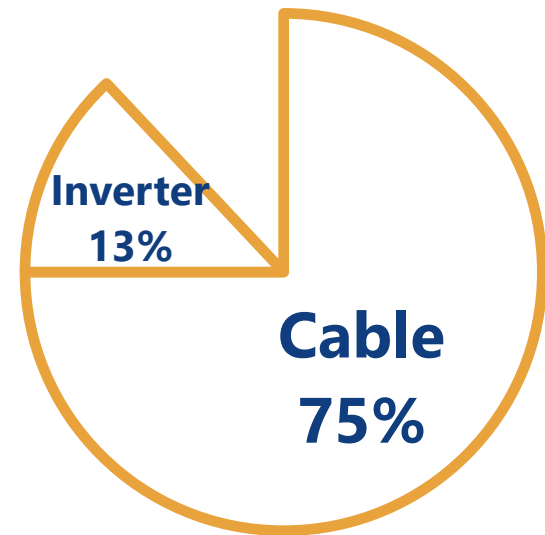


BULK MATERIALS

Aluminum 510-1 100 Mt

Copper 145-280 Mt

Solar-grade silicon 60-120 Mt



PRIMARY SUPPLY



COPPER PEAK ANNUAL DEMAND

30-65%



7 Mt

15 Mt

Current global
mine production

PVPS

CUMULATIVE DEMAND 2025-2050



BULK MATERIALS

Aluminum	510-1 100 Mt
----------	--------------

Copper	145-280 Mt
--------	------------

Solar-grade silicon	60-120 Mt
------------------------	-----------



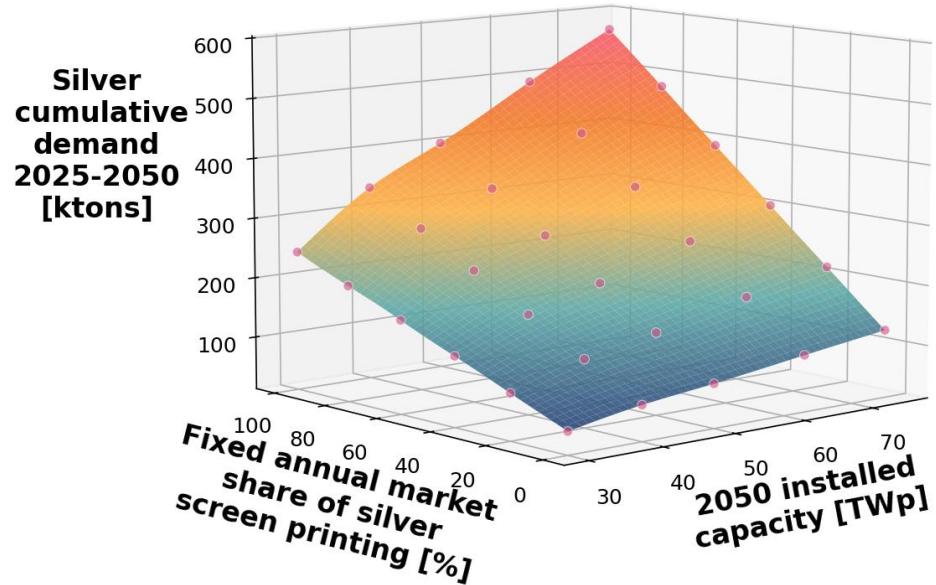
SILVER



Metallization innovation and closed-loop recycling are silver's lifeline

30-45%

of cumulative demand
could be supplied by
silver in future PV
waste



INDIUM · TRANSPARENT CONDUCTIVE OXIDES



Demand passes the global resource estimate by the mid-2040s

Reserves & resources estimate  **50 000 t ^[1]**

The bar chart for 'Reserves & resources estimate' consists of a light gray segment followed by a dark gray segment.

Low, 29 TWp  **60 000 t**

The bar chart for 'Low, 29 TWp' consists of a gold segment followed by a dark gray segment.

High, 63 TWp  **130 000 t**

The bar chart for 'High, 63 TWp' is a single solid gold segment.

INDIUM · TRANSPARENT CONDUCTIVE OXIDES



Market share to stay inside current reserves & resources estimate

30% Low, 29 TWp

15% High, 63 TWp



Solder puts tin under pressure

38-78%

Cumulative 2025-2050 demand relative to global reserves

29-65%

Peak annual demand relative to current mine production

Conclusions



01 The ongoing transition to copper metallization can substantially reduce future silver demand

02 Indium substitution in TCOs is a necessity for heterojunction and tandem technologies

03 Strong bottlenecks in the primary supply of copper and tin to meet future sector demand

Thank you for your attention!

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