PVSEC-31
13 - 15 December 2021

Analysis of Indium Availability
Not a Critical Issue for Large Scale Development of CIGS technology

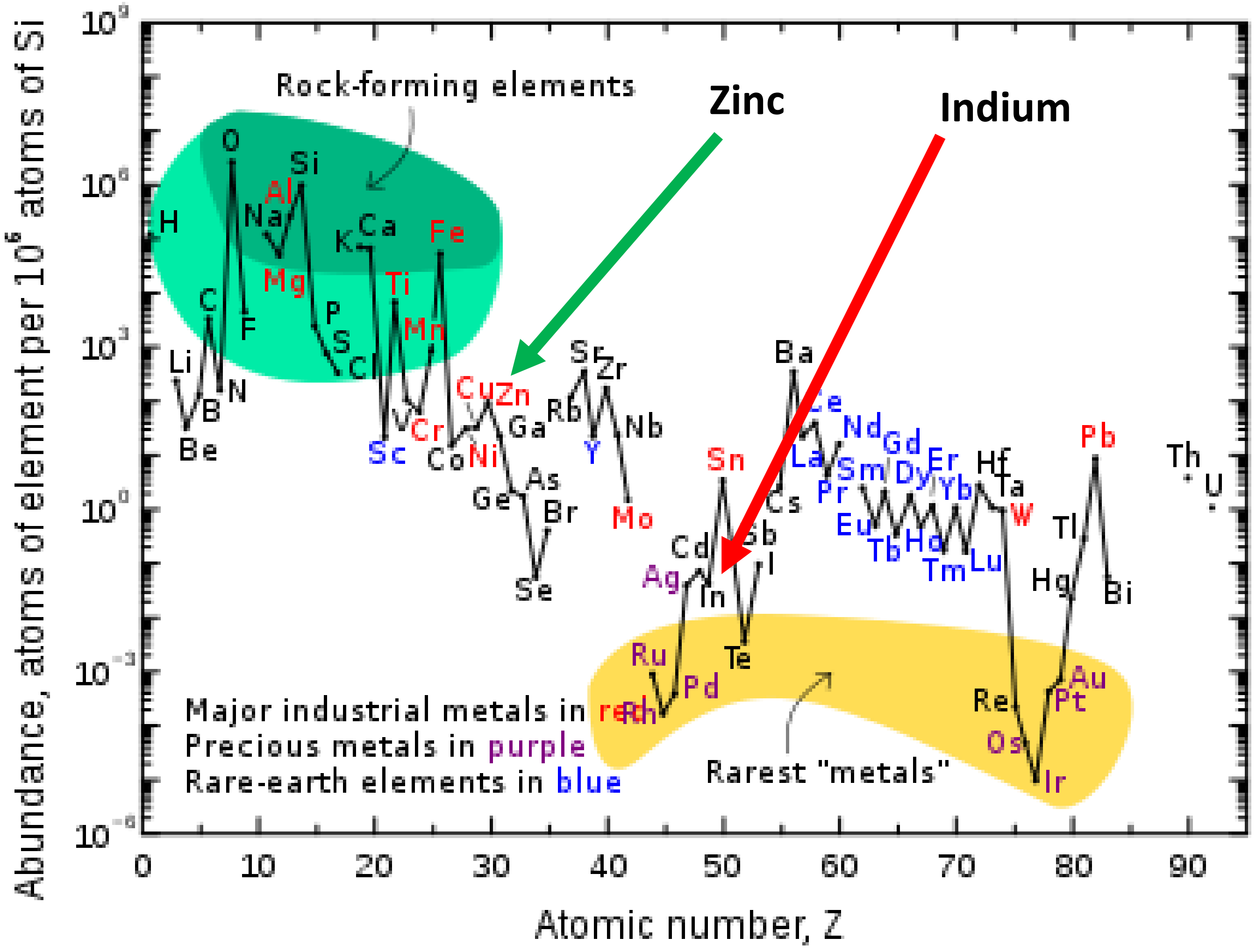
Daniel Lincot[1,11]

Contributors* : Ayodhya N. Tiwari[2], Marika Edoff[3], Susanne Siebentritt[4], Wolfram Witte[5], Sascha Sadewasser[6], Marcus Bär[7], Bart Vermang[8], Maïté Le Gleuher[9], Roland Scheer[10], Jean-Francois Guillemoles[1,11], Vasilis M. Fthenakis[12], Michael Powalla[5], Thomas Weiss[4], Hans-Werner Schock

1 cnrs
2 Empa Materials Science and Technology
3 UPPSALA UNIVERSITET
4 UNIVERSITÉ DU LUXEMBOURG
5 ZSW
6 INL INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY
7 HZB Helmholtz Zentrum Berlin
8 imec
9 brgm Géosciences pour une Terre durable
10
11 IPVF UMR 9006 Joint Research Unit
12 COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

*White paper: https://cigs-pv.net/wortpresse/wp-content/uploads/2021/07/Indium_Availability_for_CIGS_thin-film_solar_cells_in_Europe.pdf

Indium is rare but comes with an Earth Abundant Element: Zinc



1 indium atom for 10^7 Si atoms
64th rank

0.056 ppm in earth crust

but 20-200 ppm in Zinc ores

12.5 Mtons of Zinc in 2018

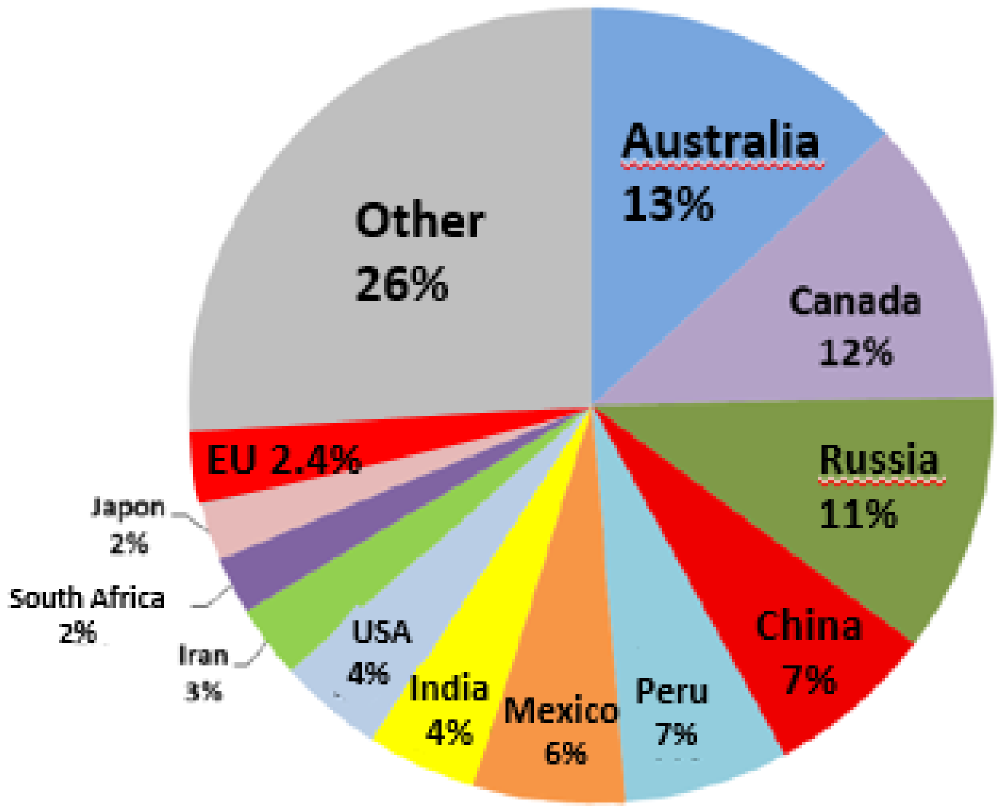
750 tons of primary In in 2018*
950 tons secondary
1700 tons total in 2018

Only small fraction recovered (1/10 -1/20)

* Indium Corporation

M. Lokanc et al (2015) NREL report "Availablity of Indium : the present, the mid term and the long term"

Distribution of world Indium resources



Total estimated resources:
356 kT of In*

"which is sufficient to meet demand for In well into the next century, even without consideration of the potential for supply from secondary sources."

"in the event of a supply restriction, In capacity could be developed elsewhere"

"steps can be made towards strategic and sustainable sourcing of In as required for this century's transition to renewable energy, increased use of digital display technologies, and/or other future applications of In"

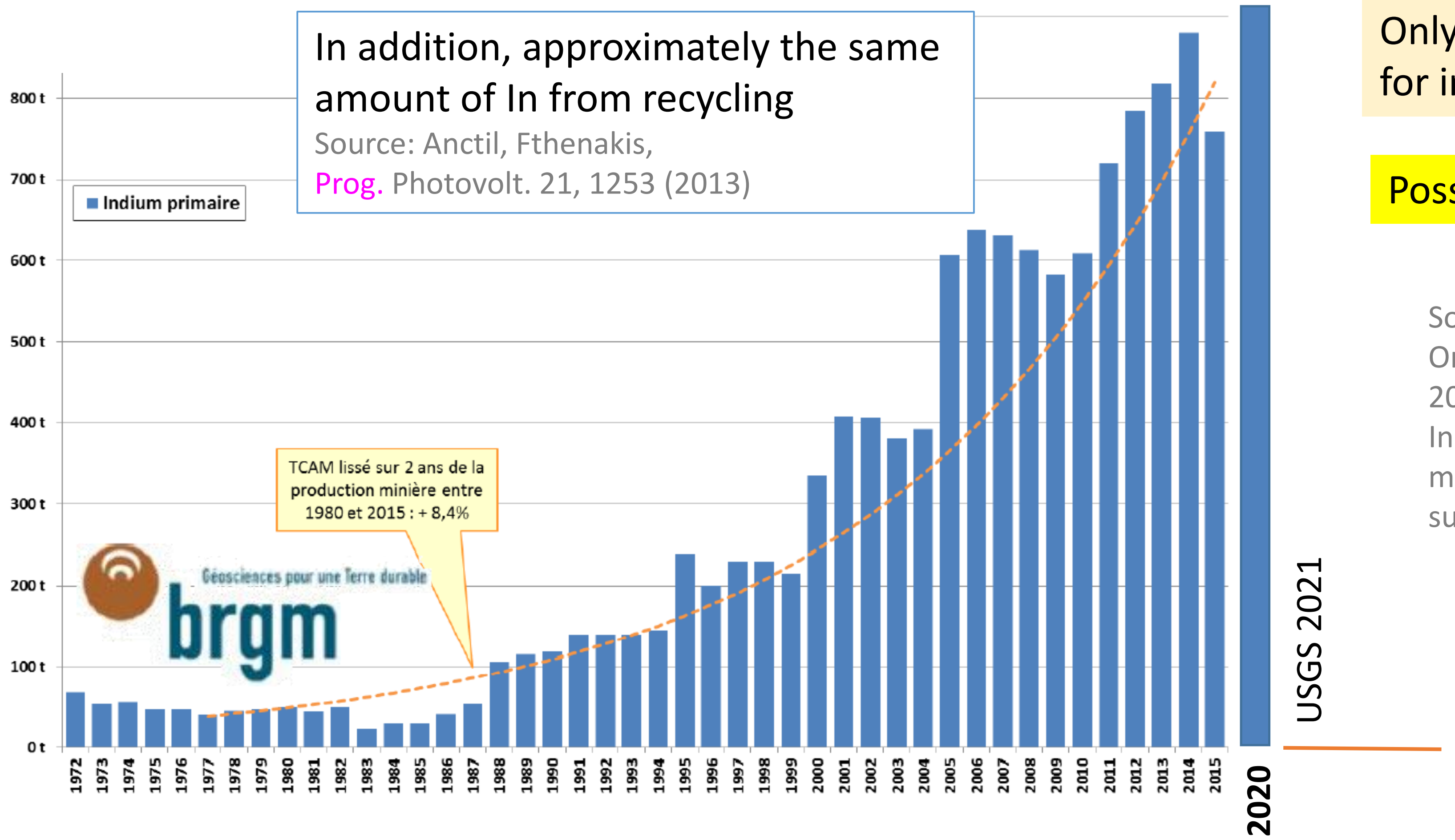
brgm Géosciences pour une Terre durable

*Source : T.T. Werner a,⇑, Gavin M. Mudda, Simon M. Jowitt
The world's by-product and critical metal resources part III: A global assessment of indium, Ore Geology Reviews 86 (2017) 939–956

Evolution of Indium Production

Primary Indium

In addition, approximately the same amount of In from recycling
Source: Anctil, Fthenakis, Prog. Photovolt. 21, 1253 (2013)



Only 35% of Zinc sites are equipped for indium recovery

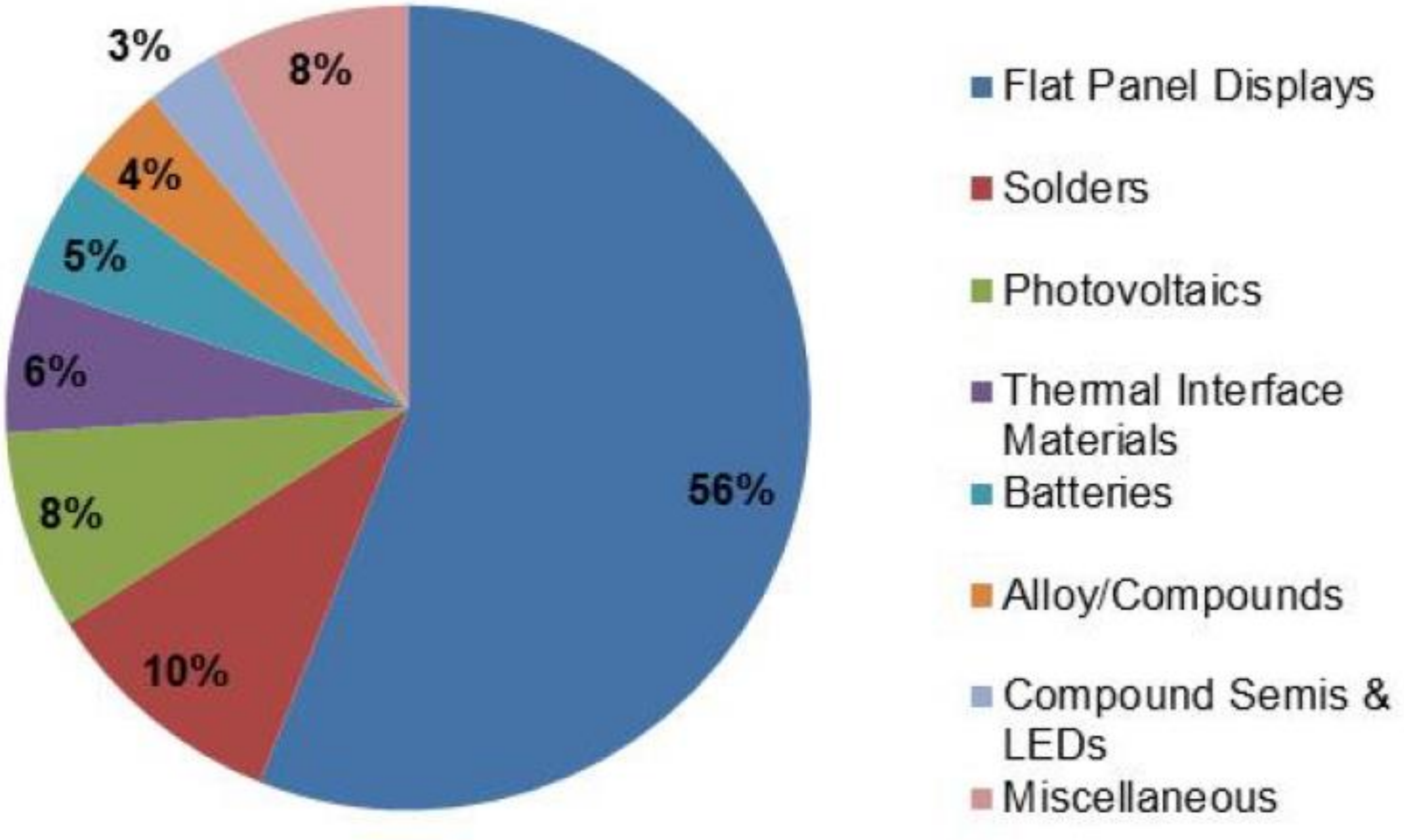
Possible ramp up to 4000 t/year

Source: Werner, Mudd and Jowitt, Ore Geology Reviews, Jan 2017
2015-Applied Earth Science
Indium: key issues in assessing mineral resources and long-term supply from recycling

Source: BRGM, criticality study 2017

End Use Applications of Indium (2012)

Total production of about 1500 tons



Sources : Willis, P; Chapman, A.; Fryer, A.; (2012) “Study of By-products of Copper, Lead, Zinc, and Nickel”
M. Lokanc et al (2015) NREL report “Availablity of Indium : the present, the mid term and the long term”

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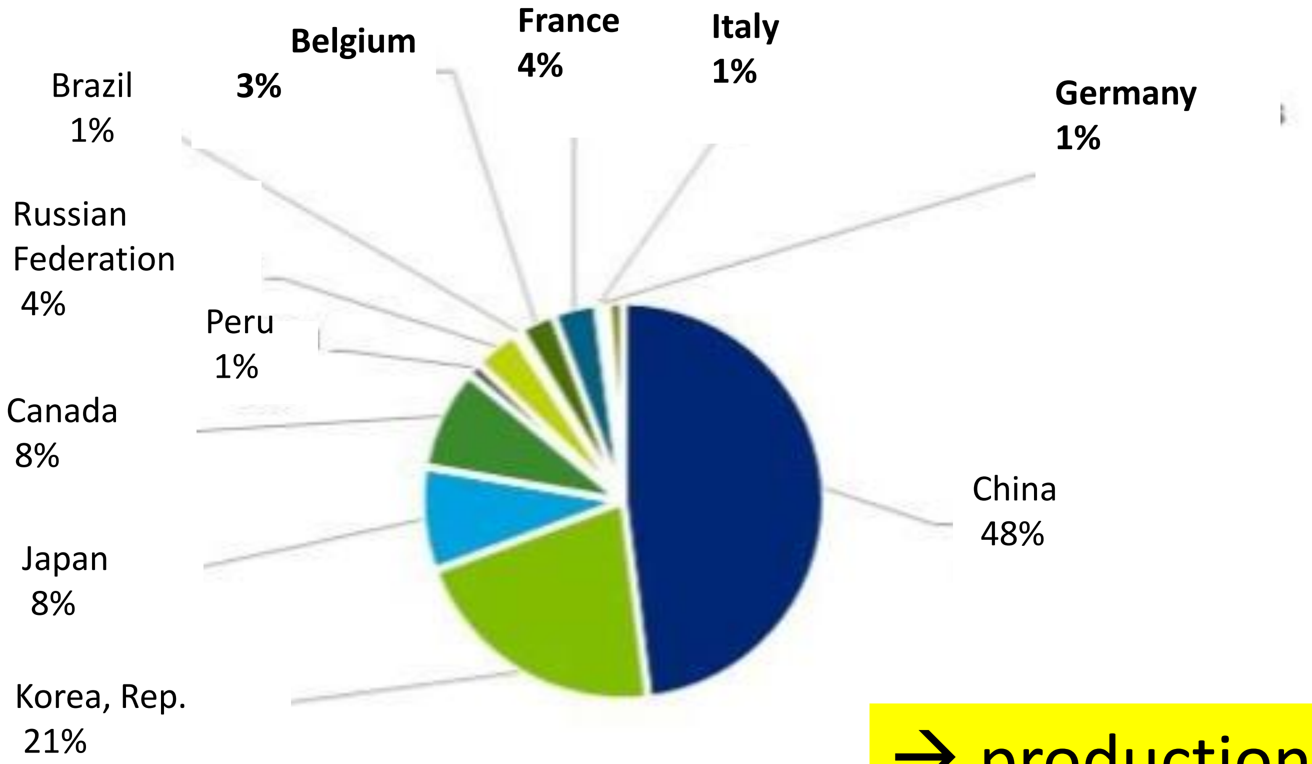
World Refinery Production of Indium

Average annual refinery production between 2012 and 2016: 827 tons



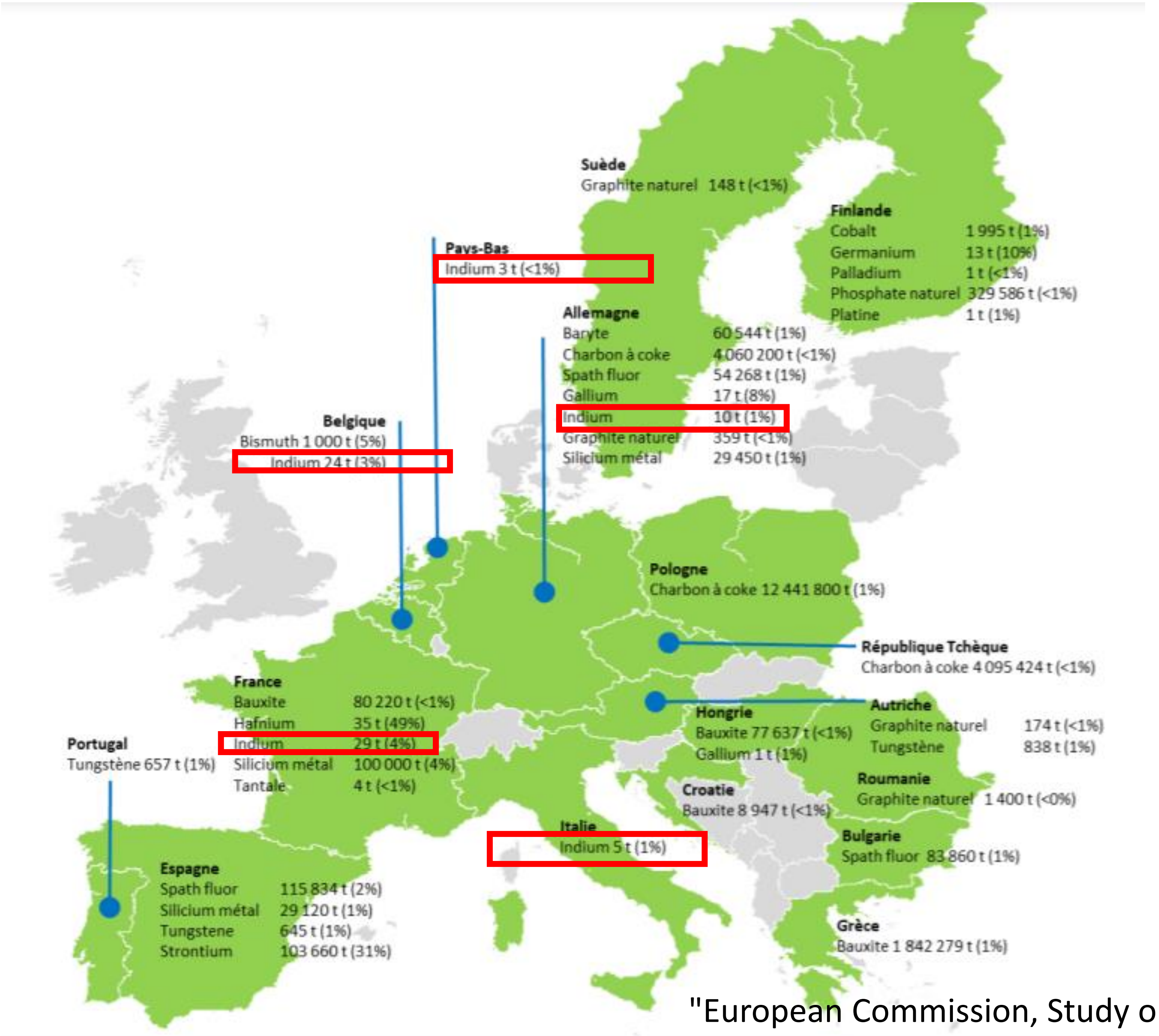
Refinery production in 2019 and 2020

	Refinery production 2019	Refinery production 2020[e]
United States	—	—
Belgium	20	20
Canada	61	50
China	535	500
France	40	50
Japan	70	65
Korea, Republic of	225	200
Peru	12	10
Russia	5	5
World total (rounded)	968	900

→ production is distributed worldwide
→ nearly 10% produced in the EU

Source: Study on the EU's list of critical raw materials (2020) https://op.europa.eu/s/pbIA

Source : US Geological Survey, January 2021



Country	Indium production (T)	%
France	29 T	4
Belgium	24 T	3
Germany	10 T	1%
Italy	5 T	<1%
Netherlands	3 T	<1%

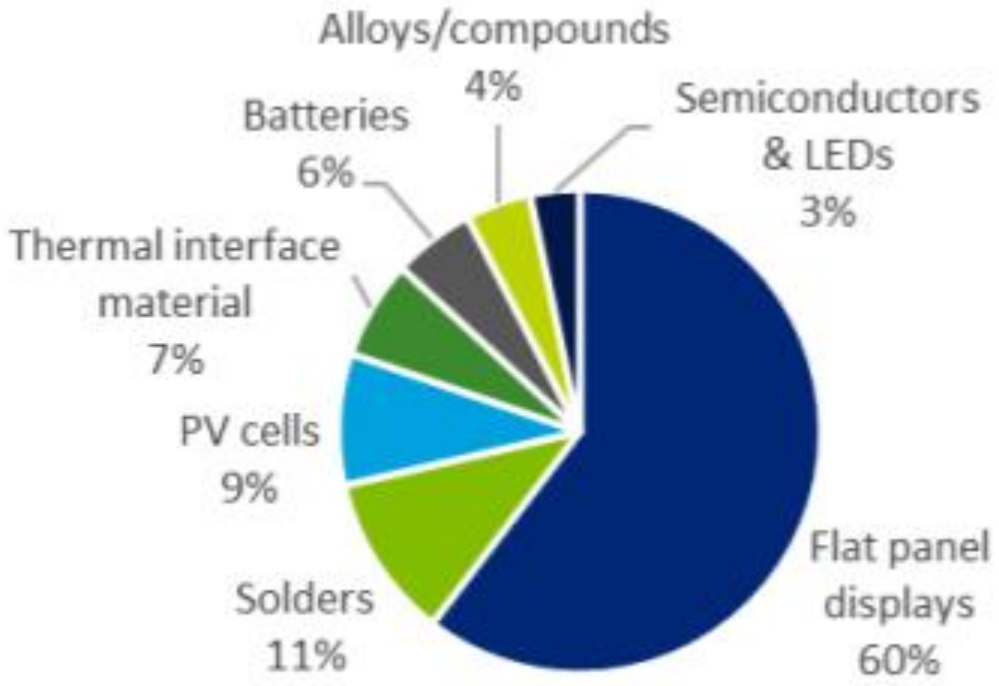
Total EU : 71 tons (9%)

Main producer of Indium for EU
France : 28%

Note : Main producer of Gallium for EU
Germany : 35 %

"European Commission, Study on the EU's list of Critical Raw Materials (2020)"

End uses of Indium and annual average EU sourcing of Indium, 2012-2016



EU consumption: 30 tonnes

EU sourcing estimation : 104 tonnes

Is Indium Critical ?

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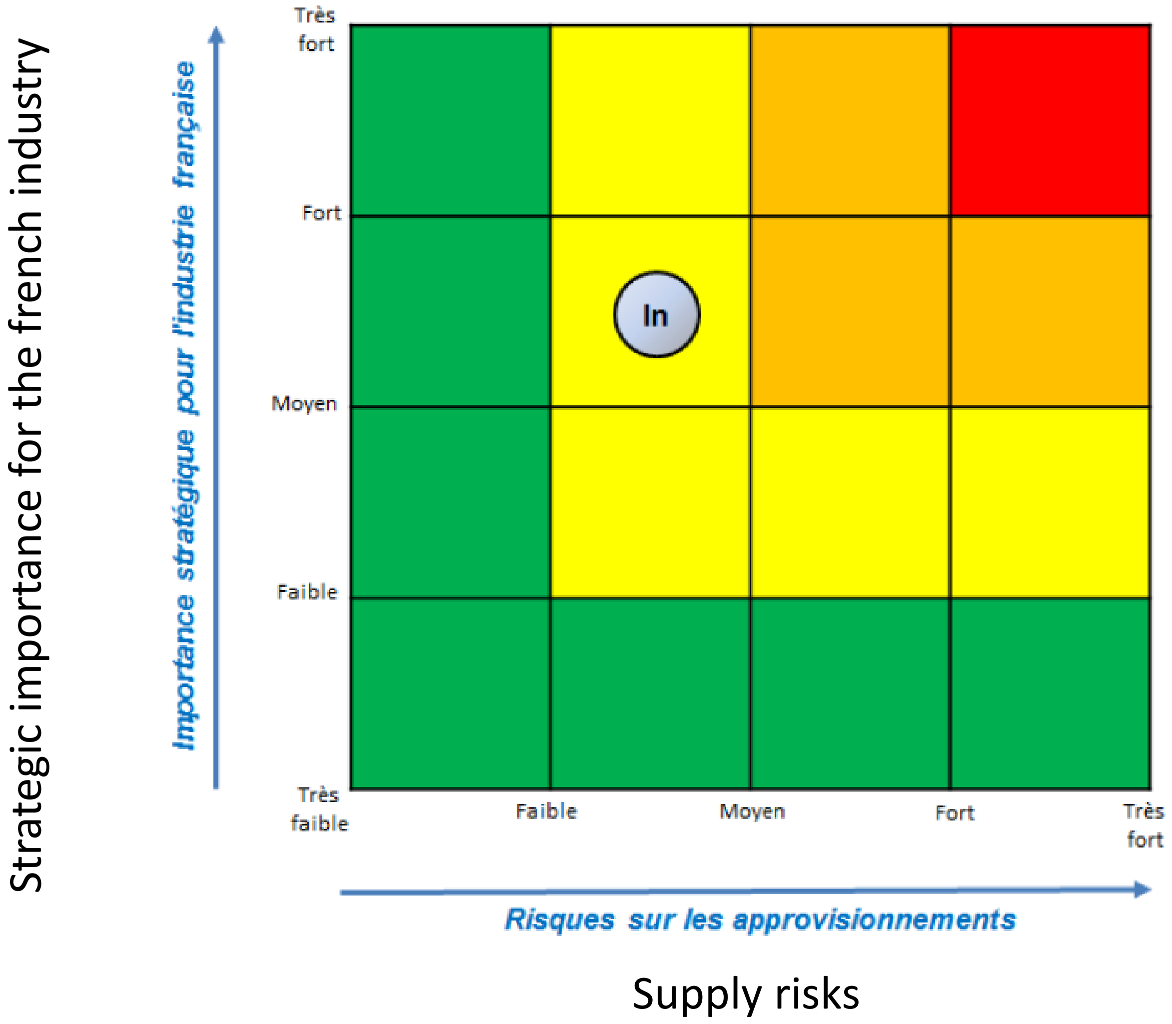
Evolution of Indium prices

Evaluation of Indium criticity for France (2017)

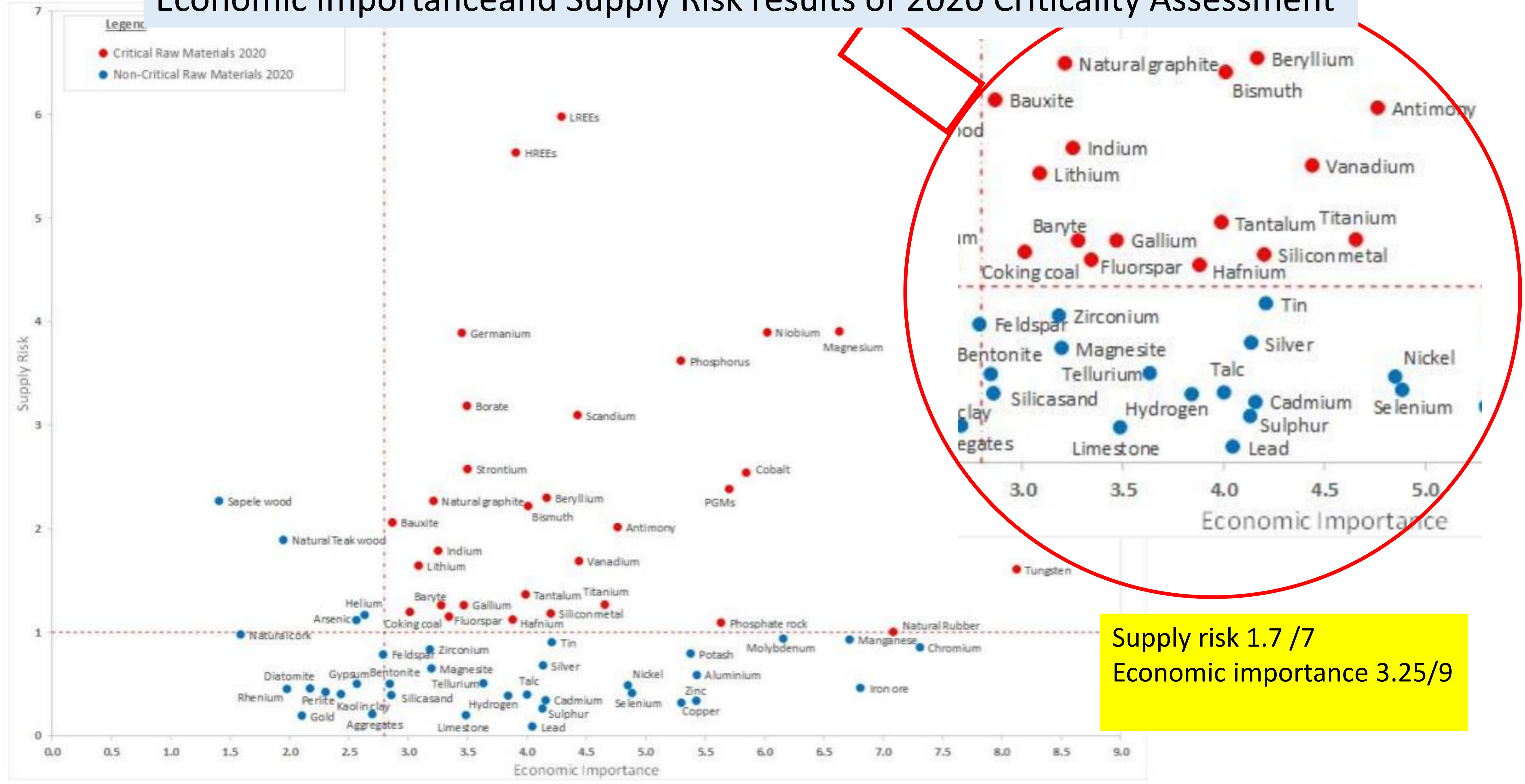


Indium criticity is low from the supply risk
Indium criticity is mean from the strategic importance

European
Commission

Study on the EU's list of Critical Raw Materials (2020)

Economic Importanceand Supply Risk results of 2020 Criticality Assessment



Supply risk 1.7 /7
Economic importance 3.25/9

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"European Commission, Study on the EU's list of Critical Raw Materials (2020)"

Economic importance and supply risk results for indium in the assessments of 2011, 2014, 2017, 2020 (European Commission, 2011; European Commission, 2014; European Commission, 2017)

Assessment	2011		2014		2017		2020	
Indicator	EI	SR	EI	SR	EI	SR	EI	SR
Indium	6.7	2.0	5.6	1.8	3.1	2.4	3.25	1.79

"European Commission, Study on the EU's list of Critical Raw Materials (2020)"

The criticity of Indium is low and tends to decrease for the European Union

Annex 1: List of Critical Raw Materials

Raw materials	Stage	Main global producers	Main EU sourcing[33] countries	Import reliance[34]	EoL-RIR[35]	Selected Uses
Indium	Processing	China (48%) Korea, Rep. (21%) Japan (8%)	France (28%) Belgium (23%) UK (12%) Germany (10%) Italy (5%)	0%	0%	• Flat panel displays • Photovoltaic cells and photonics • Solders
Magnesium	Processing	China (89%) United States (4%)	China (93%)	100%	13%	• Lightweight alloys for automotive, electronics, packaging or construction • Desulphurisation agent in steelmaking

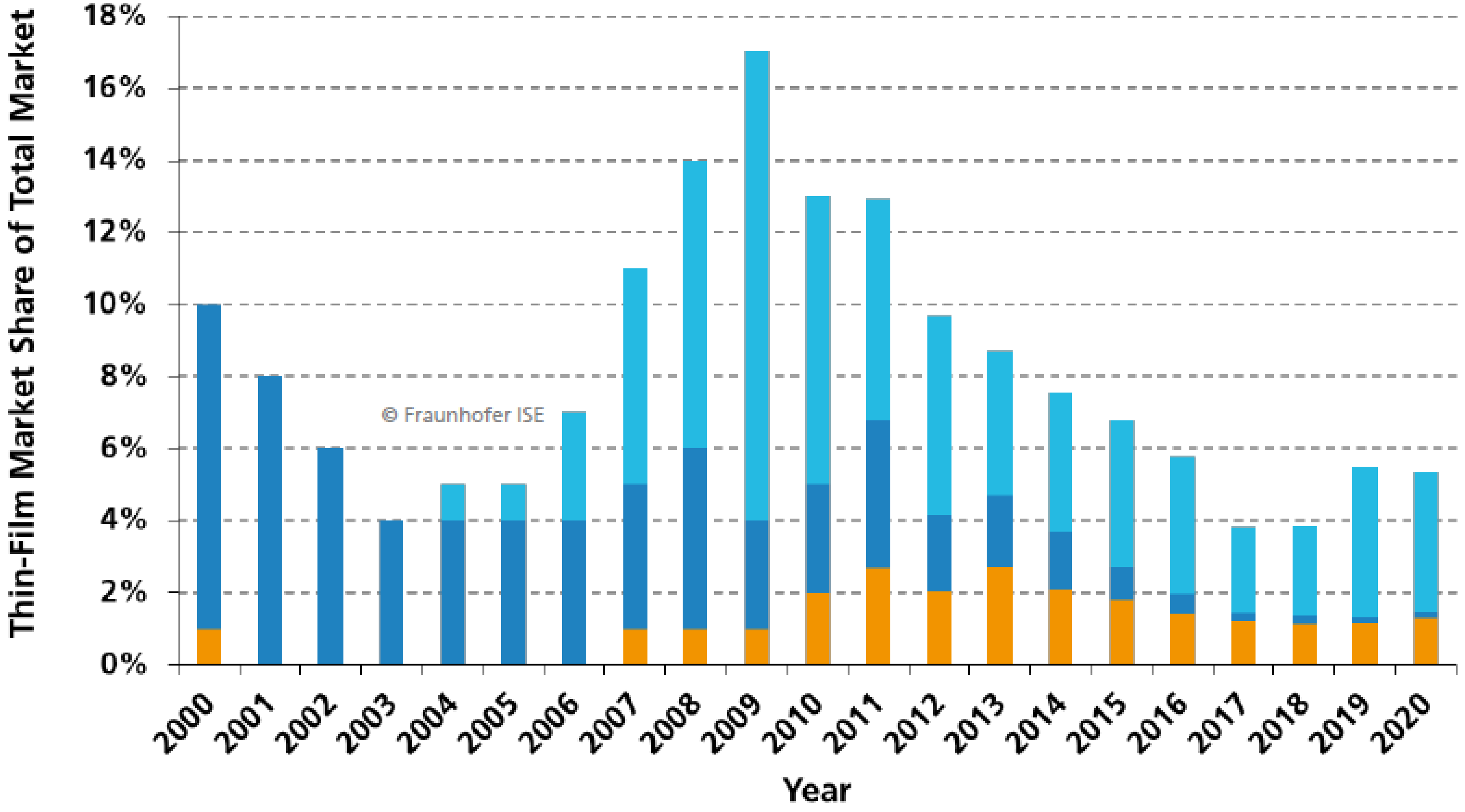
"European Commission, Study on the EU's list of Critical Raw Materials (2020)"

What are the situation and consequences for CIGS technology?

Citation from the executive summary of the European Union Study

**Given its use in PV cells and in batteries,
Indium can play a role in enabling low-carbon energy solutions
in the EU economy, contributing to achieve the objectives of the “European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy"**

Thin film technologies in the PV market



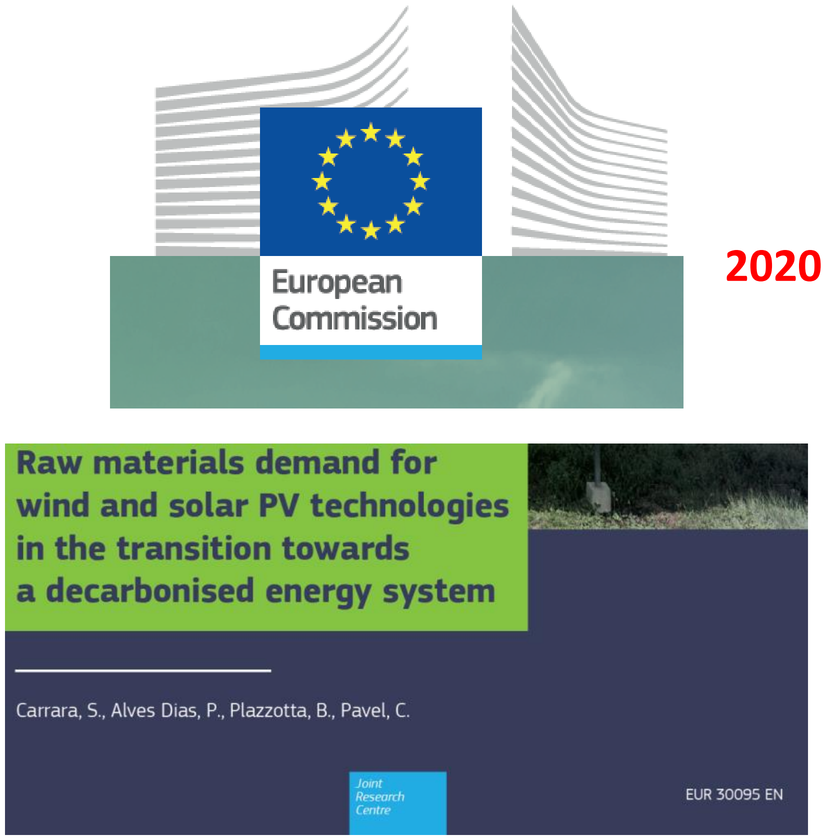
Total market : 135 GW

Production 2020 (GWp)

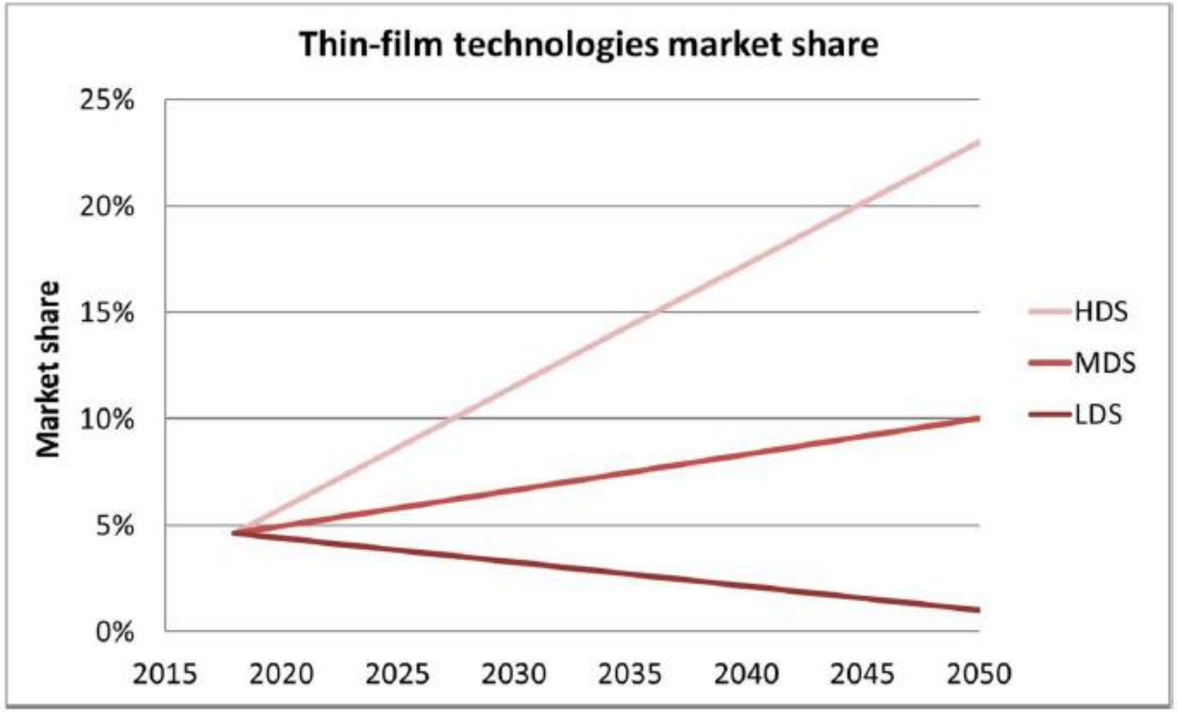
CdTe	6.1
a-Si	0.2
CI(G)S	1.5

Thin film technologies 7.8 GW

Thin film technologies are central in future PV technologies



2020



Source: JRC analysis.

With HDS : about 30-40 GW/ Year of TFSM in 2030 out of 300-400 GW/year → > 200 GW in 2050

TFSM: CdTe, CIGS, Perovskite, CZTS, aSi, OPV

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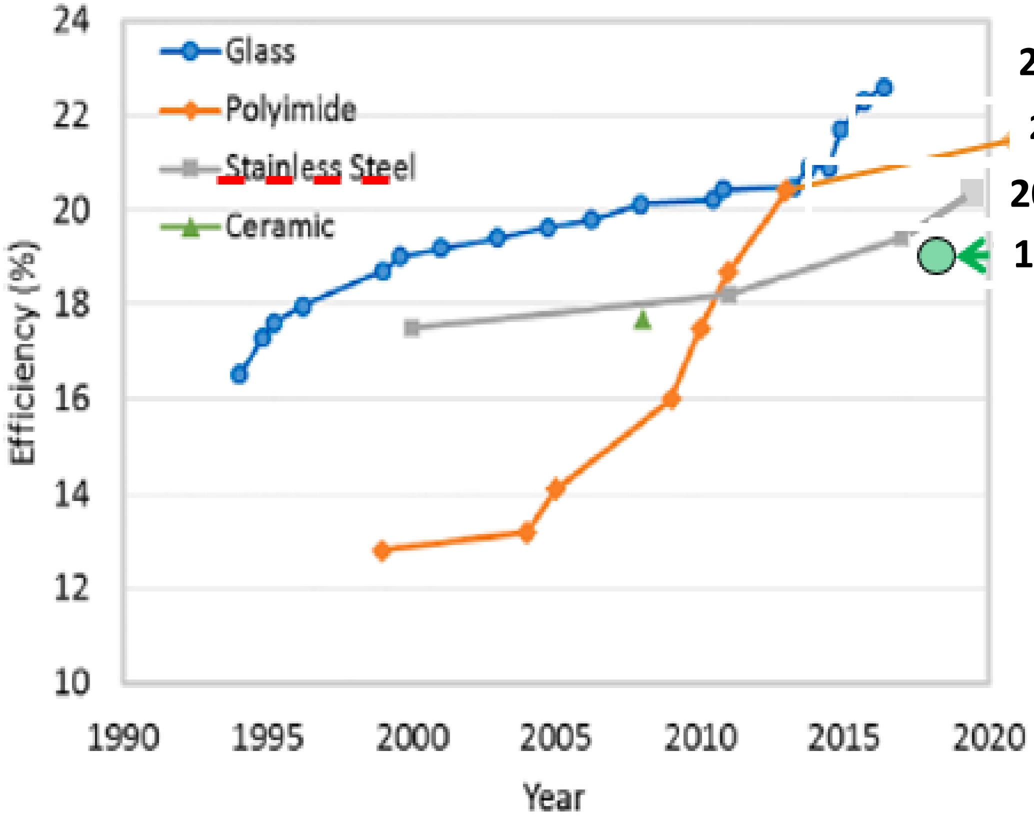
Key Advantages of CIGS

CIGS Single Junctions



23.3 % SOLAR FRONTIER

21.4% Empa

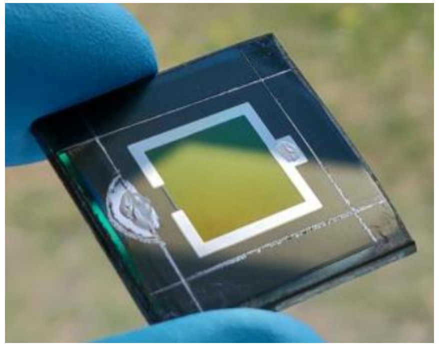
20.6% MiaSolé

18.8% IPVF

J. Ramanujam et al. Progress in Materials Science 110 (2020) 100619

Light Weight Flexible Modules (Flisom)

CIGS Tandems



CIGS-Perovskite

24.16 % 2T monolithic HZB Helmholtz Zentrum Berlin

27.1% 4T SOLLIANCE MiaSolé

Si- CIGS in progress IPVF

Scale Up potential of CIGS PV with Current Technology

How much Indium per GW?

2 microns CIGS with In/(In+Ga) = 0.7 → about 2.8 g of In by m^2

18% efficiency, 180 W/m^2 → 0.015 g of In per Watt

→15 tons /GW

How much GW per Year ?

1000 tons/year total In with 30 % for CIGS : 300 tons for CIGS

→20 GW/year (2 GW in EU) compatible EU HDS Scenario in 2030

compared with 1.9 GW in 2019

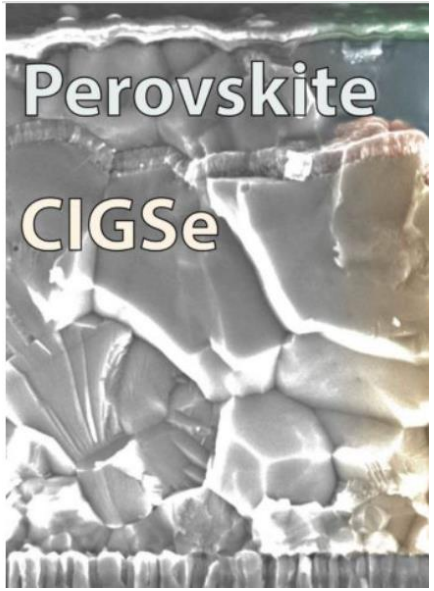
Accelerating factors

→30-40 GW for CIGS tandems with perovskites or silicon

more % from displacement of Usages (Flat screen technologies, replacement of ITO)

increase of In production towords 4000 tons per year → 80 GW/Year

24.16 % HZB



A credible avenue towards >100 GW/year : reduction of thickness

Medium risk :

factor of 4 : 400-500 nm → 3-4 tons/ GW

→ 80-100 GW /Year

High Risk, disruptive :

Factor of 10 or more : < 200 nm

→>200 GW/ Year

Accelerating factors

Increase of In production, shift in usage

→ Towards TW/year

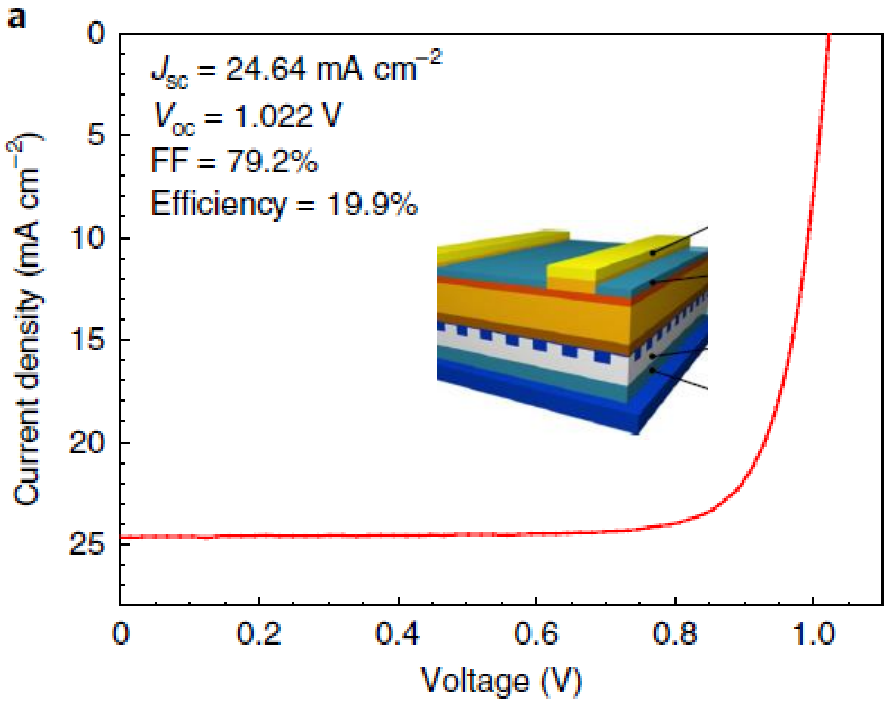
Challenges:

Development of new architectures,

passivated selective contacts, plasmonics

2019

Exemple : 200 nm GaAs solar cell with 19.9%*

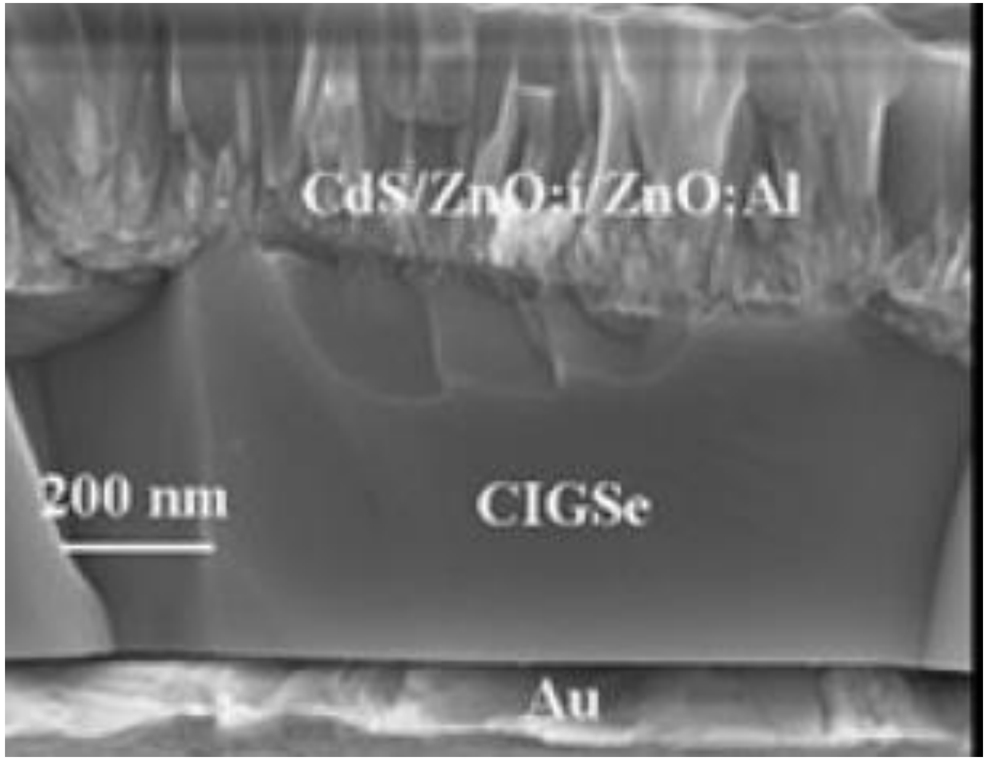


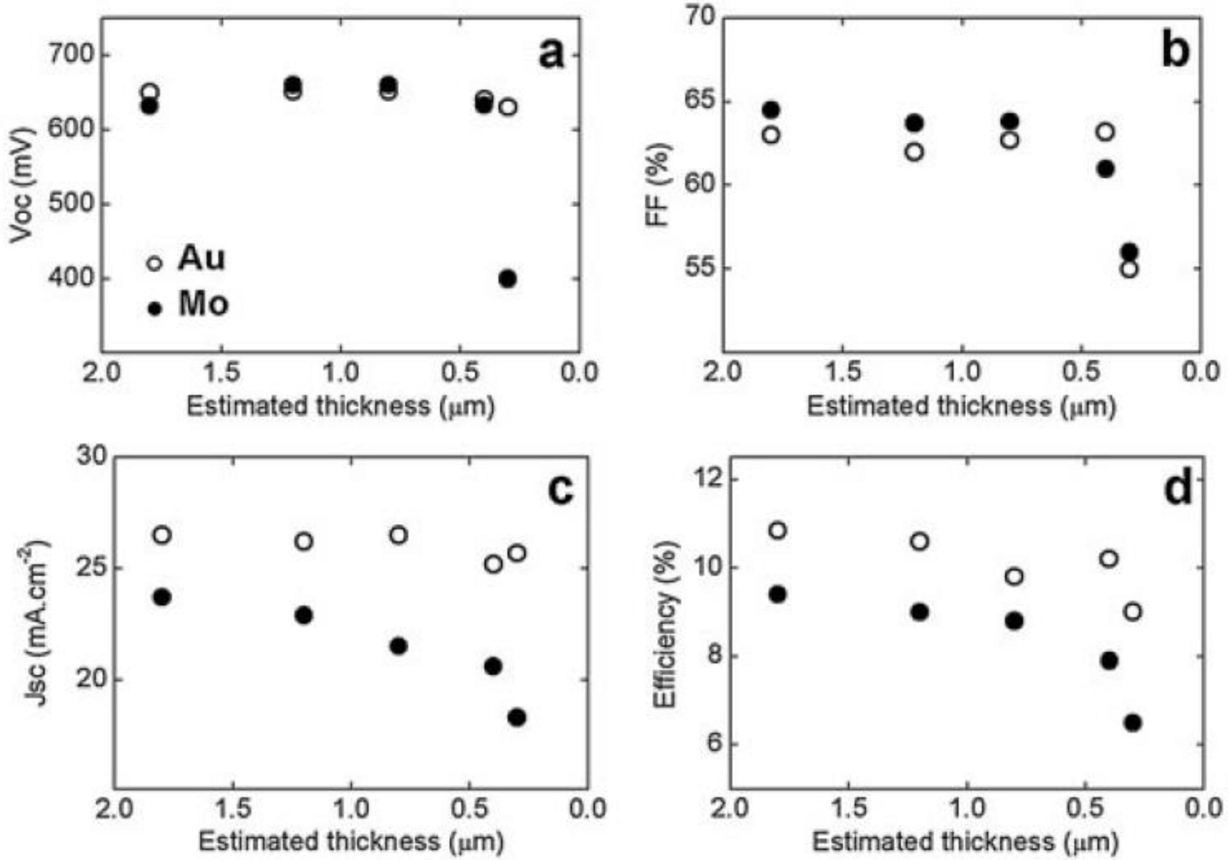
*S. Collin et al., Nature Energy (2019)
https://doi.org/10.1038/s41560-019-0434-y
Also : **Progress and prospects for ultrathin solar cells**
Nature Energy 5 (2020)959

Prog. Photovolt: Res. Appl. 2012; 20:582–587

Towards ultrathin copper indium gallium diselenide solar cells: proof of concept study by chemical etching and gold back contact engineering

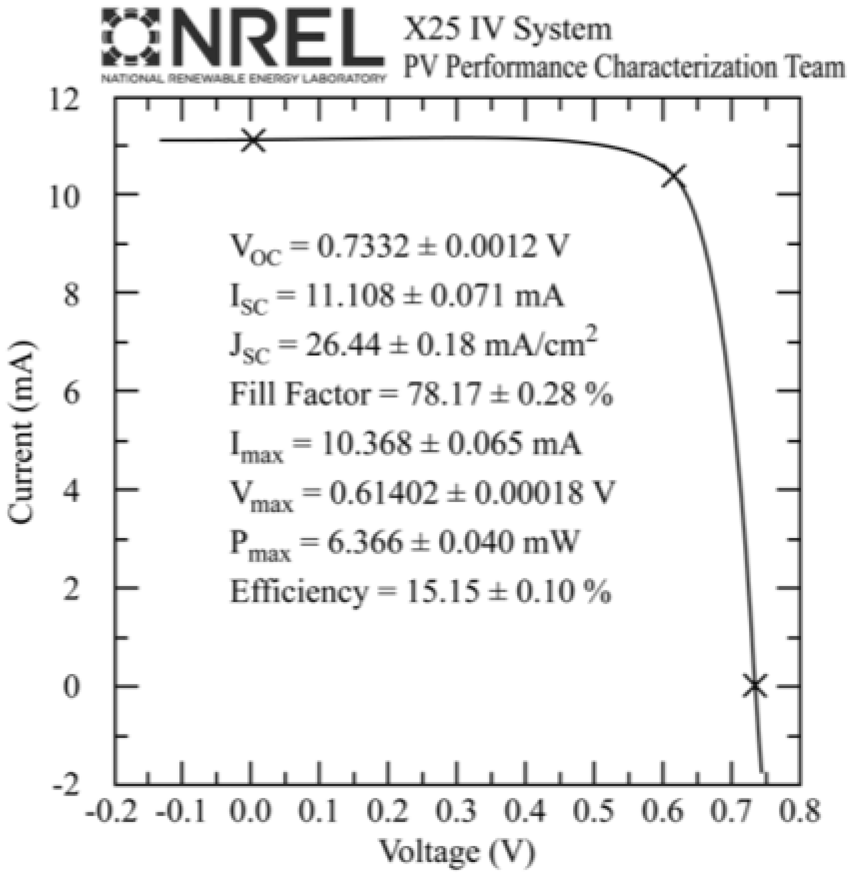
Zacharie Jehl Li-Kao[1]*, Negar Naghavi[1], Felix Erfurth[1], Jean François Guillemoles[1], Isabelle Gérard[2], Arnaud Etcheberry[2], Jean Luc Pelouard[3], Stephane Collin[3], Georg Voorwinden[4] and Daniel Lincot[1]

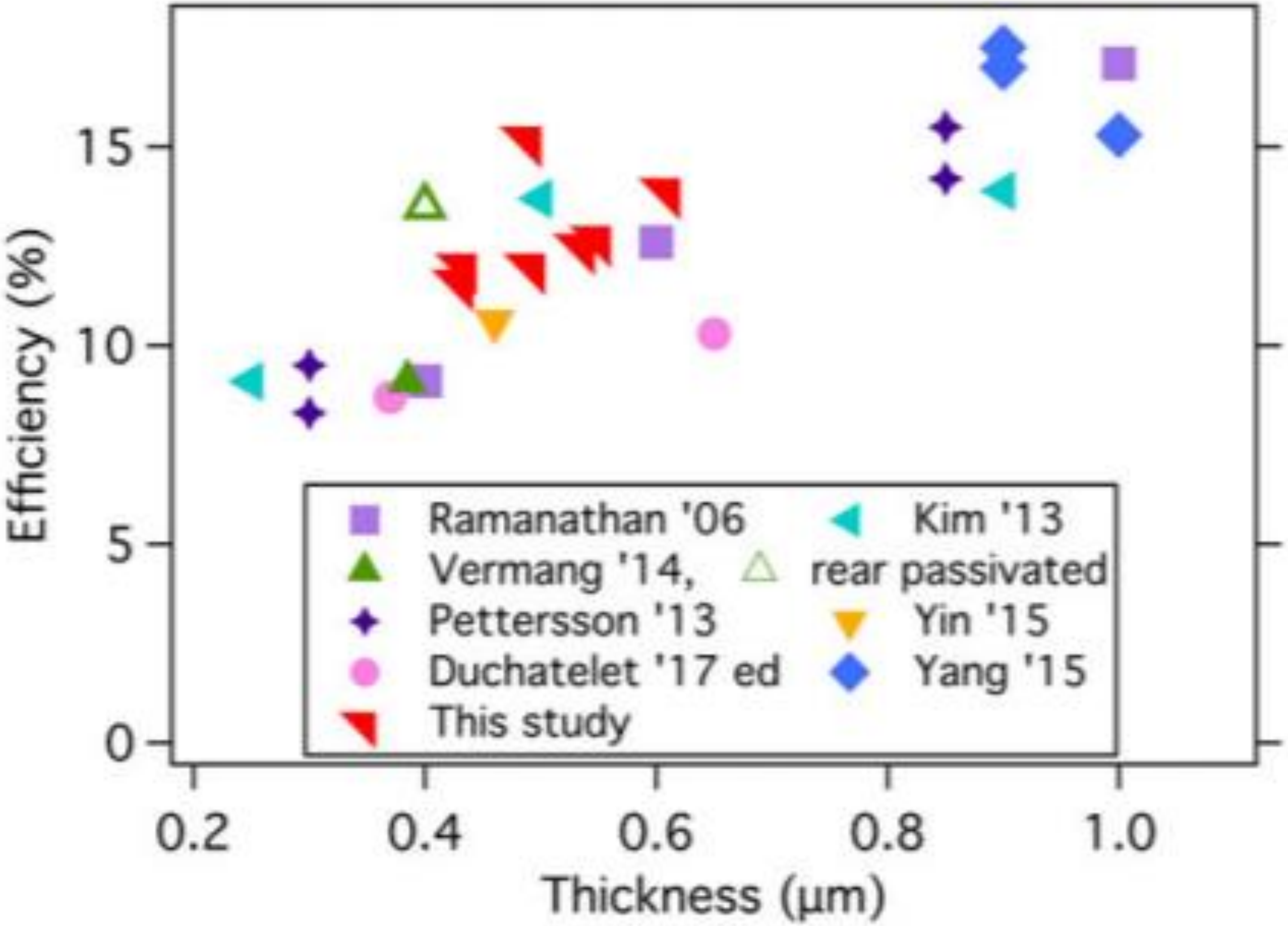




Progress in Ultra-Thin CIGS Solar Cell

2018





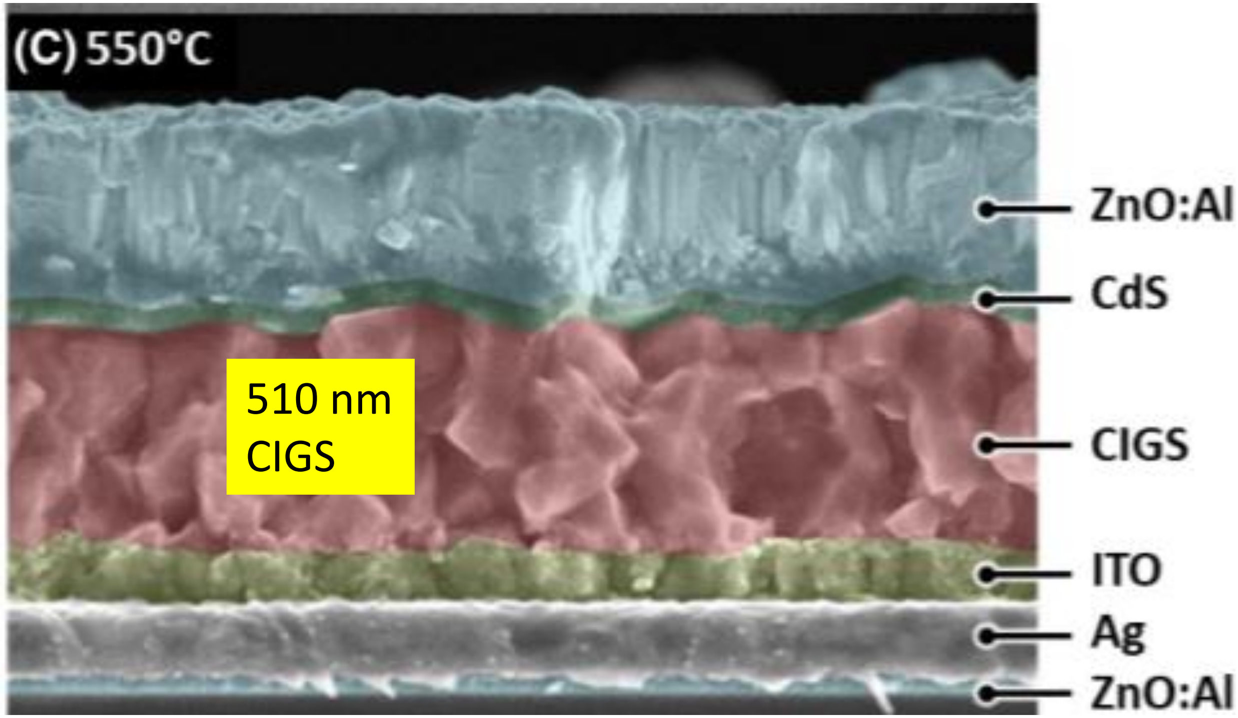
Mansfield LM et al. Progress in Photovoltaics, 26(2018)949

Interface engineering of ultrathin $Cu(In,Ga)Se_2$ solar cells on reflective back contacts

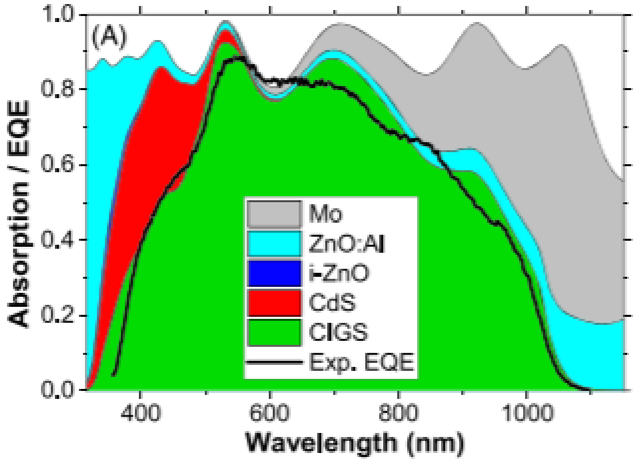
Prog Photovolt Res Appl. 2021;29:212–221

Louis Gouillart[1,2] | Andrea Cattoni[1] | Wei-Chao Chen[3] | Julie Goffard[1] | Lars Riekehr[3] | Jan Keller[3] | Marie Jubault[4] | Negar Naghavi[2] | Marika Edoff[3] | Stéphane Collin[1]

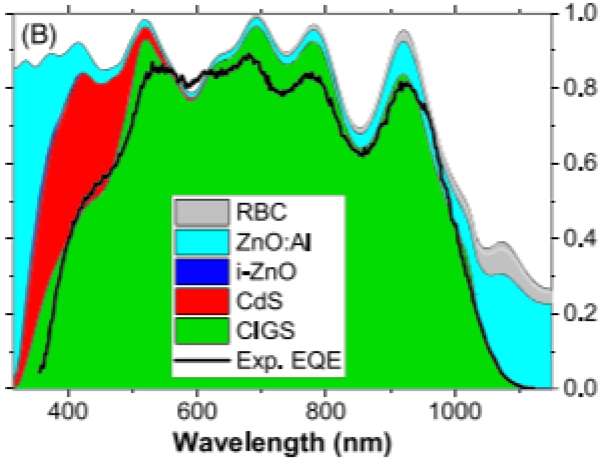
2021



Mo



RBC

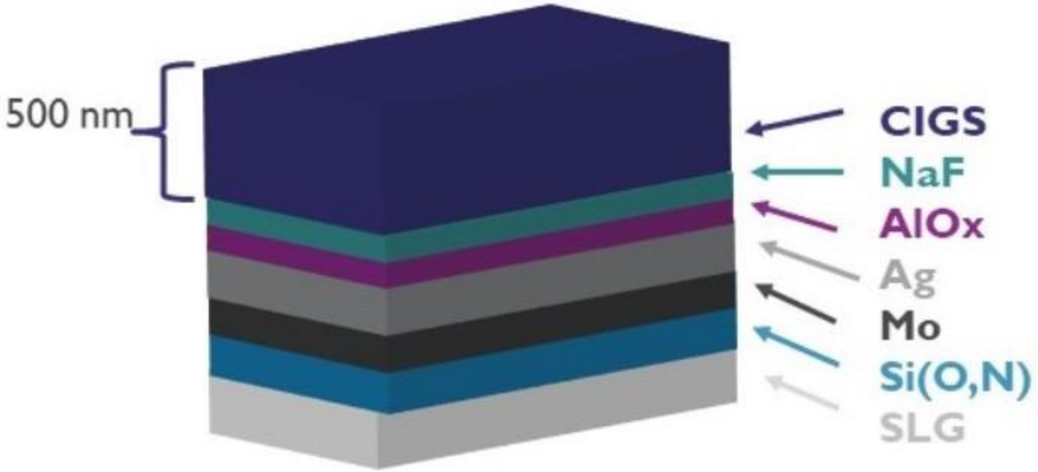


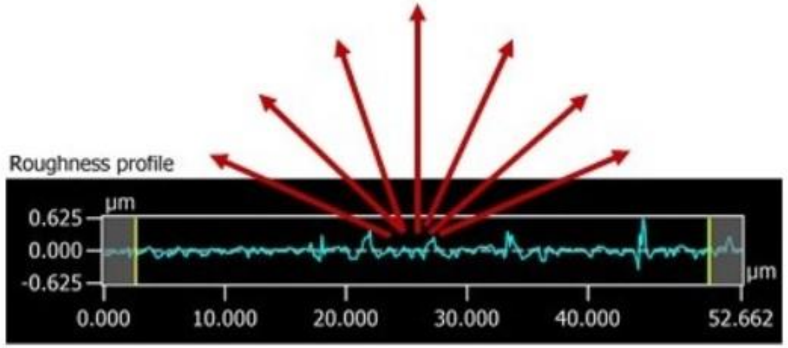
Voc = 644 mV
Jsc = 28.9 mA/cm^2
FF = 72.7 %
Eff = 13.5 % without ARC

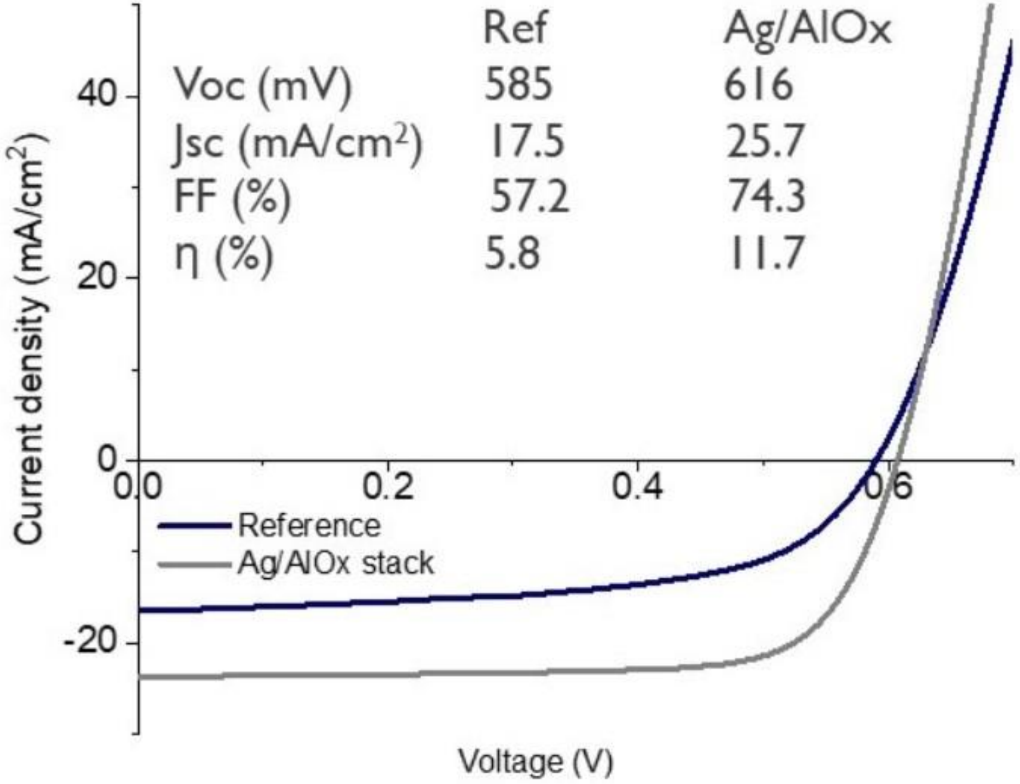
Ultrathin $Cu(In,Ga)Se_2$ Solar Cells with Ag/AlO_x Passivating Back Reflector

Energies **2021**, 14, 4268.

Jessica de Wild [1,2,3,*], Gizem Birant [1,2,3], Guy Brammertz [1,2,3], Marc Meuris [1,2,3], Jef Poortmans [1,3,4,5] and Bart Vermang [1,2,3]







CIGS in a Terawatt perspective
Disruptive concept : Microcells under concentration

Medium risk :

factor of 100 : → 150 kg/ GW

→ 2 TW /Year

High Risk, disruptive :

Factor of 500 (x100, 400 nm CIGS)

30 kg/GW

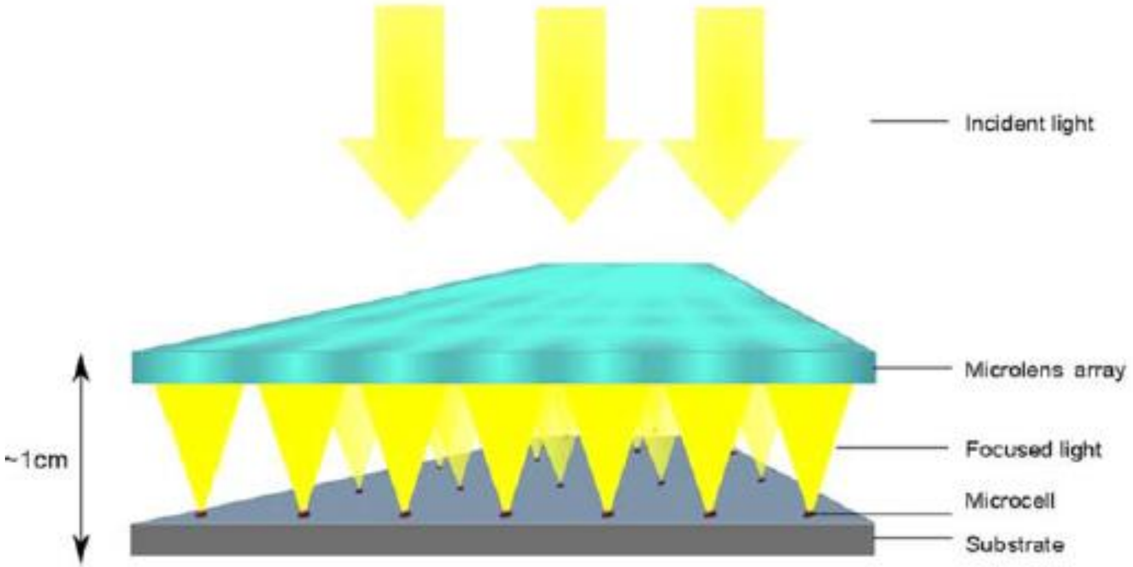
→10 TW/ Year

Accelerating factors:

Development of new architectures,

passivated selective contacts,

plasmonics



Paire M, Lombez L, Donsanti F, Jubault M, Lincot D, Guillemoles J-F, Collin S and Pelouard J-L **2013** Thin-film microcells: a new generation of photovoltaic devices SPIE Newsroom 5 2–3

2013

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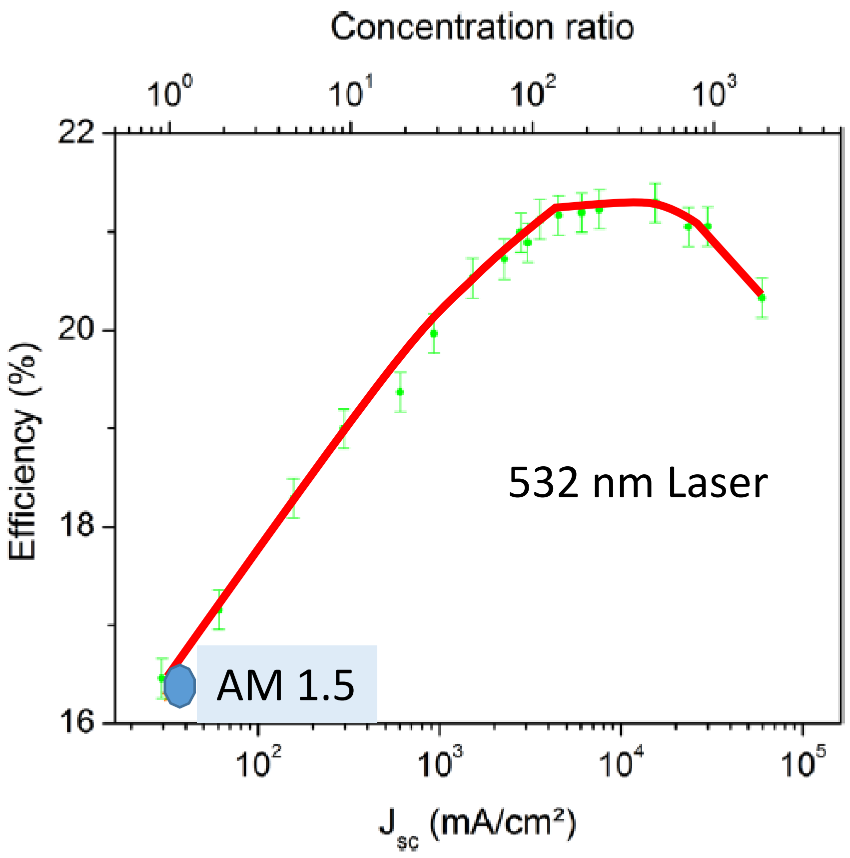
JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY 5, 011202 (2013)

$Cu(In, Ga)Se_2$ microcells: High efficiency and low material consumption

Myriam Paire,[1,2,3,4] Laurent Lombez,[1,2,3] Frédérique Donsanti,[1,2,3]
Marie Jubault,[1,2,3] Stéphane Collin,[5] Jean-Luc Pelouard,[5]
Jean-François Guillemoles,[1,2,3] and Daniel Lincot[1,2,3]



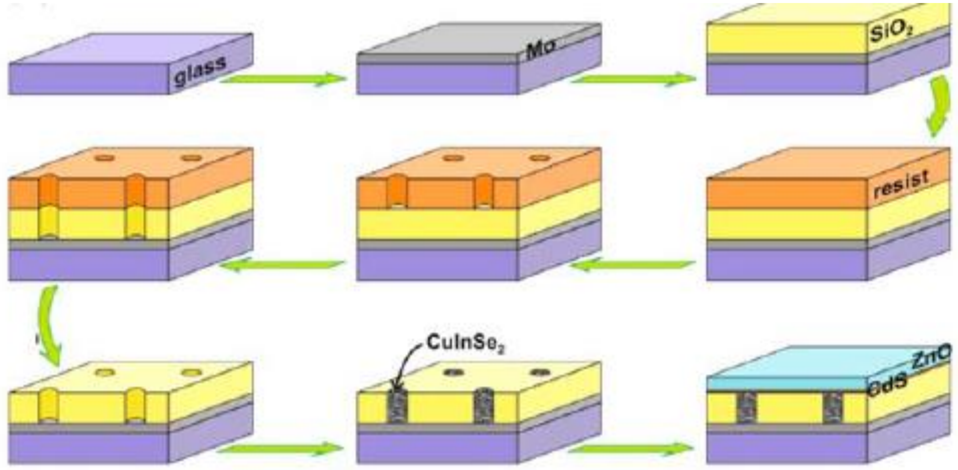
21.3%
X300

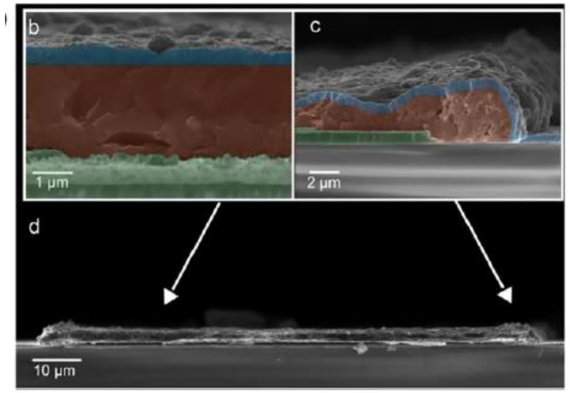
J. Phys.: Energy 2 (2020) 012001

TOPICAL REVIEW

Thin-film micro-concentrator solar cells

Marina Alves[1], Ana Pérez-Rodríguez[1], Phillip J Dale[2]
César Domínguez[3,4] and Sascha Sadewasser[1,5]



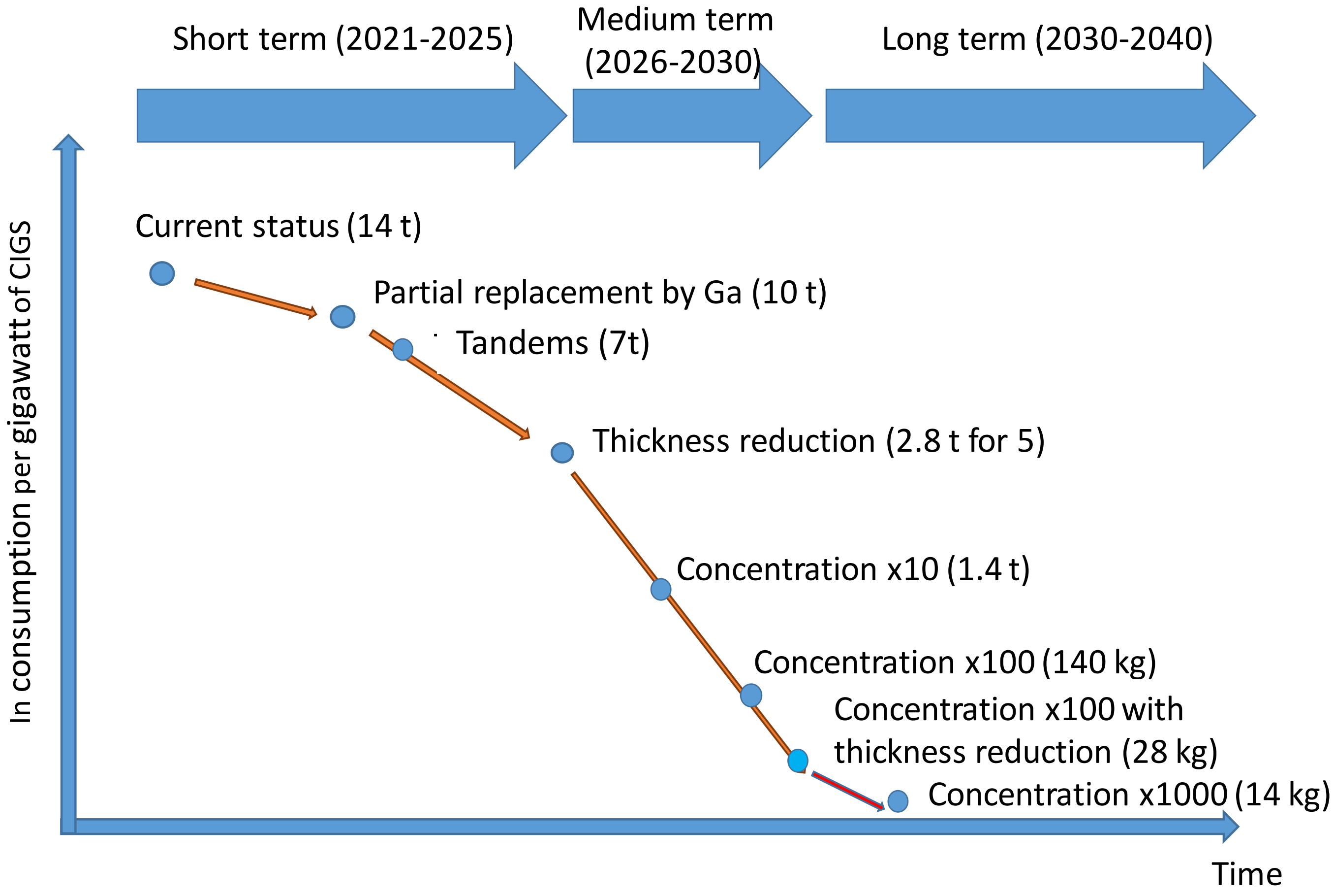


2016

Duchatelet A, Nguyen K,
Grand P P, Lincot D
and Paire M
2016 Appl. Phys. Lett.
109 253901

Conclusion

Indium availability and criticity is not an issue for future development of CIGS technology for the Energy Transition. Economy of Atoms is a key driver.



Earth abundance is an important criterion for all PV.

It is fullfilled by Indium up to the level of ~100 GW/y based on current CIGS technology.

Research on more advanced concepts may allow to increase this number toward TW level.

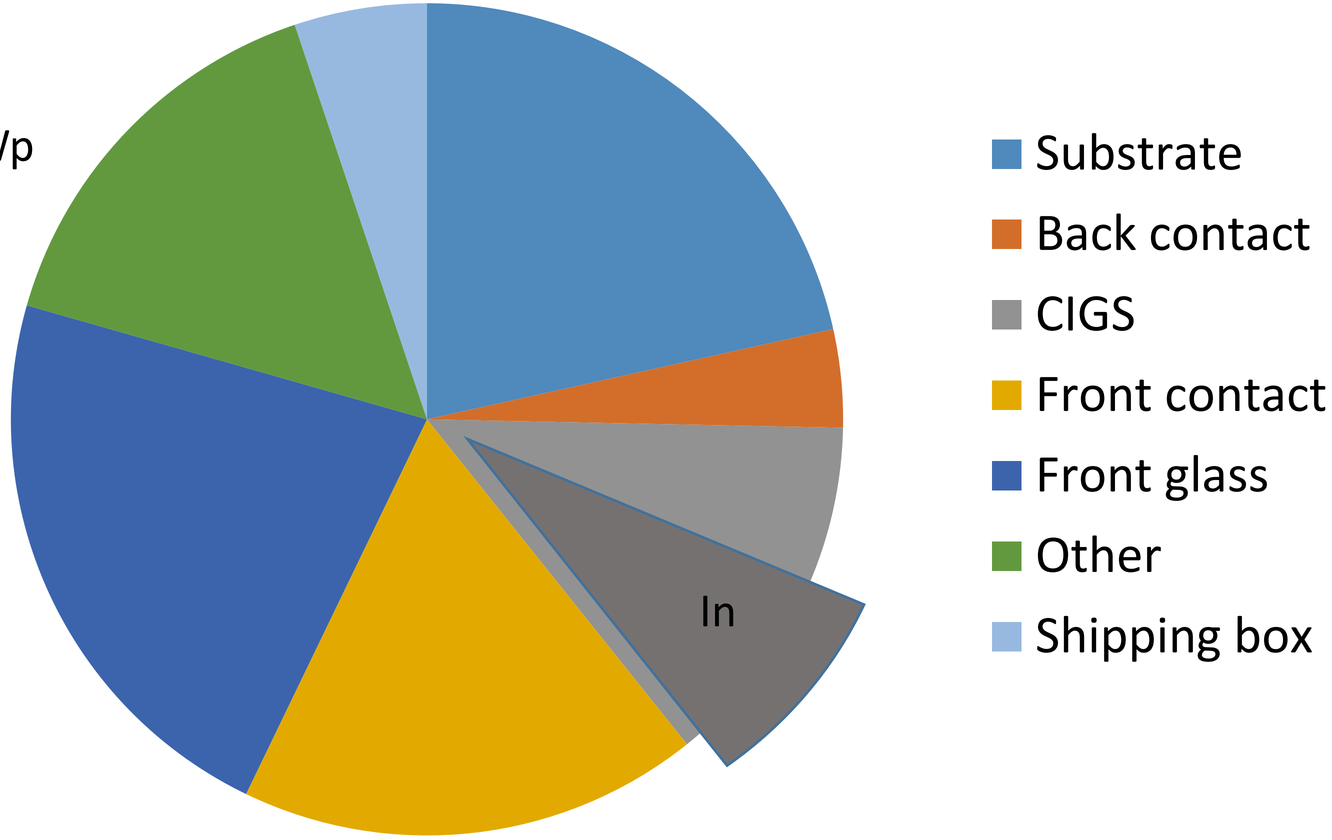
Acknowledgments:
CIGS International Network (https://cigs-pv.net)
CNRS-IPVF Project Proof
PERCISTAND H2020 project

Additional Transparencies

Indium price is not a significant cost factor

Indium contributes only 7% or 1.3c/Wp
- to the cost of a CIGS module
- even at a price 500$/kg

➢ current In price is 150$/kg



Cost repartition of a CIGS module

Indium corresponds to 50 % of CIGS BOM at 500 USD/kg
Indium corresponds to 40 % of CIGS BOM at 300 USD/kg

Source: https://www.statista.com/statistics/1060354/price-of-indium-united-states/

data from Solibro 2018