CIGS Thin Film Photovoltaics for EU's prosperity, energy transition and enabling net zero emission targets

Indium production in Europe is sufficient for more than 100 GW per year PV production with potential to meet TW challenges in a cost effective manner

Coordinated developments are essential for industrialisation and applications of CIGS PV

EU can reach a leading position in future markets

Source: https://cigs-pv.net

Contact: E-Mail: info@cigs-pv.net

Contribution of CIGS thin film PV to EU's prosperity

Study on the EU's list of Critical Raw Materials (2020) recognizes the beneficial impact:

**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"**

Source: https://op.europa.eu/en/publication-detail/-/publication/8dabb4c1-f894-11ea-991b-01aa75ed71a1/language-en

Executive summary

- CIGS-PV is crucial for the energy transition

research results indicate:
more than 30% efficiency in a tandem device is possible

new markets,
not covered by wafer technologies
light weight
flexible

minimal CO_2 emissions

- CIGS-PV is a multi GW technology

high efficiency
stable
non-toxic
cost competitive

nearly 2% of the world market
production increasing

- there is enough Indium for TW production

35% of predicted Indium production is enough for 100GW/year with current CIGS technology

innovation avenues to reduce Indium need per unit power are available

- Indium supply is sufficient

more than 8 countries, including European countries, contribute significantly to the world Indium production

Indium resources are widespread throughout the world and Europe

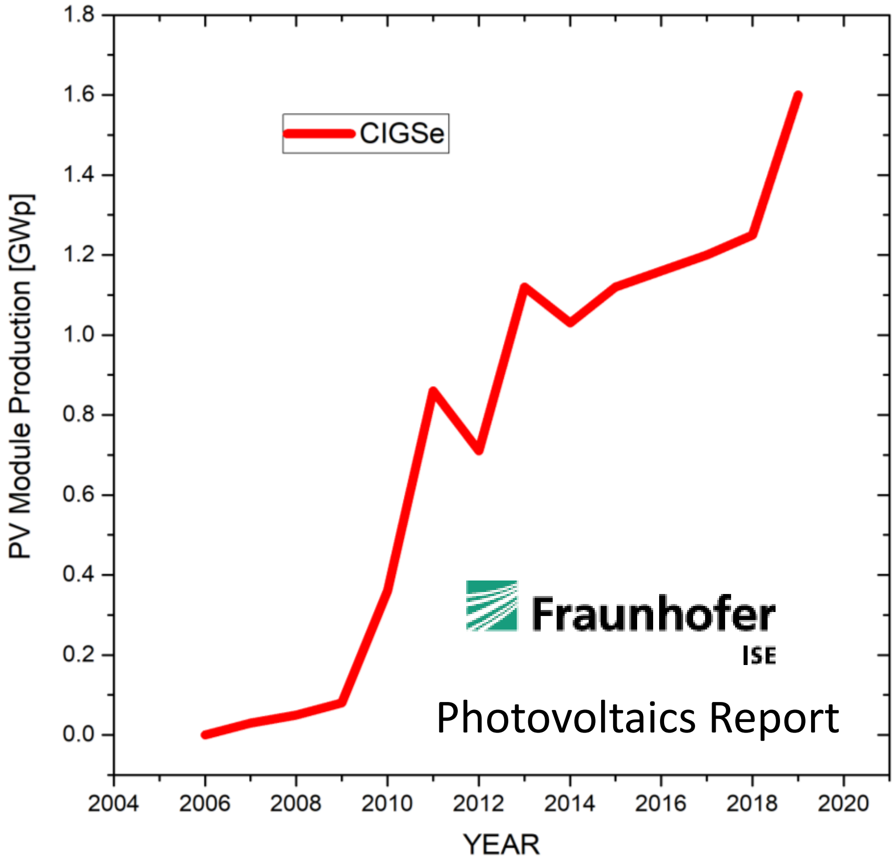
- Indium price is non-critical

Indium contributes only 7% to the cost of a CIGS module

CIGS-PV is already now a GW technology

- efficiency above 23.3% for laboratory cells and above 19.6% for modules
- CIGS PV modules and cells are stable in accelerated aging test as well as in the field
- CIGS PV modules do not contain toxic elements
- thin film module prices are 10% higher than Si PV, at a yet much lower production volume
- thin film technologies will be at the heart of next generations of PV at the TW level:
  - ➢ simple processing
  - ➢ low cost
  - ➢ high throughput
  - ➢ excellent dispachability

CIGS PV module production is significant and increasing



Source: Nakamura, Yamaguchi, Kimoto, Yasaki, Kato, Sugimoto, Cd-free Cu(In,Ga)(Se,S)$_2$ thin-film solar cell with record efficiency of 23.35% IEEE J. Photovolt. **9**, 1863 (2019); https://www.avancis.de/en/avancis-achieves-new-efficiency-record-for-cigs-solar-modules/ ; http://pvinsights.com/

CIGS-PV is crucial for the energy transition

- High efficiency, lightweight and flexible modules are especially attractive for a large range of applications where Si wafer based heavy and rigid modules have severe limitations.

CIGS modules produce less green house gas emissions than Si PV technologies

- all thin film tandem cells with 24 % achieved

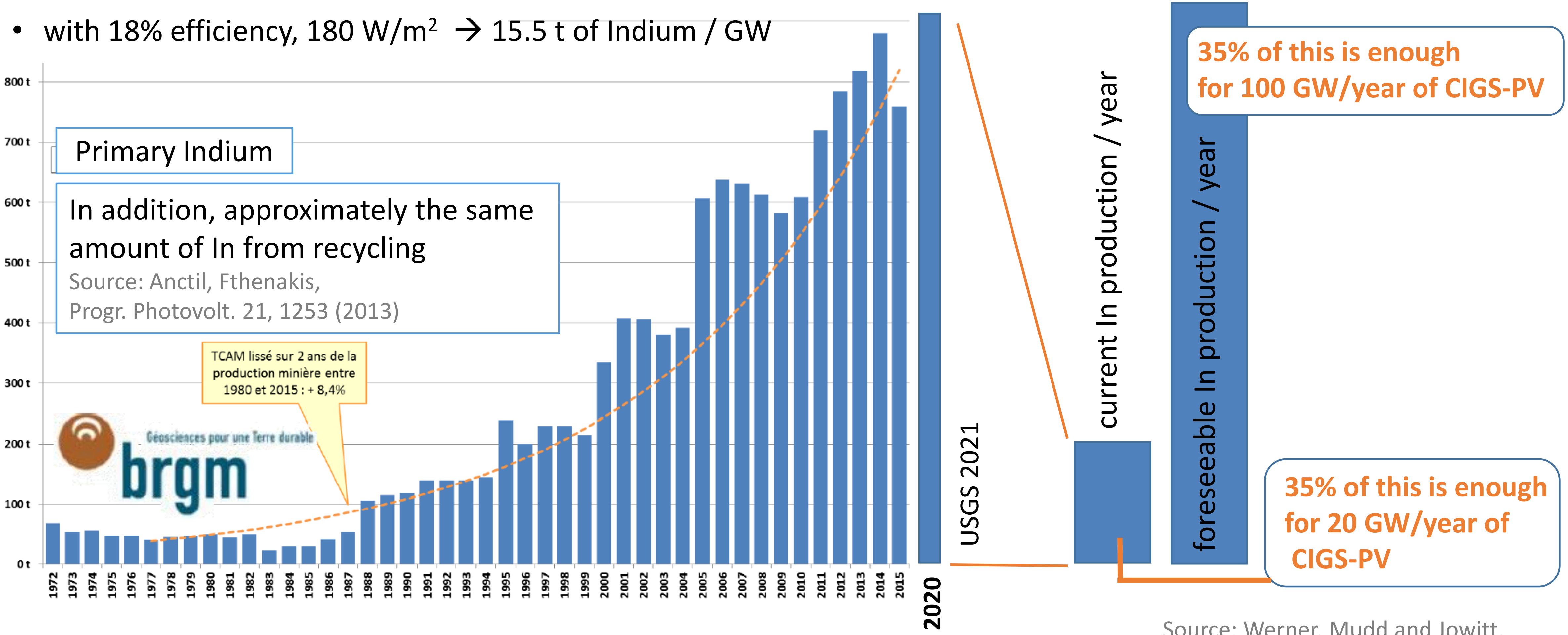
- all thin film tandem or tandem with Si with more than 30% feasible

Source: https://www.helmholtz-berlin.de/pubbin/news_seite?nid=21263&sprache=en
https://www.takagreen.com/rtcl_listing/solar-cloth-system-revetements-et-tissus-photovoltaiques/

There is enough Indium for about 20 GW to 100 GW per year production of CIGS-PV with 35% utilization of actual and available resources

- state-of-the-art: 2 microns CIGS with In/(In+Ga) = 0.7 need 2.8 g of In by m^2
- with 18% efficiency, 180 W/m^2 → 15.5 t of Indium / GW

prediction based on **mineral availability** and **extrapolated need**: 4000 t

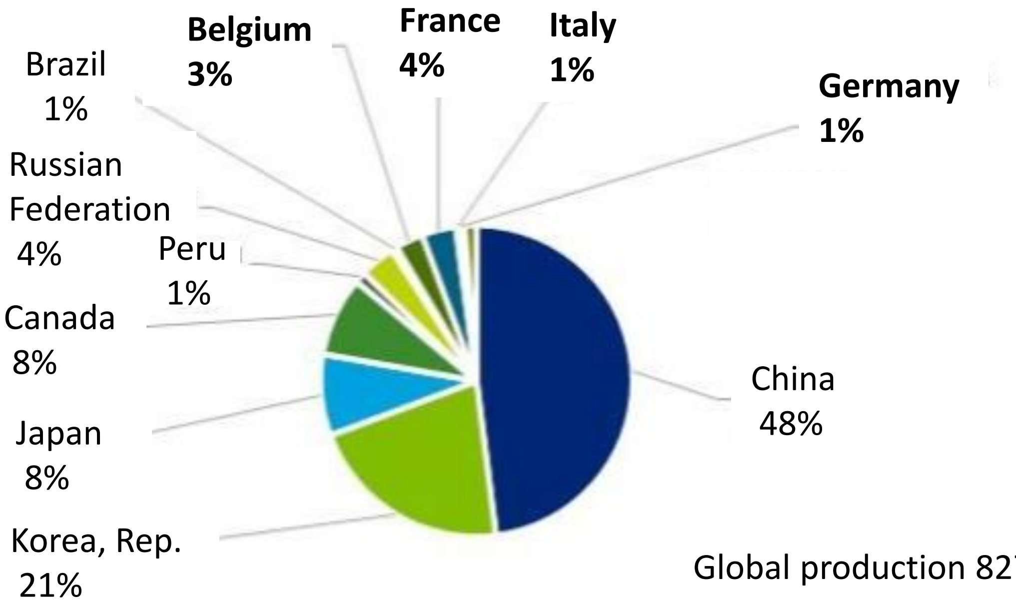


Source: BRGM, criticality study 2017

Source: Werner, Mudd and Jowitt, Ore Geology Reviews, Jan 2017

EU Indium supply is sufficient to support an EU production

Distribution of world Indium refinery production



Global production 827 tonnes

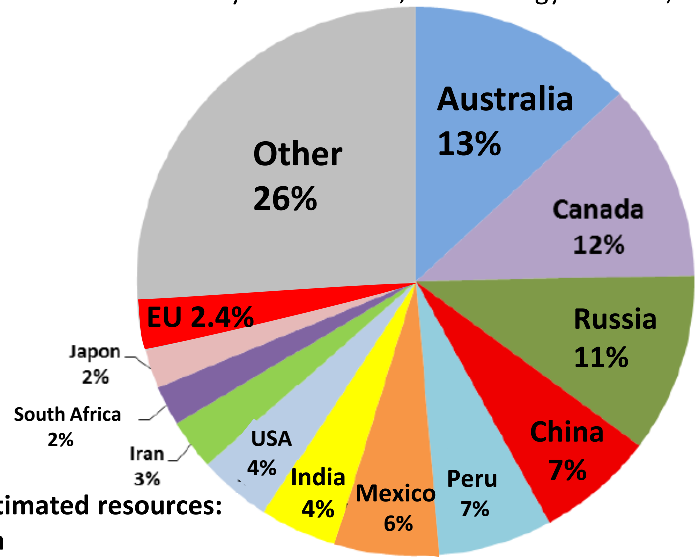
Average annual production between 2012 and 2016

- 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

Distribution of world Indium resources

as reviewed by Werner et al, Ore Geology Reviews, 2017



Total estimated resources:
356 kt In
(excluding domestic waste estimated at an additional 24 kt)

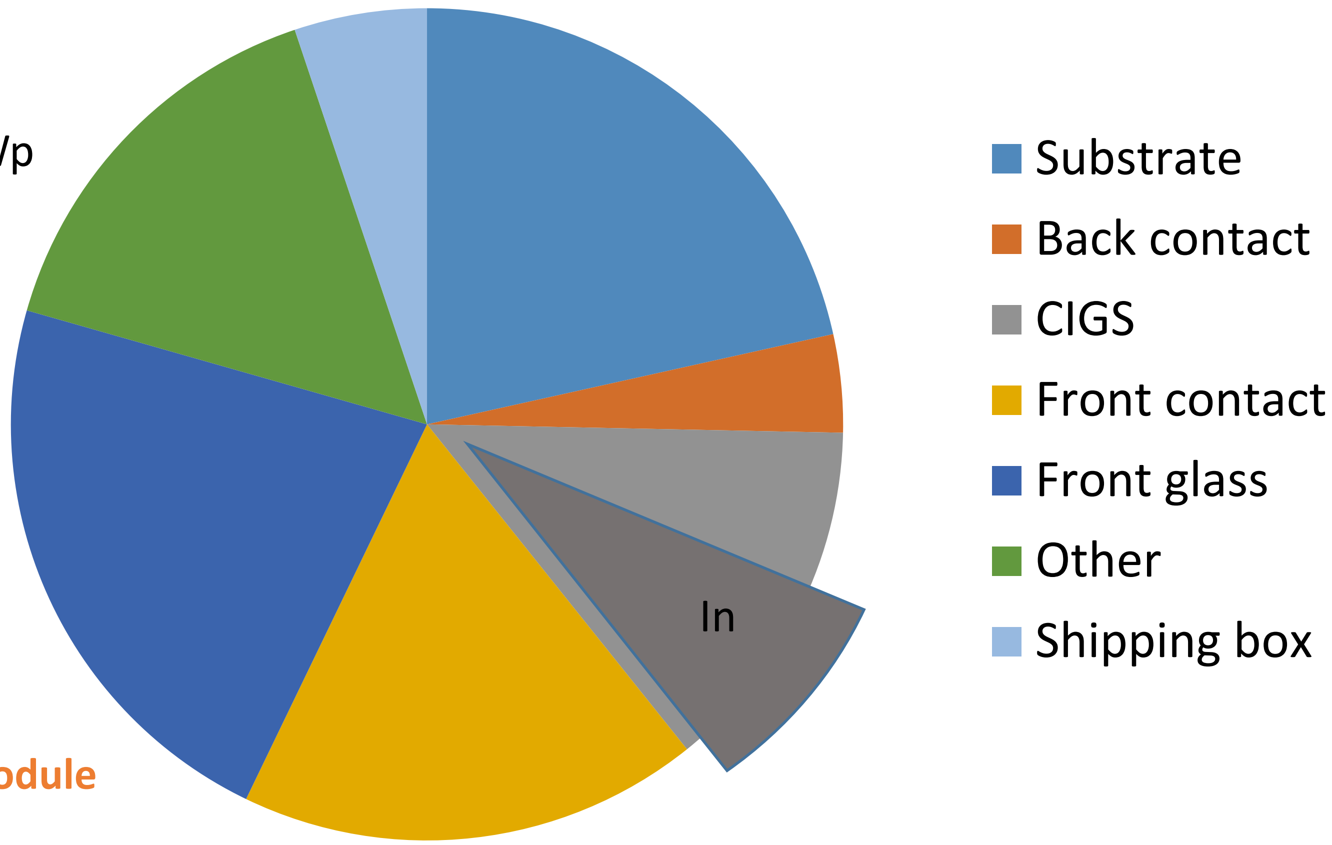
Broad distribution of resources:

- only 7% in China
- 93% in the rest of the world, with 2.4% in the EU
- 35% of zinc production sites are not retrieving Indium
- wide margin for increasing the refinery production in Europe (> 10%)

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/

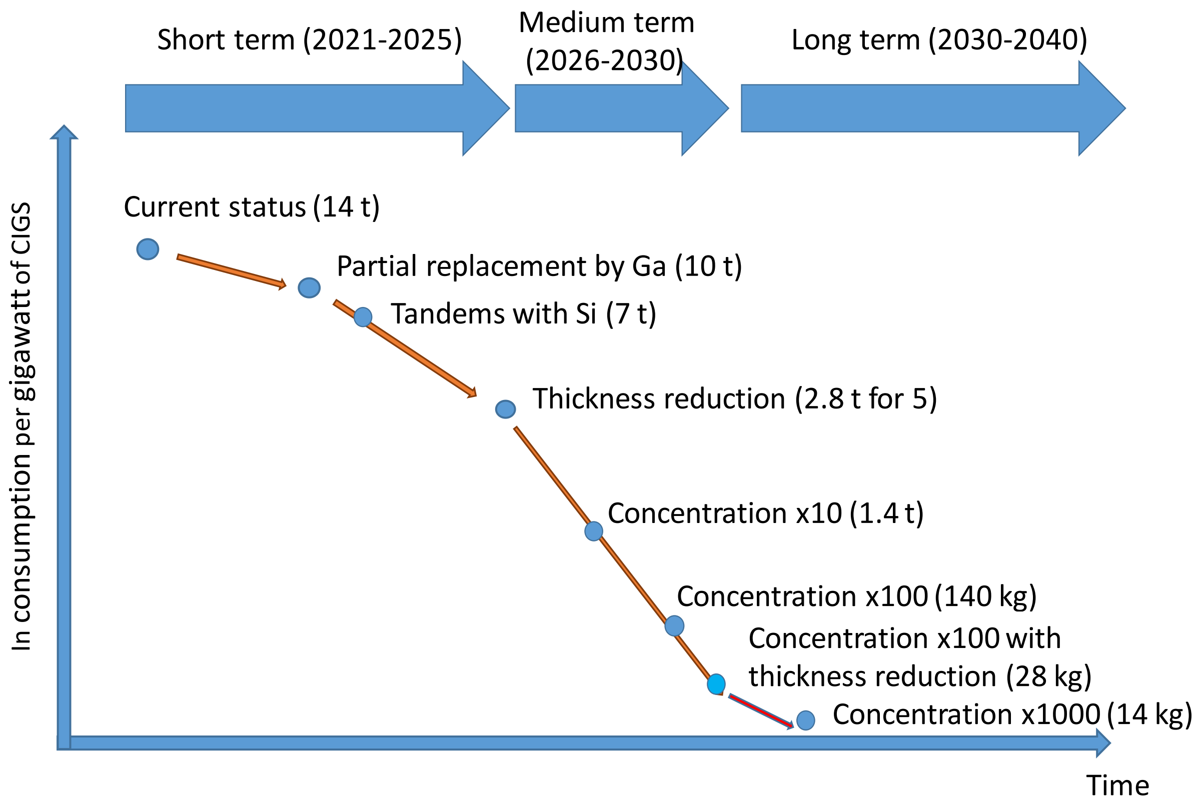
data from Solibro 2018

Emerging CIGS PV technologies need even less Indium

Routes for less Indium per GW are available in the laboratories

- tandem concepts increase efficiency beyond current technologies
- 2.8 t/GW with thickness reduction:
  → 90 GW/year with actual production

- micro solar cells with concentrators
  → 140 kg/GW is within reach with x100 concentration
- ➢ corresponding to 1 TW/year based on actual production
- ➢ > 10 TW/year with disruptive evolutions



Source: S. Jutteau. "Design, prototyping and characterization of micro-concentrated photovoltaic systems based on Cu(In,Ga)Se_2 solar cells." doctoral thesis Université Pierre et Marie Curie - Paris VI, 2016

Building a strong CIGS PV industry is crucial and Indium is sufficiently available in Europe

Europe's leading role in CIGS research prepares the future of photovoltaics:

- high efficiency tandem technologies
- ultralow weight, flexible thin film PV
- excellent environmental footprint

Indium production in the EU is sufficient to ensure several GW/year CIGS production in Europe

Additional references:

2000
B.A. Anderson, Materials availability for large scale thin film photovoltaics, Progress in photovoltaics, 8(2000)61-76

2006
A.A. Green, Improves estimates for Te and Se availability from Cu anode slimes and recent price trends, Progress in Photovoltaics, 14(2006)743-751

2009
V. Fthenakis, Sustainability of photovoltaics : the case of thin film solar cells, Renewable and sustainable energy reviews, 13(2009)2746-2750
M.A. Green, Estimates of Te and In prices from direct mining of known ores, Progress in photovoltaics, 17(2009)347-359

2010
UC Santa Barbara, Materials implications for large scale adoption of photovoltaic technologies (presentation on web)

2011
V.M. Fthenakis, H.C. Kim, Photovoltaics : life cycle analyses, Solar Energy 85(2011)1609-1628

2012
C. Candelise, M. Winskel, R. Gross, Implications for CdTe and CIGS technologies production costs of indium and tellurium scarcity, Progress in photovoltaics,
V.M. Fthenakis, Sustainability metrics for extending thin-film photovoltaics to terawatt levels. MRS Bulletin, 37(4), 425-430, 2012.

2013
USGS, fact sheet, Gallium a smart metal
M.J. de Wild Scholten, Energy pay back time and carbon footprint of commercial photovoltaic systems, Solar Energy Materials 119(2013)296-305

2014
M. Marwede, A. Reller, Estimation of life cycle materials costs of cadmium telluride and copper indium gallium diselenide photovoltaic absorber materials based on life cycle materials flows, Journal of Industrial Ecology, 18(2014)254-267

2015
L. Grandell, M. Hook, Assessing rare metal availability challenges for solar energy technologies, Sustainability, 7(2015)11818-11837
H. Duan, J. Wang, L. Liu, Q. Huang, J. Li, Rethinking china's strategic mineral policy on indium : implication for the flat screens and photovoltaic indsutries, Progress in Photovoltaics, (2015)
M. Redlinger, R. Eggert, M. Woodhouse, Evaluating the availability of gallium indium and tellurium from recycled photovoltaic modules, Solar Energy materials 138(2015)58-71
T.T. Werner, G.M. Mudd, S.M. Jowitt, Indium :key issues in assessing mineral resources and long term supply from recycling, Applied Earth Science 124(2015)213-226
P. Viebahn, O. Soukup, S. Samadi, J. Treubler, K. Wiesen, M. Ritthoff, Assessing the need for critical minerals to shift german energy system towards a high proportion of renewables, Renewable and sustainable energy reviews, 49(2015)655-671
J. Jean, P.R. Brown, R. L. Jaffe, T. Buonassisi, V. Bulovic, Pathways for solar photovoltaics, Energy and Environmental Science, 8(2015)1200-1219 and supplementary material
M. Lokanc, R. Eggert, M. Redlinger, The availability of indium :the present, medium term and long term, NREL report M. Woodhouse, NREL/SR-6A20-62409, 2015

2016
W. Maret, The metals in the biological periodic system of the elements : concepts and conjectures, International journal of molecular sciences, 17(2016)66
D. Huy, M. Liedtke, Supply and demand of lithium and gallium, Information center of ministry of land and resources, china and Germany
Le gallium, éléments de criticité, Fiche de synthèse du BRGM, France august 2016

2017
L'indium, éléments de criticité, Fiche de synthèse du BRGM, France August 2017
M. Frenzel, C. Mikolajczak, M. A. Reuter, J. Gutzmer, Quantifying the relative availability of high tech by product metals. The cases of gallium, germanium and indium, Resources Policy 52(2017)327-335
Indium, USGS 2017 Mineral Yearbook, April 2020
Gallium, USGS 2017 Minerals Yearbook, April 2020
T.T. Werner, G.M. Mudd, S.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

2018
S. Amarakoon, C. Vallet, M. A. Curran, P. Haldar, D. Metacarpa, D. Fobare, J. Bell, Life cycle assessment of photovoltaic manufacturing consortium (PVMC) copper indium gallium diselenide (CIGS) modules, Int. J. Cycle assessment 23(2018)851-866
L. Ciacci, T. T. Werner, I. Vassura, F. Passarini, Backlighting the european indium recycling potentials, Journal of industrial ecology 23(2018)426-437
Gallium, l'élémentarium, Société Française de Chimie, 2018

2019
Indium, l'élémentarium, Société Française de Chimie, 2019

2020
M.K. van der Hulst, M.A.J. Huijbregts, N. van Loon, M. Theelen, L. Kootstra, J. D. Bergesen, M. Hauck, A systematic approach to assess the environmental impact of emerging technologies. A case study for the GHG footprint of CIGS solar photovoltaic laminate, Journal of Industrial Ecology,24(2020)1234-1249
N.M. Kumar, S.S. Chopra, M. malvoni, R. M. Elavarasan, N. das, Solar cell technology selection for a PV leaf based on energy and sustainability indicators-a case of multilayered solar photovoltaic tree, Energies 13(2020)6439
M. Tao, H. Hamada, T. Druffel, J.J. Lee, K. Rajeshwar, Review-research needs for photovoltaics in the 21st century, ECS Journal of solid state science and technology, 9(2020)125010
S.M. Jovitt, G.M. Mudd, J.F.H. Thomson, Future availability of non renewable metal resources and the influence of environmental, social and governance conflicts on metal production, Communications earth and environment, 1(2020)
P. Main, A. Kumar, Ecological and human health risk assessment of metals leached from end of life photovolatics, Environmental pollution 267(2020)115393
Study on the EU's list of critical raw materials, European Commission, Final report (2020)

2021
M. K.H. rabaia, M.A. Abdelkareem, E.T. Sayed, K. Elsaid, K.Y. Chae, T. Wilberforce, A.G. Olabi, Environmental impacts of solar energy systems, a review, Science of the Total Environment, 754(2021)141989
K. Ren, X. Tang, M. Hook, Evaluating metal constraints for photovoltaics : perpectives from China's PV development, Applied Energy 282(2021)116148
S. Schuyler Anderson, Indium, Mineral commodity summaries, USGS, 2021

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