Horizon 2020 Programme

SCRREEN2

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SCRREEN

Solutions for CRitical Raw materials - a European Expert Network

FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

INDIUM

AUTHOR(S):

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INDIUM

Indium (chemical symbol In, atomic number 49) is a very soft, ductile and malleable silvery metal with a hardness of 1.2 on Mohs scale. It has a density of 7.31 g/cm^3 (similar to tin's), a low melting point of 156.6°C, a high boiling point of 2072°C and becomes superconducting at 3.37 K (-269,78°C). The most important commercial source of indium is the zinc mineral sphalerite. Approximately 95% of the refined primary indium produced in the world comes from zinc ores processing (Lokanc, M. et. al., 2015). Indium is assessed at extraction and processing stage (indium metal), by considering trade of unwrought indium; Indium powders (trade code CN81129281)

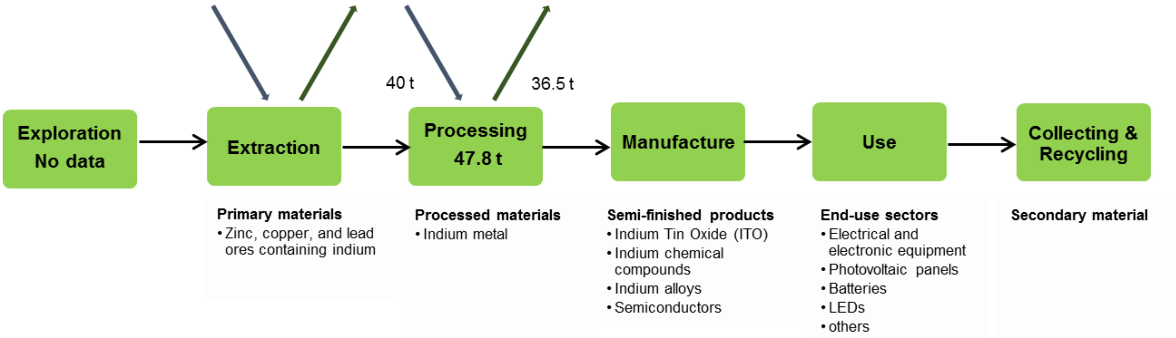

Figure 1. Simplified value chain for indium in the EU[1]

Table 1. indium supply and demand in metric tonnes, 2016-2020 average

Global production (t)	Global Producers	EU consumption (t)	EU Share	EU Suppliers	Import reliance
845	China 50% Korea 26% Japan 8% Canada 8% France 4%	6.5	0.8%	China 43% Taiwan 25% United States 14% Great Britain 9% South Korea 3%	2.5%

Prices: Prices of indium were supported by stockpiling at the Fanya Metals Exchange (FME) which was established in 2011 in Kunming, China, until its collapse in August 2015 (USGS, 2016). In 2015, Kunming municipal government announced a criminal investigation against FME for illegal fund raising. Since the collapse of FME, indium prices have dropped from USD 700 to USD 200 per kilogram in 2018 (USGS, 2016).

Primary supply: Indium is found as a trace element in some zinc, copper, lead and tin minerals but is mostly recovered from the zinc-sulphide mineral sphalerite. Indium abundance in the Earth continental upper crust is estimated at 0.056 ppm (Rudnick & Gao, 2014). The world refinery production of primary indium was

[1] JRC elaboration on multiple sources (see next sections)

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approximatively 845 tonnes per year on average over the period 2016-2020 (WMD, 2022).) China continued to be the major producer with almost half of the global production (50%). The remaining production was predominantly in South Korea (25% share), Japan (8%), Canada (8%), and Russia (4%). The EU production of refined indium amounted to 54 tonnes per year on average on the period 2016-2020 and represented around 6% of the world production.

Secondary supply: World secondary refined indium production resulted almost exclusively from the recycling of manufacturing waste (new scrap = semi-finished product or pre-consumer scrap) rather than recovery from end-of-life (EoL). New scrap used in the secondary production of indium consists mainly of spent Indium Tin Oxide (ITO) sputtering targets, which are used as ITO source material to produce thin film coatings on flat panel liquid-crystal displays (LCD), light-emitting diodes (LED) or plasma screens, which stands for approximately 84% of total global indium consumption. Indium recycling at EoL is nonexistent because of minor indium concentrations in consumer products, a lack of appropriate technology, or low economic incentives compared to recycling costs (Ylä-Mella J., 2016).

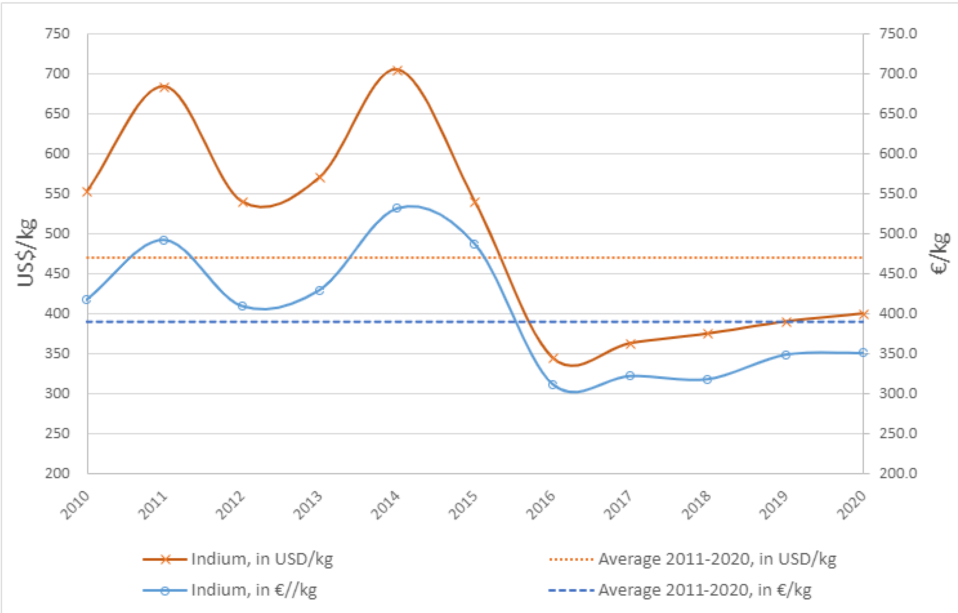

Figure 2. Annual average price of indium between 2000 and 2020 (USGS, 2021)[2].

Uses: The primary application of indium is as ITO thin films. ITO is a mixture of indium (III) oxide (In2O3) and tin (IV) oxide (SnO2), typically 90% In2O3, 10% SnO2 by weight. ITO is used in flat-panel displays (FPDs) ITO thin films are applied to car and aircraft windshields for defogging and de-icing and were used to make touch screen cathode ray tubes (CRTs) found, e.g., in some bank ATMs, although these being phased out (Vulcan, 2013). Indium is used as a low-temperature solder and a lead-free solder, either as alloys or as pure metal. Indium reduces the melting point in solder alloys and can improve the thermal fatigue performance of solders. Indium semiconductor compounds (CuIn1-xGaSe2) are used as a light absorber material in CIGS (Copper indium gallium diselenide) and CIS (without gallium) thin film solar cells. Due to their excellent thermal conductivity and ductility indium metal, alloys and composites are also used as thermal interface materials

[2] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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(TIMs) in electronics devices. Moreover, indium is one of many substitutes for mercury in alkaline batteries to prevent the zinc anode from corroding and releasing hydrogen gas.

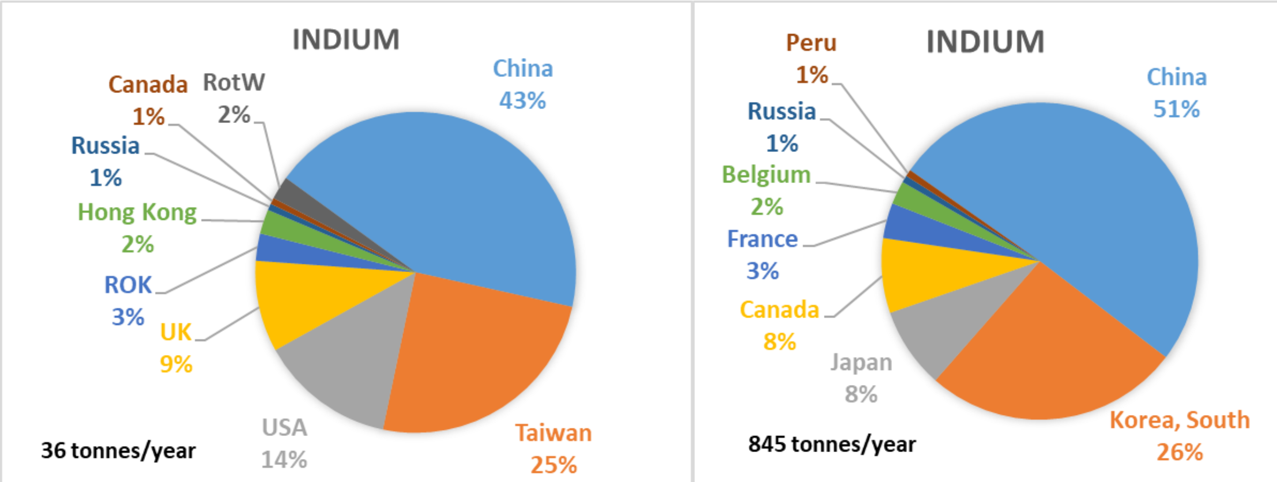

Figure 3. EU sourcing of indium (Eurostat 2022) and global production (WMD 2022), (average 2016-2020,)

Substitution: Indium-thin-oxide (ITO) is substitutable in LCDs by antimony-tin-oxide (ATO). However, antimony is also classified as critical raw material (European Commission 2020). Indium phosphide can be replaced by gallium arsenide in solar panels. However, gallium is also classified as critical raw material (European Commission 2020). Tin-bismuth alloys can replace tin-indium alloys for low temperature bonding and soldering applications. Silicon has largely replaced indium and germanium in transistors but there is no substitute for indium gallium nitride-InGaN in LEDs.

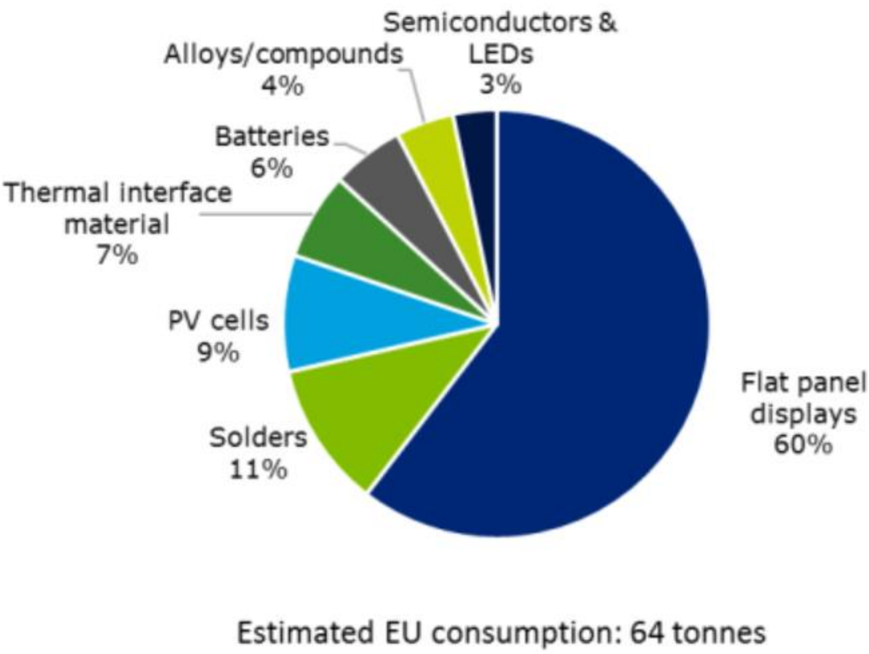

Figure 4: EU uses of indium, average 2012-2016, no new data (Atlantic, 2016)

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Table 2. Uses and possible substitutes

Application	%*	Substitute(s)	SubShare	Cost	Performance
Flat Display Screens (Indium Tin Oxide (ITO))	60%	Aluminium-doped zinc oxide (AZO)	5%	Similar or lower	Reduced
		Fluorine-doped tin oxide (FTO)	5%	Similar or lower	Reduced
		Antimony-tin-oxide (ATO)	5%	Similar or lower cost	Reduced
Solders	11%	Tin-bismuth alloys	50%	Similar or lower costs	Similar
		Lead-based alloys	0%	Similar or lower costs	Similar
PV Cells	9%	Cadmium telluride (CdTe)	4%	Similar or lower costs	Similar
		Amorphous silicon thin film	0.1%	Similar or lower costs	Similar
		Multi-Si and Mono-Si	94.9%	Similar or lower costs	Similar
Batteries (alkaline)	5%	Mercury	5%	Slightly higher costs (up to 2 times)	Reduced
Alloys / compounds	4%	Not assessed, under 10%			
Semiconductors & LEDs	3%	No substitute			

Other issues: Exposure of industrial workers to insoluble indium compounds, such as indium arsenide, indium phosphide, and ITO, may lead to interstitial lung damage and other respiratory problems (USGS 2017, Mitsuhashi 2020). In Germany, the OEL (Occupational Exposure Limit) for indium exposure in dust is limited to 0.0001 mg/m3 regarding the respirable fraction (GESTIS 2022, Pitzke 2021). A similar threshold limit value is recommended by the American Conference of Governmental Industrial Hygienists (ACGIH TLV) while a less strict limit of 0.01 mg/m3 is accepted in Korea and Japan (Gwangyong 2021, Kim 2021). Few studies have focused on the ecological impacts of indium mobility in the environment. Some effects of indium nitrate exposure have been found in aquatic organisms when indium concentrations were orders of magnitude greater than those in reported natural systems (USGS 2017).

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3: Indium (processing) supply and demand in metric tons, 2016-2020 average

Global production (t)	Global Producers	EU consumption (t)	EU Share	EU Suppliers	Import reliance
845	China 50% Korea 26% Japan 8% Canada 8% France 4%	6.5	0.8%	China 43% Taiwan 25% United States 14% Great Britain 9% South Korea 3%	2.5%

World production of indium over 2016-2020 was 845 tonnes, with majority of production in China (about 50%), followed by South Korea (about 26%).

The worldwide market value of indium in 2019 was USD 420 million and it is expected to grow at a CAGR of roughly 4.2% over the next five years, reaching USD 540 million in 2024 (Marketwatch, 2019). Indium is traded in metal exchange.

Indium resources and reserves are generally derived from zinc and copper resources. In Europe, most of the indium mineralisation is located in Variscan units and, to a small extend, in Proterozoic (Sweden), Caledonian and Alpine formations. Portugal and Germany also have some reserves.

Countries extracting zinc in the EU are Finland, Greece, Portugal, Romania, Bulgaria, Spain, and Sweden, Ireland and Poland. All these countries are potentially extracting indium as a by-product, excluding Poland and Ireland. Outside the EU, Peru, China, Australia, and Canada are also extracting indium. Global production of primary indium is estimated at 21,200 tonnes, with an EU27 potential production of 50 tonnes.

Over the period 2016-2020 the EU imported 36 tonnes of processed indium annually, mainly from China (43% of EU sourcing), Taiwan (25% of EU sourcing), the United States (14% of EU sourcing), and the United Kingdom (9% of EU sourcing).

In the EU, the most well- known producer of virgin indium from primary feed is Auby, Nyrstar in France. Vital Materials (Germany) is also producing indium metal, chemicals and alloys from secondary feeds.

Major uses of indium in the EU include flat panel displays (56%), solders (10%), photovoltaics (8%), thermal interface materials (6%), batteries (5%), and alloys (4%). In transparent conducting oxides (TCOs) used in flat panels displays and in amorphous silicon and CdTe PV cells, indium can be replaced by other TCOs. There is no commercially available substitute for indium in semiconductors (CIGS and CIS) used in thin-film solar cells.

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”[122]. The main demand drivers from 2022 onwards will be thermal interface materials, alloys, and LED.

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World secondary refined indium production resulted almost exclusively from the recycling of manufacturing waste (new scrap) rather than recovery from end-of-life (EoL). Indium is most commonly recovered from Indium Tin Oxide (ITO) scrap, for example in Japan and the Republic of Korea (USGS, 2019). Precise data on the amount of secondary indium recovered from scrap are not available, though are estimated to exceed primary indium production (European Commission, 2017).

EU TRADE

Table 4. Relevant Eurostat CN trade codes for Indium

Processing	
CN trade code	**title**
81129181	Unwrought indium; indium powders

Indium reserves are an estimated 15,000 tonnes, more than two thirds of which are in China. Indium is produced mainly as a by-product of zinc, and to a lesser extent as a by-product of copper, tin, and polymetallic deposits from mineral ores containing less than 100 parts per million (ppm) (or less than 0.01%) indium. Recovery of indium from zinc ores is inefficient, and improvements in recovery efficiencies represent the largest medium-term source of new supply.

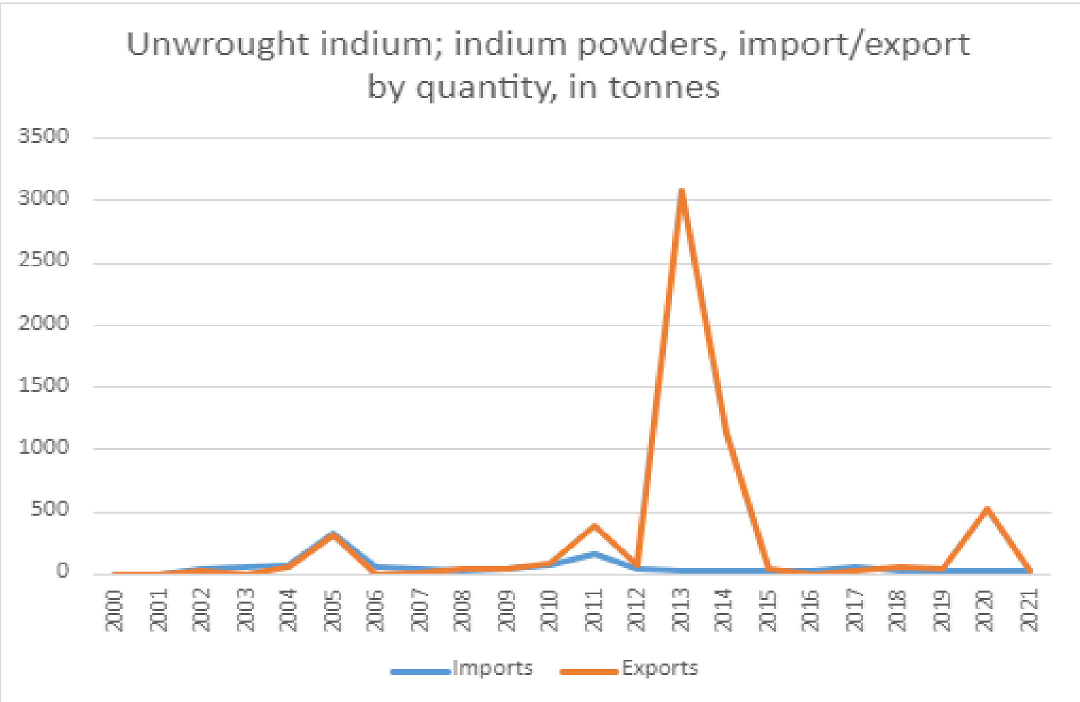

Figure 5. EU trade flows of Unwrought indium; indium powders (CN 81129181) from 2000 to 2021 (Eurostat, 2022)

The EU is a net exporter of Indium as visible from the trade flow trend in the figure above. The EU is essentially indium self-efficient. In 2013, more primary indium was produced in Europe than consumed. The cost to use indium is low, and the lack of any foreseeable shortage means it is readily available for future applications.

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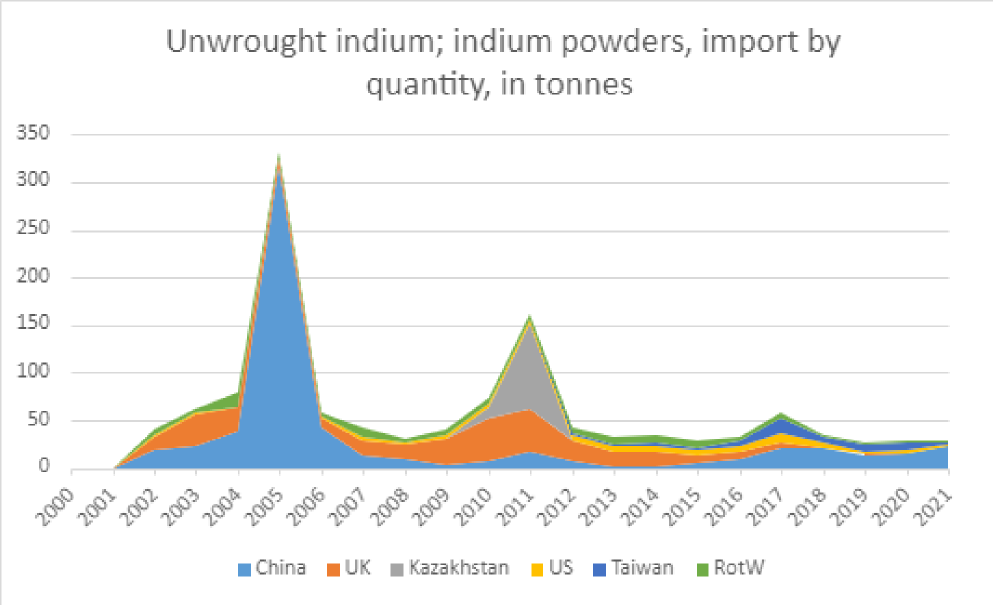

Figure 6. EU imports of Unwrought indium; indium powders (CN 81129181) by country from 2000 to 2021 (Eurostat, 2022)

PRICE AND PRICE VOLATILITY

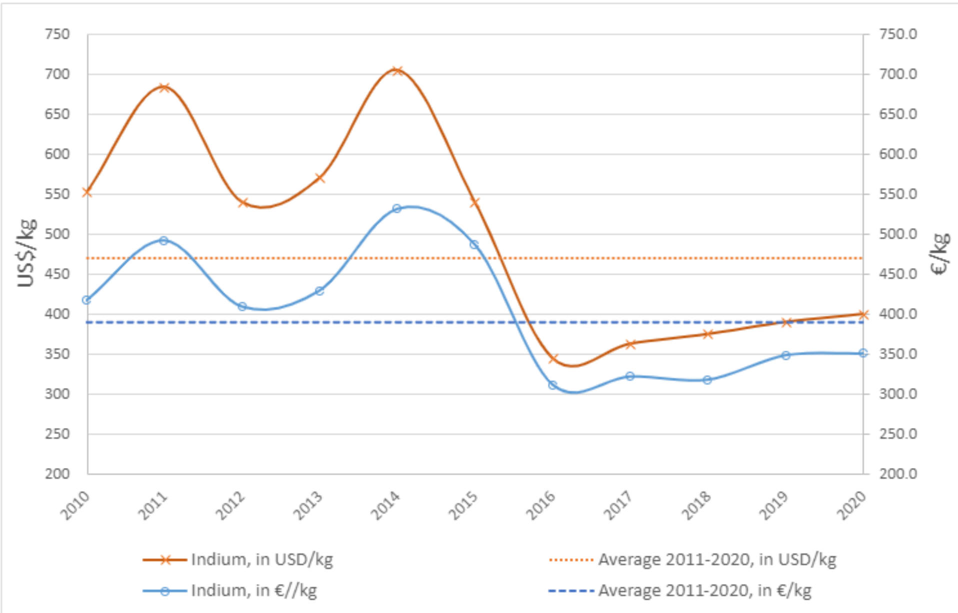

Figure 7. Annual average price of indium between 2011 and 2020, in US$/t and €/t, New York dealer[3]. Dash lines indicate average price for 2011-2020 (USGS, 2021)

[3] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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Prices of indium were supported by stockpiling at the Fanya Metals Exchange (FME) which was established in 2011 in Kunming, China, until its collapse in August 2015 (USGS, 2016). In 2015, Kunming municipal government announced a criminal investigation against FME for illegal fund raising. Since the collapse of FME, indium prices have dropped from USD 700 to USD 200 per kilogram in 2018 (USGS, 2016). Earlier in 2019, prior to the retrial against the FME's owner at the Yunnan superior court, the Kunming court held two auctions of stocks from FME. The Yunnan court's decision indicates that the authorities are likely to hold more auctions of Fanya stocks in the future.
During the COVID-19 pandemic, the EU demand for indium decreased in 2020-2021. However, indium exports from China to EU has increased since the first quarter of 2022, and EU buyers started to build up indium stocks to ensure they had enough supply (USGS, 2022a).

OUTLOOK FOR SUPPLY AND DEMAND

The annual demand growth for primary indium worldwide is stable. Industrial re-processing of ITO scrap is a proven way of returning a significant amount of indium to the global market. The technology to do so is very efficient and the process cycle time very fast.

Indium consumption is expected to be strengthen by the continued ITO demand for LCD screens and the growth of the emerging IGZO (Indium Gallium Zinc Oxide) display market

To maintain the current level of self-efficiency in Indium supply, and to expand on the low cost and proven technological benefits of indium use, EU policy makers should focus on increasing market access by reducing tariff barriers on indium bearing substances, encouraging domestic production and investing in improving economically viable recovery technologies from the growing amount of EOL products.

EU DEMAND

EU DEMAND AND CONSUMPTION

Indium processing stage EU consumption is presented by HS code CN 81129281 Unwrought indium; Indium powders. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022). Due to data anomaly, export and demand data was left out for years 2013-2014.

Over years 2016-2020, EU has mainly imported from China (43%), Taiwan (25%) USA (14%) and UK (9%). Except peaks in 2005, 2011 and 2017, the amount of imported indium is low, between 30 and 40 tonnes per year.

Average import reliance of indium at processing stage is 2.5 % for 2016-2020.

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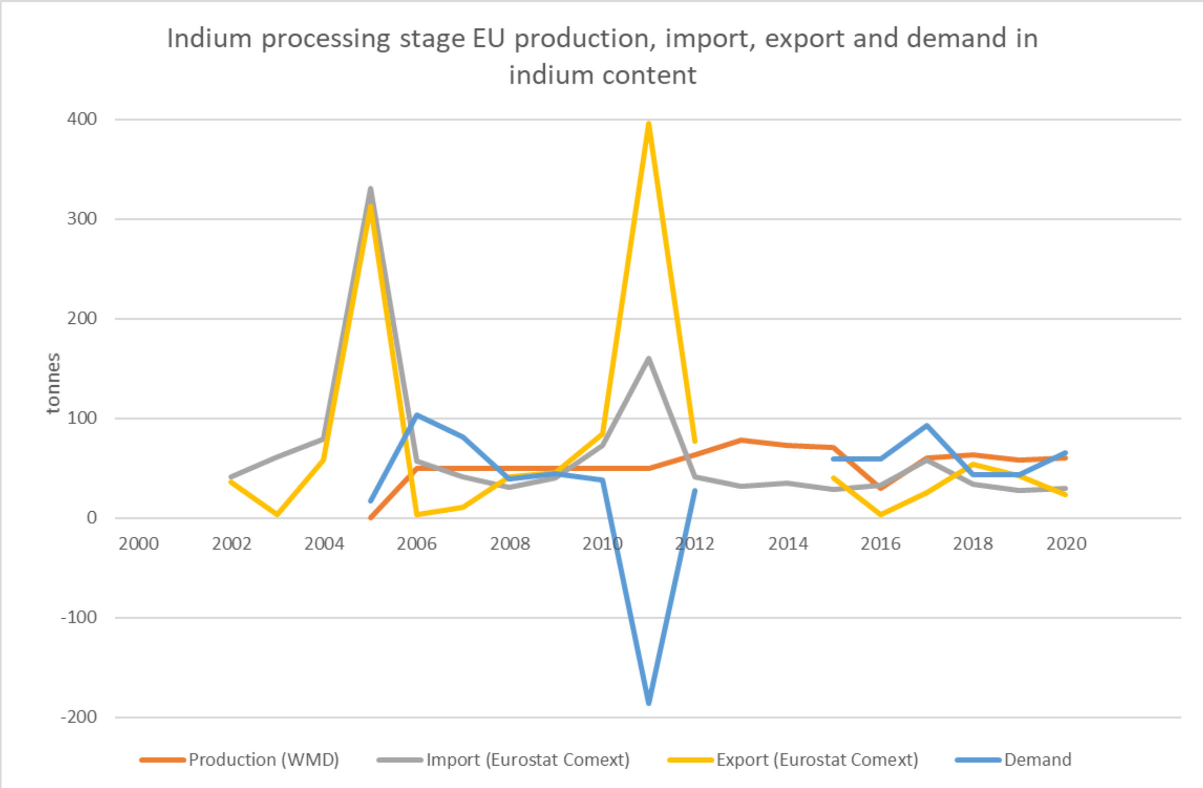

Figure 8. Indium (CN 81129281) processing stage apparent EU consumption. Production data is available from WMD (2022) for 2005-2020. Consumption is calculated in indium content (EU production+import-export).

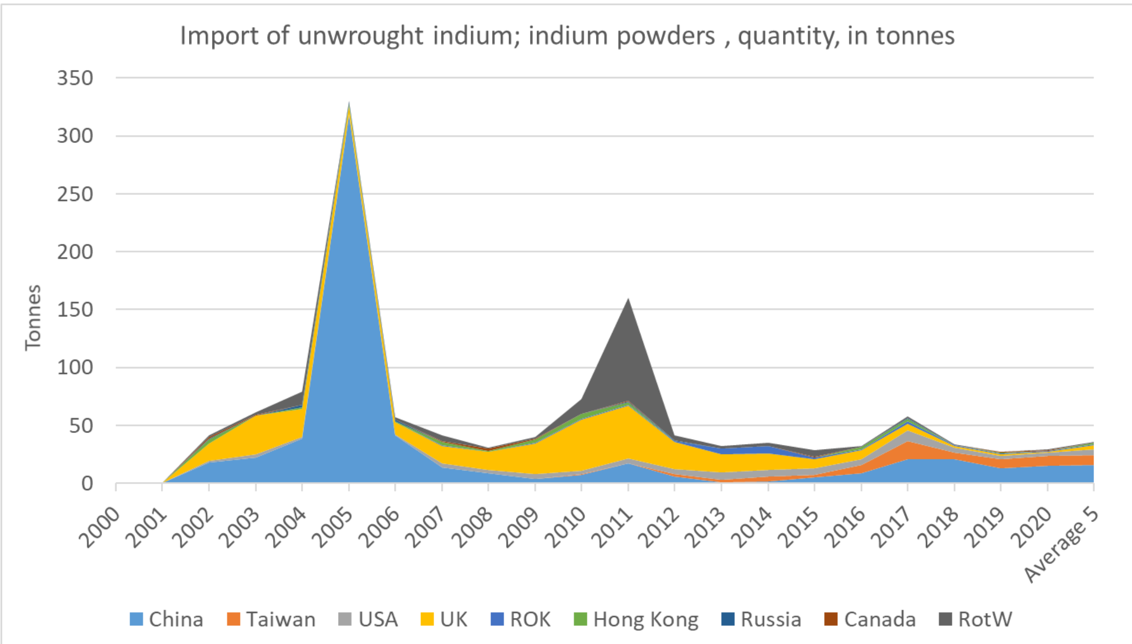

Figure 9. Indium EU imports by country from 2000 to 2021 (Eurostat, 2022)

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GLOBAL AND EU USES AND END-USES

Figure 10 presents the share of main uses of indium in the EU.

Indium manufactured in the EU is mainly used in form of ITO (indium tin oxide) in various display technologies for electronic equipment and, to a lesser extent, in smart windows for architectural and automotive glasses.

Other uses comprise alloy additions for batteries, solders and in semiconductor compounds for solar cells and LEDs.

The relevant industry sectors for the application of indium in the EU are described using the NACE sector codes (Eurostat 2022), presented in Table 5 and Figure 11.

Table 5. Indium applications, 2-digit NACE sectors and examples of associated 4-digit NACE sector, and value-added per sector (Eurostat 2022).

Applications	2-digit NACE sector	Value-added of sector (millions €)	Examples of 4-digit NACE sector
Flat panel displays	C26 - Manufacture of computer, electronic and optical products	84,020.90	C26.2.0 – Manufacture of computers and peripheral equipment
Solders	C26 - Manufacture of computer, electronic and optical products	84,020.90	C26.1.1 – Manufacture of electronic components
PV cells (CIGS, CIS and CdTe)	C26 - Manufacture of computer, electronic and optical products	84,020.90	C26.1.1 – Manufacture of electronic components
Thermal interface material	C26 - Manufacture of computer, electronic and optical products	84,020.90	C26.1.1 – Manufacture of electronic components
Batteries	C27 - Manufacture of electrical equipment	98,417.10	C27.2.0 – Manufacture of batteries and accumulators
Alloys/compounds	C24 - Manufacture of basic metals	71,390.80	C24.4.5 - Other non ferrous metal production
Semiconductors & LEDs	C26 - Manufacture of computer, electronic and optical products	84,020.90	C26.1.1 – Manufacture of electronic components

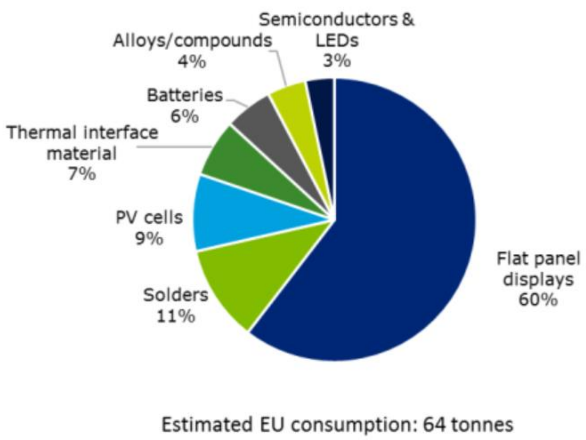

Figure 10: EU end uses of Indium in 2016. (source: EC, 2020). No further updates during the 2022 factsheet update (EC CRM Data 2023).

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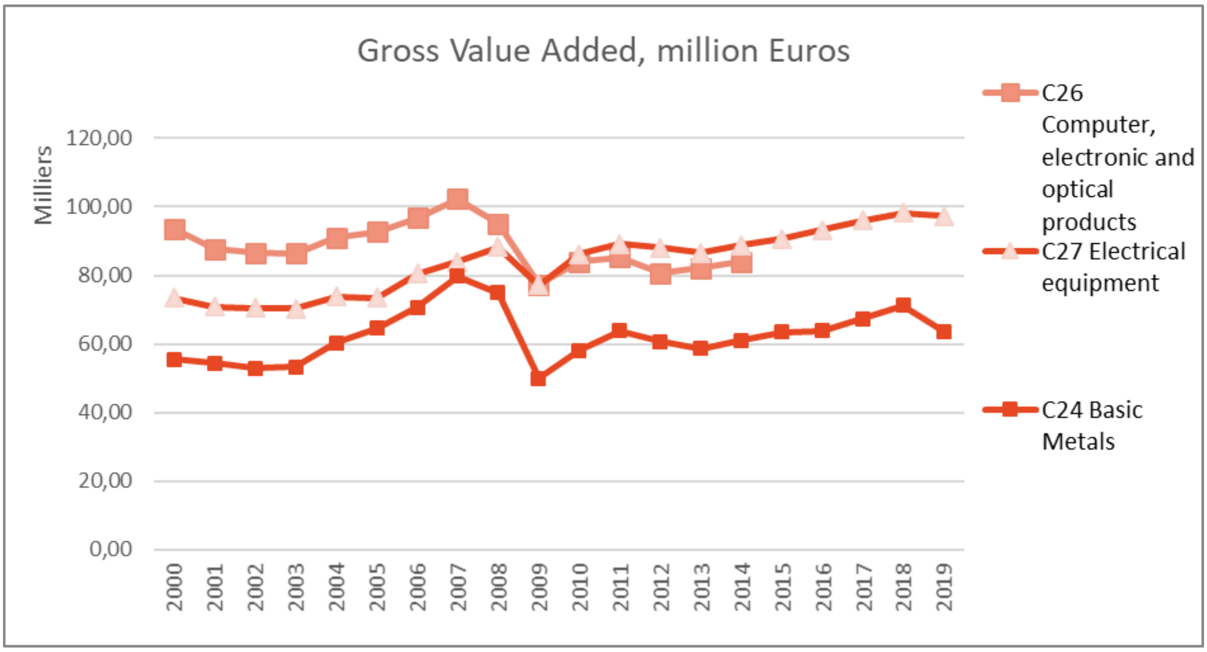

Figure 11: Value added per 2-digit NACE sector over time (Eurostat, 2022)

APPLICATIONS OF INDIUM

FLAT PANEL DISPLAYS:

The primary application of indium is as ITO thin films. ITO is a mixture of indium (III) oxide (In_2O_3) and tin (IV) oxide (SnO_2), typically 90% In_2O_3, 10% SnO_2 by weight. When deposited as thin film on glass or clear plastic, it functions as a transparent electrode.

ITO is used in flat-panel displays (FPDs) - whether liquid crystal displays (LCDs), plasma display panels (PDPs) or OLED displays (organic light emitting diodes) - for televisions, laptops, notebooks and mobile phones.

ITO thin films are applied to car and aircraft windshields for defogging and de-icing and were used to make touch screen cathode ray tubes (CRTs) found, e.g., in some bank ATMs, although these being phased out (Vulcan, 2013). All 275 flat panel displays are made in Japan, South Korea and China. This application accounted for 56% of the global indium use in 2013 (Indium Corporation, 2013).

FPDs represent a source of valuable materials: besides indium, they contain glass and the polarizing films, which recovery could lead to both economic and environmental advantages. Indium-containing panels are currently not properly treated and indium recovery from this residual fraction at industrial scale is still a challenge. Since Indium has been included in a list of critical raw materials by the European Commission and its recovery from secondary sources is gaining increasing attention among the scientific community.

SOLDERS:

Indium is used as a low-temperature solder and a lead-free solder, either as alloys or as pure metal.

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Indium reduces the melting point in solder alloys and can improve the thermal fatigue performance of solders used in the electronics industry, even in a small amount. Its ductility and malleability are retained at cryogenic temperatures so that an assembly can maintain an effective seal, even in harsh environments.

Indium solders are also used for glass-to-glass or glass-to-metal joints.

PV CELLS (CIGS, CIS AND CDTE):

Indium semiconductor compounds (CuIn1-xGaSe2) are used as a light absorber material in CIGS (Copper indium gallium diselenide) and CIS (without gallium) thin film solar cells. ITO (indium tin oxide) is used as a top transparent electrode of CIGS, amorphous silicon and CdTe cadmium telluride PV cells. The transparent conductive oxide (ITO) maximizes light transmission of the incoming light into the solar cell absorber materials (CIGS, amorphous silicon or cadmium telluride layers).

THERMAL INTERFACE MATERIAL:

Due to their excellent thermal conductivity and ductility indium metal, alloys and composites are used as thermal interface materials (TIMs) in electronics devices.

TIMs transfer heat generated by semiconductors to a heat sink to prevent the device from overheating. The extreme malleability of indium allows it to fill in any microscopic gaps between the two surfaces, thereby increasing heat flow.

BATTERIES:

Indium is one of many substitutes for mercury in alkaline batteries to prevent the zinc anode from corroding and releasing hydrogen gas.

Indium functions like mercury by forming zinc alloy to inhibit zinc corrosion.

ALLOYS/ COMPOUNDS:

Indium is a component of low melting-point alloys which can be used for glass-to-glass or glass-to-metal joints and in a variety of other applications: in semiconductor compounds in LEDs (e.g. indium gallium nitride-InGaN), laser diodes (indium phosphide InP), etc.

OTHER:

Indium in indium antimonide (InSb) and indium gallium arsenide (InGaAs) are used for infrared technologies.

Indium phosphide (InP) is used for laser diodes.

SUBSTITUTION

Substitutes have been identified for the applications of indium.

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Table 6: Substitution options for indium by application (SCRREEN Validation Workshop, 2022; EC Data 2023 files). USGS 2022.

Application	%*	Substitute(s)	SubShare	Cost	Performance
Flat Display Screens (Indium Tin Oxide (ITO)	60%	Aluminium-doped zinc oxide (AZO)	5%	Similar or lower	Reduced
		Fluorine-doped tin oxide (FTO)	5%	Similar or lower	Reduced
		Antimony-tin-oxide (ATO)	5%	Similar or lower cost	Reduced
Solders	11%	Tin-bismuth alloys	50%	Similar or lower costs	Similar
		Lead-based alloys	0%	Similar or lower costs	Similar
PV Cells	9%	Cadmium telluride (CdTe)	4%	Similar or lower costs	Similar
		Amorphous silicon thin film	0.1%	Similar or lower costs	Similar
		Multi-Si and Mono-Si	94.9%	Similar or lower costs	Similar
Batteries (alkaline)	5%	Mercury	5%	Slightly higher costs (up to 2 times)	Reduced
Alloys / compounds	4%	Not assessed, under 10%			
Semiconductors & LEDs	3%	No substitute			

FLAT DISPLAY SCREENS

Indium-thin-oxide (ITO) is substitutable in LCDs by antimony-tin-oxide (ATO). However, antimony is also classified as critical raw material (European Commission 2020).

For architectural glasses with low emissivity coating, ITO can be replaced by Fluorine-doped-thin-oxide (FTO).

Smart window applications with double glazing (moisture protected) Aluminium-doped-Zinc-Oxide (AZO) or Zinc Oxide (ZnO) can be used instead of ITO.

In thin film solar cells and flat panel displays, it is possible to use FTO or AZO as Transparent Conductive Oxide (TCO) instead of ITO, however not without a loss in performance with respect to conductivity and/or transparency.

AZO, FTO and ATO might represent together about 15% of the substitutions for ITO at the global level (ass validated at the SCRREEN2 Workshop, 2022).

There is also competition between indium and “transparent carbon” nanotubes in the manufacture of glasses, and perhaps also in mass production of LCDs (Techniques de l’Ingénieur, 2022). Carbon nanotube coatings have been developed as an alternative to ITO coatings in flexible displays, solar cells, and touch screens.

Poly(3,4-ethylene dioxythiophene) (PEDOT) has also been developed as a substitute for ITO in flexible displays and organic light-emitting diodes; and copper or silver nanowires have been explored as a substitute for ITO in touch screens.

PV CELLS

Indium phosphide can be replaced by gallium arsenide in solar panels. However, gallium is also classified as critical raw material (European Commission 2020).

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CdTe or a-Si based thin film solar cells can be used instead of CIGS/CI Sbased semiconductors in thin film solar cells (CIGS represents 1% of the installed capacity worldwide).

SOLDERS

Tin-bismuth alloys can replace tin-indium alloys for low temperature bonding and soldering applications.

Lead-based alloys can be used instead of indium and indium-tin alloys.

Lead based solders are not used in the EU (there are a few exemptions) (SCRREEN2 Validation Workshop)

ALKALINE BATTERIES

Indium is replacing mercury in zinc powders used in alkaline batteries (SCRREEN2 Validation Workshop)

SEMI-CONDUCTORS

Silicon has largely replaced indium and germanium in transistors.

No substitute for indium gallium nitride-InGaN in LEDs.

In diodes, GaAs is possible to replace InP but not used or in some minor applications only. However, gallium is also classified as critical raw material (European Commission 2020).

OTHERS

According to USGS (2022):

- Carbon nanotube coatings have been developed to replace ITO coatings in flexible displays, solar cells, and touch screens;
- Poly(3,4-ethylene dioxythiophene) (PEDOT) has been developed as an ITO substitute in flexible displays and organic light-emitting diodes.
- Graphene has been developed to replace ITO electrodes in solar cells.
- Hafnium can replace indium in nuclear reactor control rod alloys.

SUPPLY

EU SUPPLY CHAIN

At extraction stage, some of the zinc concentrates produced in the EU present significant indium contents. At Neves Corvo in Portugal, indium grades vary within the range 20 to 1,100 ppm per tonne in the massive zinc and lead-zinc ores of the deposit (Pinto et al., 2014). However it is not known if indium was recovered from concentrates produced within the EU during the period 2012-2016. In general, the quantity of indium recoverd from zinc concentrates produced globally are not publicly reported.

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At refining stage, the EU has refining capacity, producing between 30 (2016 minimum produced amount) and 63 tonnes (2018 maxium produced amount) in the period 2016-2020 (average produced amount 54.2 tonnes). EU imported an annual average amount of 36.1 tonnes in the same period. China, Taiwan and United States consists the main importers. The respective average annual exported amount was 29.6 tonnes. An extremely low recycling rate (<1%) is reported (**Eurostat, 2021**).

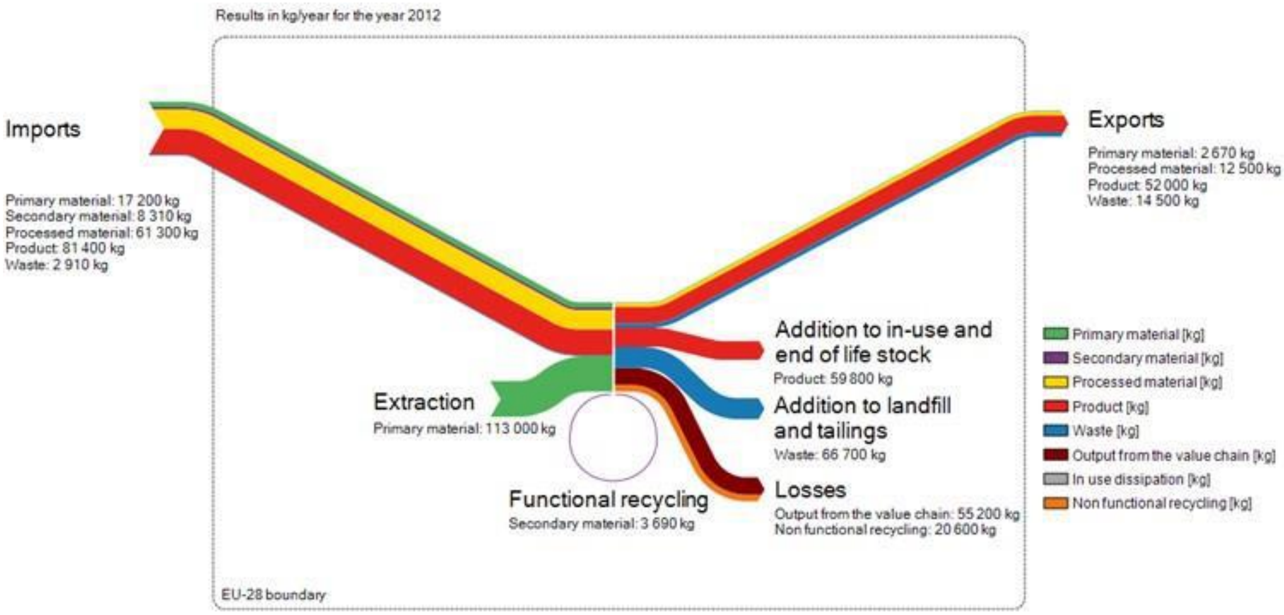

Figure 12: Simplified material system analysis diagram of indium in the EU, reference year 2012 (BioIntelligence, 2015)

SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF INDIUM

GEOLOGICAL OCCURRENCE:

Indium is found as a trace element in some zinc, copper, lead and tin minerals but is mostly recovered from the zinc-sulphide mineral sphalerite. Indium abundance in the Earth continental upper crust is estimated at 0.056 ppm (Rudnick & Gao, 2014).

The most important deposits are volcanic and sediment-hosted base-metal sulphide deposits, which are generally characterised by high metal abundance and large tonnages. The concentration of indium in these ores is in the range 20–200 ppm. Other types of deposits containing significant and recoverable amounts of indium include polymetallic vein-type deposits, vein-stockwork deposits of tin and tungsten and epithermal deposits (Schwarz-Schampera, 2014).

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GLOBAL RESOURCES AND RESERVES:

Being mainly recovered as a by-product of zinc production, indium resources and reserves are generally derived from zinc resources and reserves data using an average indium content of zinc ores.

A study undertaken by the Indium Corporation (Mikolajczak, 2009) estimated that primary indium resources and reserves in identified base metal mines amounted to approximatively 50,000 tonnes of indium, with some 47% in China and the Commonwealth of Independent States (CIS), and 53% in other countries.

Global resources and reserves of indium calculated from global zinc resources and reserves reported by USGS (2012), using an average zinc ore indium content of 50 gram per tonne, have been estimated at 95,000 tonnes and 12,500 tonnes, respectively (Schwarz-Schampera, 2014). When also considering recoverable indium in copper deposits and using an average indium content of 10 gram per tonne, total resources and reserves amounted to 125,000 tonnes and 18,800 tonnes in 2012.The indium content of zinc deposits from which it is recovered ranges from less than 1 part per million to 100 parts per million (USGS, 2019).

NREL estimated as much as 15,000 tonnes of indium reserves are available from zinc ores, with the largest reserves located in China (Table 72). There are no more recent precise data concerning the global amount of reserves (USGS, 2022).

Table 7: World indium resources and reserves calculated from global zinc and copper resources and reserves reported by USGS in 2012 (Data from Schwarz-Schampera, 2014)

Estimated world indium resources and reserves (tonnes of indium)	
Resources in zinc ores	95,000
Reserves in zinc ores	12,500
Resources in copper ores	30,000
Reserves in copper ores	6,300
World total indium resources	125,000
World total indium reserves	18,800

Table 8: World Indium Reserves124 (Lokanc, M. et. al., 2015)

Country	Indium reserves (tonnes of indium)
Canada	180
China	10,400
Peru	480
Russia	80
United States	200
Other	3,700
Total	15,000

EU RESOURCES AND RESERVES:

There is no mineral resource and reserve data for indium reported in the Minerals4EU (2019) project. In Europe, most of the indium mineralisation is located in Variscan units and, to a small extend, in Proterozoic (Sweden), Caledonian and Alpine formations. The largest indium anomalies on the Iberian Peninsula overlap

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with known metallogenic districts which include deposits such as Neves-Corvo copper-zinc mine in Portugal (Ladenberger, 2015). Since indium is not recovered in all zinc and tin refineries, it is not clear how much indium is produced from the Portuguese ores (Lauri, L. et. al., 2018). Resources of indium were also reported to exist in Austrian lead-zinc deposits, copper deposit in Bulgaria, Czechia, Germany, Greece, Hungary, and Ireland (Lauri, L. et. al., 2018).

Indium is not concentrated enough to be a major commodity in deposits, but it is recovered as a by-product mainly from residues generated during zinc ore processing. A small amount (5%) is produced as a by-product of lead, tin, and copper production (EuropeanCommission, 2017). Approximatively 95% of the refined indium produced in the world comes from the processing of zinc ores (Lokanc, M. et. al., 2015).

Figures 2 and 3 present the global production of refined indium according to WMD and USGS data. As it can be seen, China and South Korea consists the major producers, with 528 and 210 tonnes respectively, in 2020 (WMD, since 1984). A notable indium production is taking place also in Canada and France with 63 and 40 tonnes, respectively.

The Neves-Corvo VMS-type Cu-Zn-Sn deposit contains the largest known indium resource in Europe, estimated at 3480 tonnes (Lauri, L. et. al., 2018). The Neves-Corvo mine produces zinc and tin concentrates that, probably, also contain significant amounts of indium. Since indium is not recovered in all zinc and tin refineries, it is not clear how much indium is produced from the Portuguese ores (Lauri, L. et. al., 2018).

WORLD AND EU PRIMARY INDIUM REFINERY PRODUCTION

Indium recovered from mine concentrates requires further refining to reach the desired purity. Most indium producers are not fully integrated; mine producers usually sell indium-bearing concentrates on the open market. Indium from zinc smelting is usually sold as a sponge.

The world refinery production of primary indium was approximatively 845 tonnes per year on average over the period 2016-2020 (WMD, 2022). (Figure 13) China continued to be the major producer with almost half of the global production (50%). The remaining production was predominantly in South Korea (25% share), Japan (8%), Canada (8%), and Russia (4%) (WMD, 2022). Data from USGS are also provided (Figure 14)

The EU production of refined indium amounted to 54 tonnes per year on average on the period 2016-2020 and represented around 6% of the world production. The EU production of indium in this period by country is presented in Figure 15. Most primary indium is produced as a by-product of zinc mining and refining. However, the indium content of zinc ores mined in the EU or the zinc ores imported into the EU are not published (Bio by Deloitte, 2015). According to recent data, indium production is not currently not taking place in Germany, Italy and Netherlands (WMD, since 1984).

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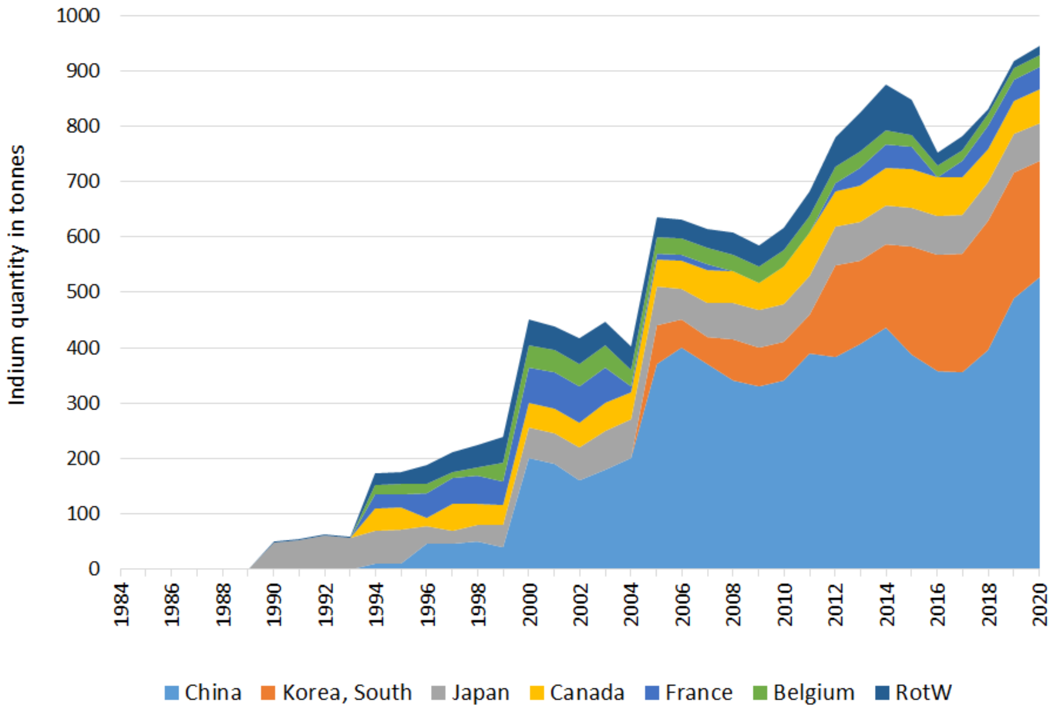

Figure 13: Global indium production since 1984 according to WMD (WMD, since, 1984)

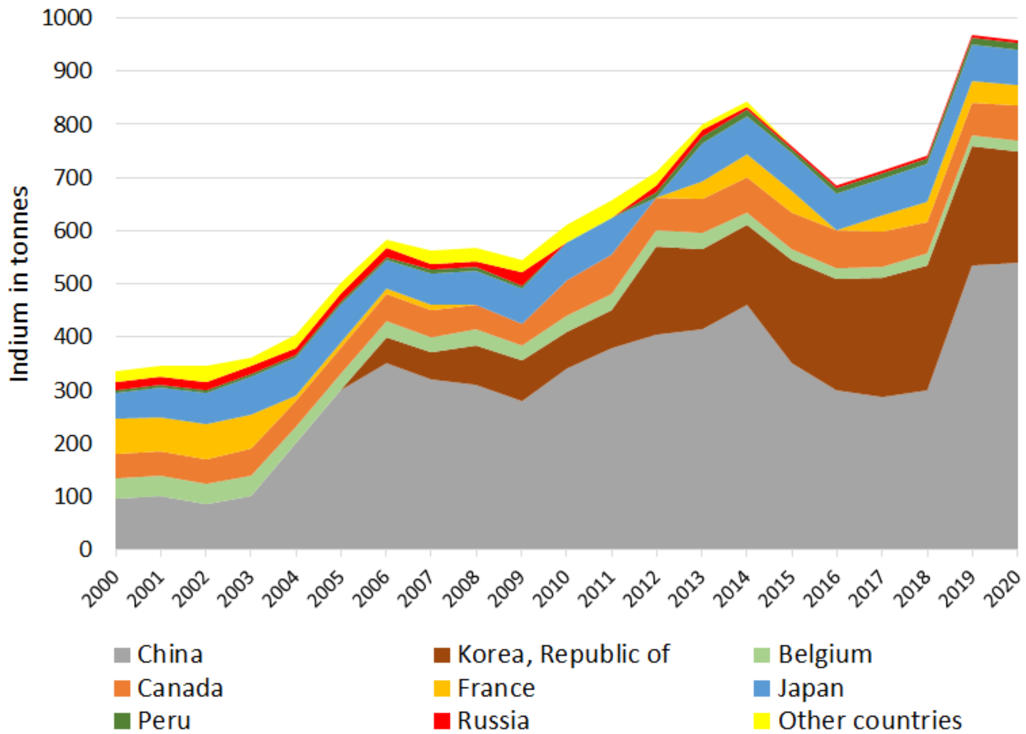

Figure 14: Figure 2: Global indium production since 2000 according to USGS (USGS, since 2000)

Belgium and France refined indium from imported concentrates, residues and slags. In France, Nyrstar commissioned a new virgin indium plant at Auby in 2012 which produced 43 tonnes of metal in 2014

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(European Commission, 2017). Auby's zinc concentrates were sourced from suppliers world-wide (Nyrstar, 2016). No indium was produced in 2016 due to a fire incident at the indium cement plant that occurred in late 2015 (USGS, 2016b). The indium plant has since been re-built with additional capacity, bringing total production capacity to 70 tonnes per year. The production has resumed in 2017. The other major producer was Umicore in Belgium. Umicore produced refined indium at its Hoboken plant from dusts and residues generated by its lead-copper processing plant. Umicore Precious Metals Refining produces a crude $In(OH)_3$ (Indiumhydroxide) for further refining. In 2019, they reported a capacity of 50 tonnes of indium contained products per year (Umicore, 2019). However, the exact quantitative data on the production of Belgium (Umicore) is not published.

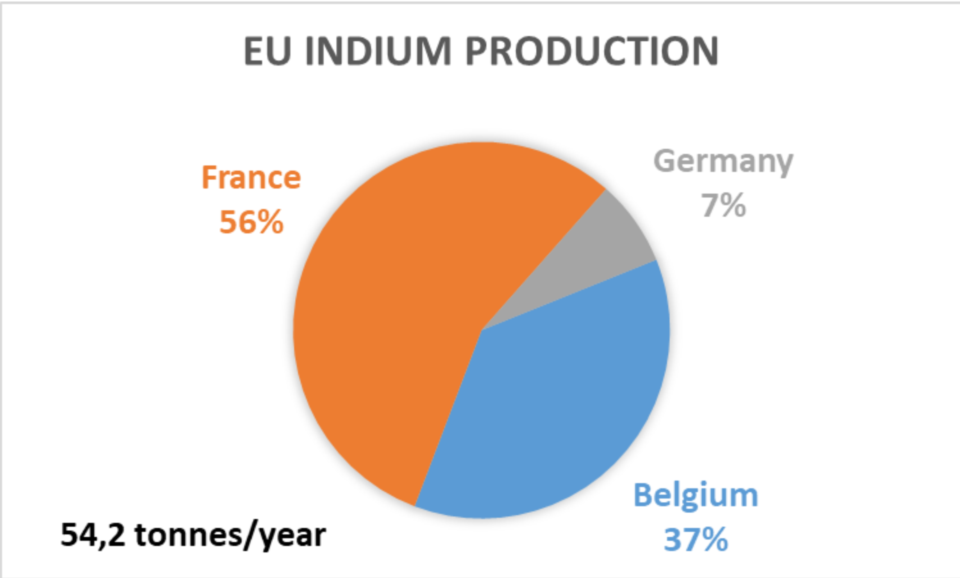

Figure 15: EU production of indium percentage. Average for the years 2016-2020. (WMD, 2022)

Germany's small production which consisted into upgrading 4N indium (99.99 In) to very high purity indium (up to 7N) (PPM Pure Metals) was not included in the EU primary production. In Germany, Saxony Minerals and Exploration AG is working at the Pöhla deposit in Saxony, Germany with the aim of starting tungsten, tin, indium and fluorite production. According to the company, pilotscale production has started in late 2017 (Lauri, L. et. al., 2018).

OUTLOOK FOR SUPPLY

China consists the largest indium resource reserves and primary indium production however, a large part of the ore required for the production of refined indium depends on the supply of end-of-life materials by foreign countries. As many countries around the world consider indium as a critical metal, risk assessment is significant. It is known that when the upstream industry is greatly affected by foreign countries, the entire industry chain will be affected to varying degrees. Furthermore, it has been reported that indium production is problematic in terms of vast quantities that are being lost through the production process. This issue should be further studied in relation to the sustainability of indium production in China (Lin et al. 2021).

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SUPPLY FROM SECONDARY MATERIALS/RECYCLING

RECCLING RATE AND SECONDARY RESOURCES

World secondary refined indium production resulted almost exclusively from the recycling of manufacturing waste (new scrap = semi-finished product or pre-consumer scrap) rather than recovery from end-of-life (EoL). National Renewable Energy Laboratory (NREL) estimated the production of refined indium from secondary supply reached 610 tons in 2013 (vs 770 tons from primary supply) (Lokanc M., 2015). Secondary sources are supposed to supplement global indium supply by about 1,000 tons every year but precise data on the amount of secondary indium recovered from scrap are not available, though are estimated to be similar to the quantity of primary production (Ciacci L., 2018).

New scrap used in the secondary production of indium consists mainly of spent Indium Tin Oxide (ITO) sputtering targets, which are used as ITO source material to produce thin film coatings on flat panel liquid-crystal displays (LCD), light-emitting diodes (LED) or plasma screens, which stands for approximately 84% of total global indium consumption. Only 30% of the ITO target material is actually deposited onto the substrate when using planar sputtering targets, which are the dominant form of targets. The thin film production efficiency has been greatly improved by the use of rotary sputtering targets. What is left of the target is recycled into indium metal. It is estimated that over 70% of the indium from the starting targets is recovered (Mikolajczak C., 2009). Japan, China, and the Republic of Korea represent together about 90% of the global ITO production capacity, and the same countries are dominant in the recovery of indium from spent ITO as well, so that the indium undergoes, in most cases, a close-loop recycling (i.e. indium is utilized and recycled in the same product type). Some producers in Belgium, Canada, and Germany also owned indium recycling capacity to a lesser extent (Lokanc M., 2015).

Indium recycling at EoL is nonexistent because of minor indium concentrations in consumer products, a lack of appropriate technology, or low economic incentives compared to recycling costs (Ylä-Mella J., 2016). Very little old scrap (1%) is recycled worldwide (UNEP, 2011). The production of growing quantities of WEEE, especially LCDs and PV installations, can be a future secondary indium source. With the aims of analyzing the dynamics of material flows and of estimating the magnitude of secondary indium sources available for recycling, the anthropogenic indium cycle in Europe has been investigated by material flow analysis. The results showed that the region is a major consumer of finished goods containing indium, and the cumulative addition of indium in urban mines was estimated at about 500 tons of indium (Ciacci L., 2018).

Indium recycling technologies

Indium recovery from secondary sources is gaining increasing attention among the scientific community. It is mostly performed at laboratory scale through hydrometallurgical and pyro-metallurgical techniques and a very few examples of pilot-plant solutions can be found in the available literature.

Several production technologies of secondary indium have been reported (Sundqvist Oeqvist L., 2018).

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Hydrometallurgical techniques are mostly carried out due to the easiness of reaction control, lower cost and smaller pollution rate. Indium can be recovered from an acidic solution (HCl, H2SO4, citric acid, ...) of ITO scrap using hot immersion techniques (80-90°C). They have also been tested for authentic waste LCD panels and EoL CIGS (Cu-In-Ga-Se alloy) (Virolainen S., 2020) (Efstratiadis V., 2022). Before obtaining pure indium products (metal or compounds), some intermediate stage is required to separate selective ions from acidic leach solution. The most common methods are: solvent extraction, homogenous liquid-liquid extraction, and ion-exchange. Indium obtained using these techniques, although it may be in a form of indium-rich concentrate, generally exists in form of indium compounds with some impurities. To receive pure product, like metallic indium or pure compounds, some other processes, like chemical precipitation, cementation or electrowinning, should be conducted (Sundqvist Oeqvist L., 2018).

Pyrometallurgical treatment can also be conducted in indium recovery from secondary resources. However, usually it requires multiple stages of high temperatures, which makes this process more complex, with the emission of toxic gases to the environment, which increase the cost of the final product.

There are also other existing techniques that could be implemented in indium recovery, such as alkali leaching, bioleaching, super- and subcritical fluid extractions or isothermal decomposition.

Figure 5 gives a schematic view of the different indium recycling technologies studied to recover indium from EoL LCD panel displays (Fontana D., 2021).

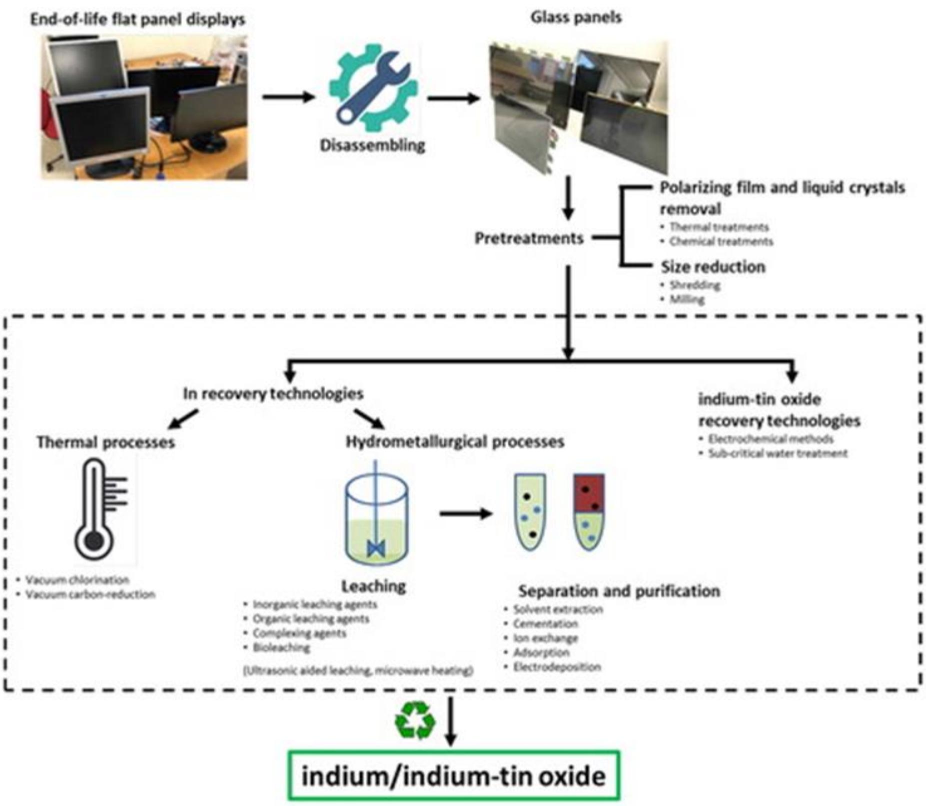

Figure 16: Schematic view of the secondary Indium recovery technologies

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The End-of-life Recycling input rate (EoI-RIR) used in the criticality assessment was set at 0%.

PROCESSING OF INDIUM

Indium is recovered by the residues generated through the metallurgical processing of zinc ores. Zinc processing comprises the: (a) calcination/roasting of primary ores, (b) leaching of the calcine to produce a zinc sulfate solution, (c) purification of zinc solution via the precipitation of various impurities (i.e. cadmium) and (d) electrowinning. Indium among other metals such as copper can be recovered at the purification step. The precipitate sludge produced at the purification step contains various metals such as Ge, In, Ga, Pb, Sn and remaining Zn. As it can be seen in Figure 6, In is obtained via successive leaching and cementation stages. In the final solution, indium is cemented (In ions converted to metallic In) with aluminum. The metallic product under briquettes disposes a high purity >99.998% and smelted into ingots.

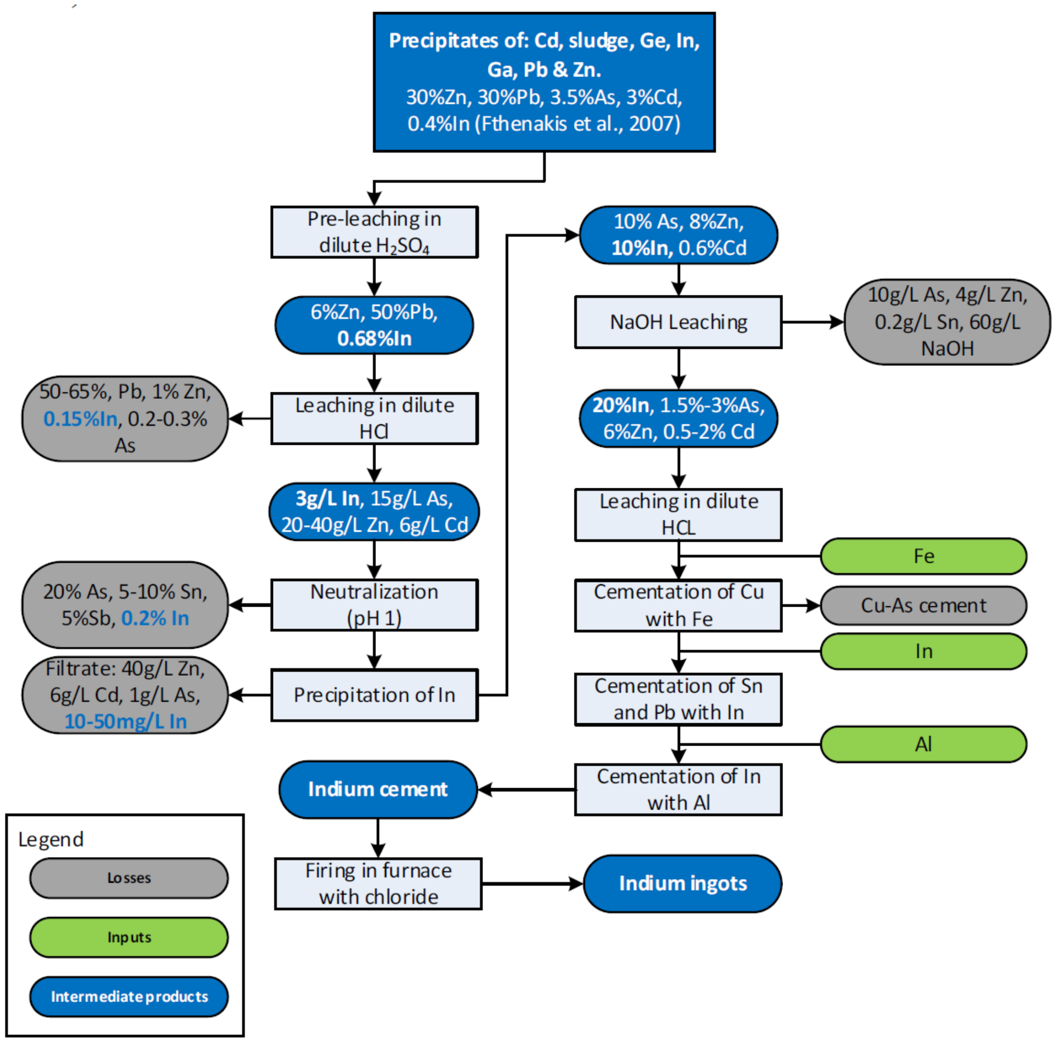

Figure 17: Recovery of indium from residues generated through the processing of zinc residues (Fthenakis et al. 2009; Lokanc et al. 2015).

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OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES RELATED TO THE RM OR SPECIFIC/RELEVANT COMPOUDS AT ANY STAGE OF THE LIFE CYCLE

In Germany, the OEL (Occupational Exposure Limit) for indium exposure in dust is limited to 0.0001 mg/m3 regarding the respirable fraction (GESTIS 2022, Pitzke 2021). A similar threshold limit value is recommended by the American Conference of Governmental Industrial Hygienists (ACGIH TLV) while a less strict limit of 0.01 mg/m3 is accepted in Korea and Japan (Gwangyong 2021, Kim 2021).

Exposure of industrial workers to insoluble indium compounds, such as indium arsenide, indium phosphide, and ITO, may lead to interstitial lung damage and other respiratory problems (USGS 2017, Mitsuhashi 2020).

ENVIRONMENTAL ISSUES

Few studies have focused on the ecological impacts of indium mobility in the environment. Some effects of indium nitrate exposure have been found in aquatic organisms when indium concentrations were orders of magnitude greater than those in reported natural systems (USGS 2017).

So far, the lack of studies and poor details on the environmental performance of available processes for indium recovery from obsolete flat panel displays, semiconductors, and similar products leaves uncertain if EoL recycling of indium would result in net environmental benefits. (Ciacci 2019). However, this challenge can be addressed by novel recycling techniques aimed at reducing the energy demand or the use of chemicals (Ciro 2022, Ciocărlie 2022, Virolainen 2020).

NORMATIVE REQUIREMENTS RELATED TO MINING/INDIUM PRODUCTION, USE AND PROCESSING OF THE MATERIAL

No specific normative requirements were found on Indium. Indium is isolated as a by product of zinc mining.

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF THE INDIUM FOR EXPORTING COUNTRIES

According to COMTRADE (2022), the shares of exports of INDIUM in the total value of exports remain below 0.1 % in each of the exporting countries so that the economic importance of these exports is limited.

SOCIAL AND ETHICAL ASPECTS

No recent data available

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RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- A promising application of indium selenide (In_2Se_3) in a photodetection and non-volatile memory application

In_2Se_3 (indium-selenium) can be considered a promising two-dimensional (2D) ferroelectric material owing to its intercoupled in-plane (IP) and out-of-plane (OOP) ferroelectricity in monolayer form. This makes the material a potential candidate for emerging artificial intelligence, information processing and memory applications. In addition, the high optical absorption and phase-dependent visible to infrared bandgap become advantageous from optoelectronics point-of-view [Mukherjee, 2022].

- Li-In alloy employment in Li-ion batteries

To overcome the problem related to a Li-ion batteries [L.-P. Hou, 2021; P. Hundekar, 2019], a Li-In alloy anode was designed and prepared by mechanical rolling of both Li and In pure metal foils together creating a three-dimensional Li-In alloy network structures. This 3D structure not only possesses strong lithium affinity but also possesses more interface between the Li matrix and the second phase formed in mechanical alloying, which can promote rapid diffusion at the interface and uniform deposition of lithium ions. As a result, the Li-In electrode shows an extremely low overpotential of approximately 35 mV at a high current density of 5 mA cm^{-2} during the lithium plating/stripping experiment. In particular, the battery revealed a higher discharge capacity of 295 mAh/g at 0.05 °C and capacity retention of 80 % after 150 cycles when the Li-In alloy was used as the anode electrode in a cell with $Li_{1.2}Ni_{0.2}Mn_{0.6}O_2$ as the cathode. The Li-In alloy can also be used as anode of Li-S (lithium-sulfur) battery, where the capacity decay rate was reduced from 0.22 % to 0.1 % after 200 cycles without any decoration treatment of S cathode except conductive carbon. In addition, the Li-In alloy can effectively protect the lithium anode and provides an idea for the practical application of lithium metal batteries [W. Jing, 2022].

- Photonic Integrated Circuits on InP technology plAtform enaBling low-cost metro netwOrks and next generation PONs - PICaboo (EU, 2021 - 2023)[4]

Cloud, 5G, and IoT applications are pushing modern networks to the edge to satisfy the stringent requirements for high capacity and low latency. Photonic integrated technologies are promising to tackle new challenges and bring new products and services to the market. The EU-funded PICaboo project plans to develop new building blocks on a photonic integrated circuit platform made of indium phosphide. Compact models of the building blocks will be compiled in a process design kit, allowing designers to explore their use in a wide range of applications. PICaboo's PIC demonstrators are expected to transform the optical metro and access networks in terms of speed, power consumption and cost.

[4] https://cordis.europa.eu/project/id/101017114

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- Indium-Phosphide Pilot Line for up-scaled, low-barrier, self-sustained, PIC ecosystem – InPulse (EU, 2019-2022)[5]

The first metal oxide semiconductor integrated circuit (IC) was commercialised more than half a century ago. Since then, ICs have revolutionised the electronics industry. By putting all the components on a single chip, ICs save space, weight and energy while enhancing performance and reducing costs related to production and packaging. Photonic integrated circuits (PICs) are poised for the next revolution, this time with photons rather than electrons, and they are a perfect match for today's (and tomorrow's) fibre optics and ever-increasing optical devices and communications technologies. However, to truly unleash innovation, Europe now needs PIC manufacturers to support its PIC developers.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- SmartPhotonics - Facilitating photonics innovation, through a modular, integration technology platform (2019-2022, EU)[6]

Advanced technologies will make sure the Telecom sector continues to grow. The role of photonic integrated circuits (PICs) and indium phosphide (InP) will be instrumental to drive expansion, but it is made only by a few enterprises. Due to this, the vast sector of data and sensor technology is deprived of the superior functionality these offer. Smart Photonics has developed a sequence of leading functional photonic modules that can be used as 'building blocks' to allow the creation of PICs. The project will facilitate the industrialisation of software to allow customers to design chips with custom functionalities and numerous applications.

- INREP - Towards Indium free TCOs (2015 – 2018, EU)[7]

The goal of INREP is to develop and deploy valid and robust alternatives to indium (In) based transparent conductive electrode materials as electrodes. In-based materials, mainly ITO, are technologically entrenched in the commercial manufacture of components like LEDs (both organic and inorganic), solar cells, touchscreens, so replacing them with In-free transparent conducting oxides (TCOs) will require holistic approach. The INREP philosophy is to meet this challenge by addressing the whole value chain via an application focused research programme aiming at developing tailor made solutions for each targeted application. This programme will produce a complete evaluation of the relevant properties of the proposed TCOs, including the impact of deposition technique, and by doing so, devise optimum processes for their application in selected, high value application areas. The selected application areas are organic and inorganic light emitting diodes (LEDs), solar cells and touchscreens. The physical properties of interest are the transparency, electrical conductivity, work function, texture, and chemical and thermal stability.

[5] https://cordis.europa.eu/project/id/824980
[6] https://cordis.europa.eu/project/id/858999
[7] https://cordis.europa.eu/project/id/641864

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- Microstructure and surface engineering through indium modification on Ni-rich layered cathode materials for enhanced electrochemical performance of lithium-ion batteries (2022)[8]

Ni-rich layered lithium transition metal oxides have been considered as one of the most promising cathodes for next-generation lithium-ion batteries (LIBs) because of their high capacities and affordable costs. However, they still suffer bulk and surface structural instability, leading to rapid performance decay and subsequent cathode failure. In this context, Ni-rich layered cathodes with indium modified crystal and surface structures are developed by a simple one-pot calcination approach. Battery tests manifest that the indium modified LiNi0.8Co0.1Mn0.1O2 electrodes exhibit remarkably enhanced rate capability and cycling stability compared to the pristine one, including under high operating voltage condition. Further studies evidence a simultaneous mitigation of intra/inter-granular mechanical cracks and resistive surface films growth, which directly embodied in a dramatically suppressed ohmic loss after long-term cycling. The research work here presented demonstrates that microstructure and surface engineering, through indium modification, offers a promising design strategy for further improvements of Ni-rich layered cathodes.

- The application of selective leaching and complex anion exchange in a novel aqueous process to produce pure indium from waste liquid crystal display panels (2022)[9]

By studying the leaching kinetics of indium from waste liquid crystal displays (LCD), it was pointed out, that recoveries of > 90 % are possible with 0.5 M HCl at 80 °C or 2 M HCl at 55 °C. The anion-exchange sorption of indium was found practically negligible from sulphate solutions, however, in chloride solutions of 2 mol/dm3 HCl (or NaCl) indium was moderately sorbed (log D = 0.83), and a further increase of the distribution coefficient (log D = 1.1) was found until 6 mol/dm3 Cl- ion concentration. Based on the determined activation energies, at low (< 1 M) HCl concentrations, the process is controlled by the formation of the complex species, while above, diffusion and transport processes are more important.

The main highlights from the research are the following: indium can be effectively leached with 2 M HCl at 55 °C; indium is not sorbed in the anion–exchange resin from sulphate solutions; anion-exchange chromatography can produce high-purity indium solution; 99.9997 % pure indium is prepared.

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