SCRREEN2

This project has received funding from the European

Union's Horizon 2020 research and innovation programme

under grant agreement No 958211.

Start date: 2020-11-01 Duration: 36 Months

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

CADMIUM

AUTHOR(S):

TABLE DES MATIÈRES

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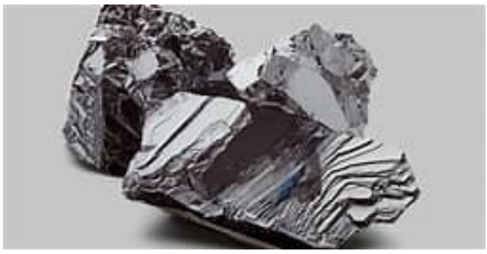
CADMIUM

OVERVIEW

Cadmium is an element with chemical symbol Cd and atomic number 48. It is a silver-white shiny metal with high ductility and malleability. Cadmium occurs in the earth's crust mainly in combination with zinc, which is why the main sources are zinc ores and concentrates. It is a rare element with a share of 0.3 ppm in earth's crust.



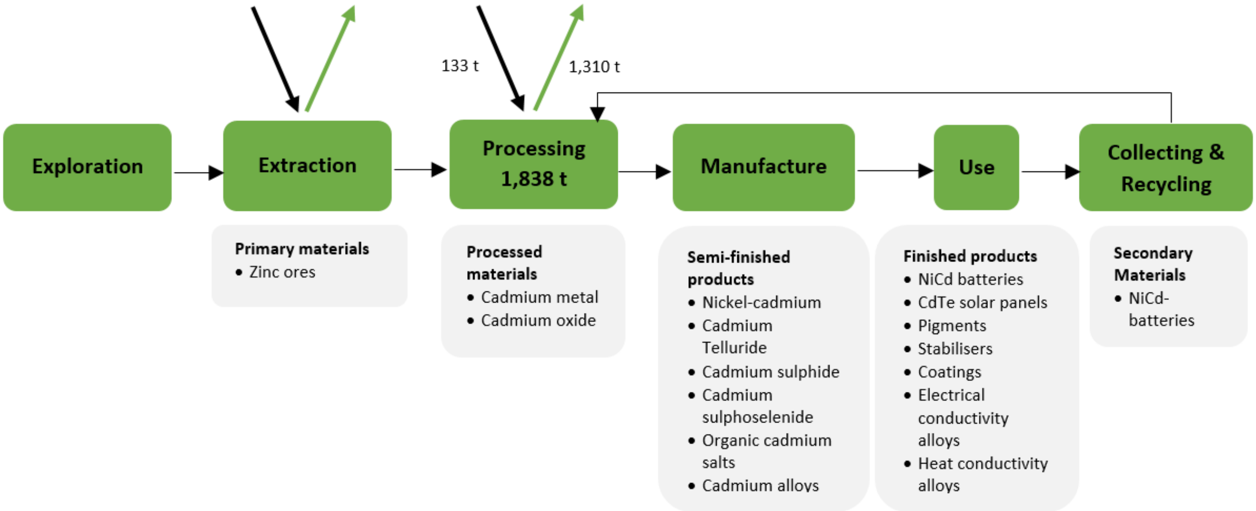


Figure 1. Simplified value chain for cadmium in the EU[1]

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
26,144	China 36% South Korea 17% Canada 7% Japan 7% Kazakhstan 7% Mexico 4% Netherlands 4% Russia 4% Peru 3%	2236	8.5%	Netherlands 40% Germany 27% Bulgaria 14% Poland 10% China 6% Russia 3%	8%

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

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Prices: Price for cadmium has been fluctuating between 3000 USD/t to 2000 USD/t in the last few years. Highest price of cadmium in the past two decades was observed during 2007 when the price reached around 7700 USD/t in 2008. Although the price fell steeply post that to an all-time low in 2016.

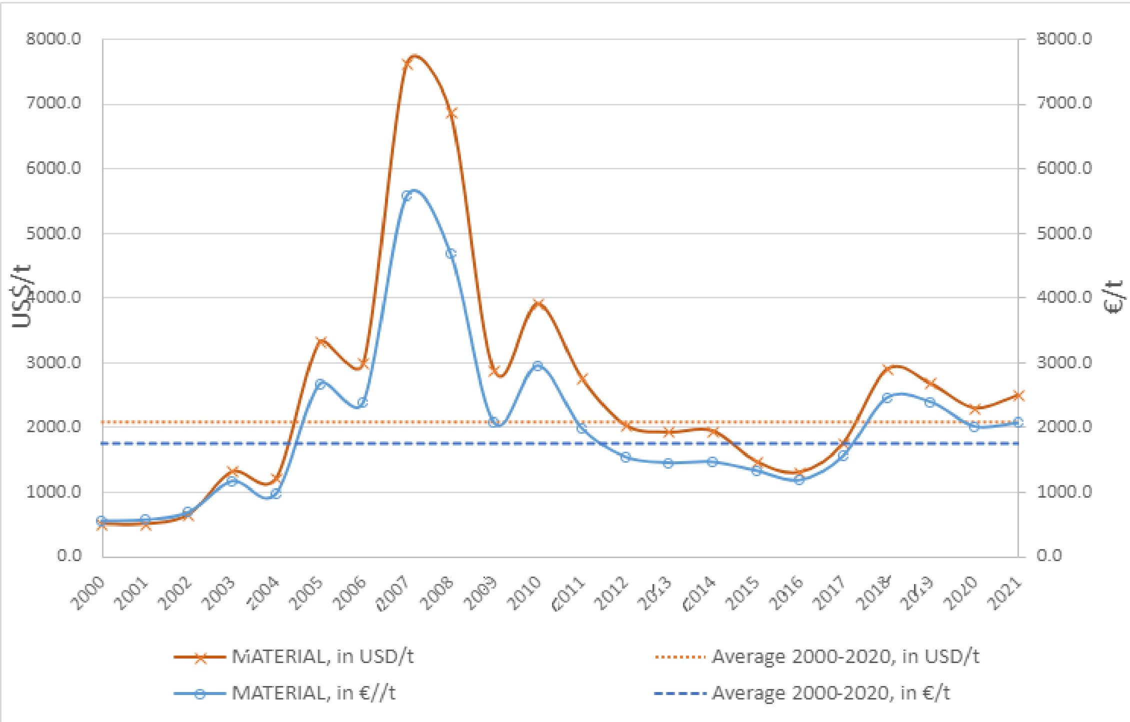

Figure 2. Annual average price of cadmium between 2000 and 2020 (USGS, 2021)[2].

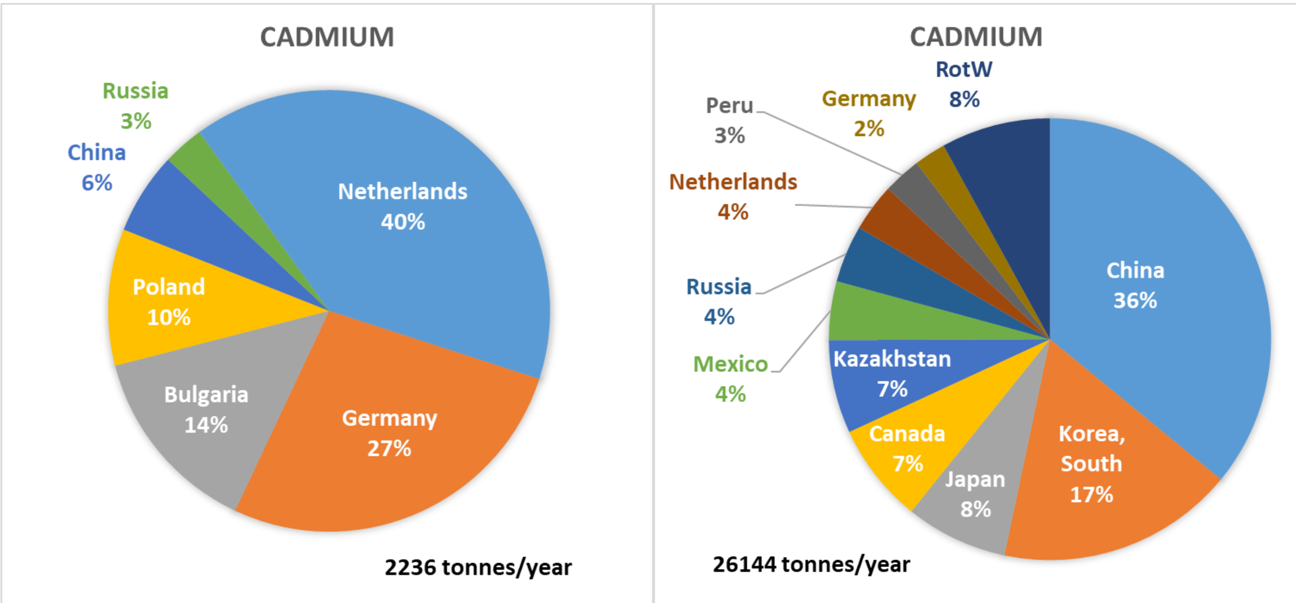

Figure 3. EU sourcing of cadmium and global mine production (update)

[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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Primary supply: The global average annual production of refined cadmium between 2016 and 2020 is around 26000 t according to WMD and USGS that are in accordance. The average annual production of cadmium in EU during the period 2016-2020, was 3957 tonnes. Netherlands, Germany, Bulgaria and Poland are the producer countries of Cd in EU.

Secondary supply: Cadmium has a rather high global recycling rate of about 30% according to UNEP (2011) which remained stable in recent years (SCRREEN Validation Workshop, September, 2022). Secondary materials and end-of-life products include Nickel-Cadmium batteries and CdTe photovoltaic modules. Secondary or recycled cadmium now accounts for about 23% of total cadmium supply (ICdA 2023).

Uses: In the EU, batteries account for most of the cadmium consumption, with the remainder used in alloys, coatings and solar applications (Cadmium Association, 2022).

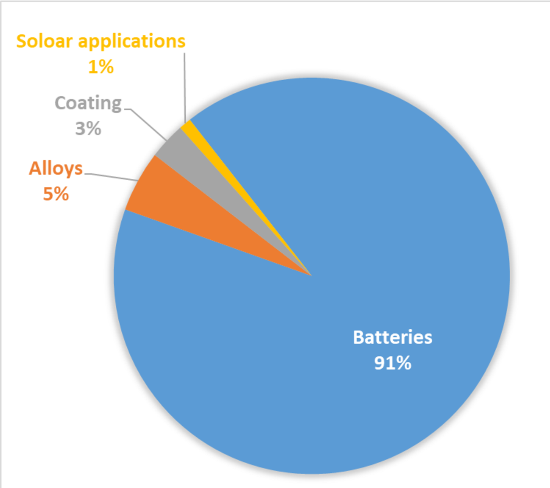

Figure 4: EU uses of cadmium

Table 2. Uses and possible substitutes

Use	Share*	Substitutes	Sub share	Cost	Performance
Batteries	91%	Lithium-ion battery	60%	Very high costs (more than 2 times)	Similar
Batteries	91%	NiMH	10%	Slightly higher costs (up to 2 times)	Similar
Batteries	91%	Fuel cell	1%	Very high costs (more than 2 times)	Similar
Batteries	91%	No substitute	29%	No substitute	
Coatings	3%	Not assessed, below 10%			
Alloys	5%	Not assessed, below 10%			
Solar	1%	Silicon based	92%	Similar or lower costs	Similar
Solar	1%	Germanium	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Gallium phosphide (GaP)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Gallium arsenide (GaAs)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Gallium antimonide (GaSb)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Indium phosphide (InP)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Indium arsenide (InAs)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Indium antimonide (InSb)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	No substitute	1%	No substitute	

* EU uses of cadmium 2020 (Cadmium Association, 2022; SCRREEN Experts 2022).

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Substitution: NiCd batteries can be substituted by lithium-ion and nickel-metal batteries. Cd batteries cannot be substituted in applications, where reliability and stability is of major importance, such as railway batteries for starting, braking, etc. Cadmium in pigments can be replaced by cerium sulphide, which is used mainly in the production of plastics. There are no alternatives for cadmium in artists' paints providing the same colour spectrum. Coatings using cadmium can be substituted by zinc, zinc-nickel, aluminium, or tin coatings, but only where the surface characteristics provided by cadmium (corrosion resistance, low friction coefficient, electric conductivity) are not of critical importance (USGS, 2022). For thin-film solar-cells, copper-indium-gallium-selenide and amorphous silicon photovoltaic cells can substitute for CdTe (USGS, 2022).

Other issues: The International Agency for Research on Cancer (IARC, 2012) includes cadmium and cadmium compounds in Group 1 carcinogens since they cause lung cancer. Moreover, the IARC mentions that a positive association has been observed between exposure to cadmium and kidney and prostate cancer. Consequently, cadmium use is severely restricted by the (REACH Regulation, 2006). Cadmium compounds are classified by the (Classification, Labelling and Packaging EU Regulation, 2008) for their acute toxicity to the environment since they are very toxic to aquatic life (H400) and very toxic to aquatic life with long-lasting effects (H410). The use of cadmium to produce batteries is associated with human poisoning, and water bodies and soil pollution. Information about the topic is scarce, but some sources (Niewenhuis, L., 2017; BBC, 2012) reported on nickel-cadmium batteries factories in China and their detrimental effect on humans and the environment.

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3. Cadmium (processing) supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
26,144	China 36% South Korea 17% Canada 7% Japan 7% Kazakhstan 7% Mexico 4% Netherlands 4% Russia 4% Peru 3%	2236	8.5%	Netherlands 40% Germany 27% Bulgaria 14% Poland 10% China 6% Russia 3%	8%

The total value of the cadmium market has been decreasing, while it was at USD 69.2 million in 2011 the average value between 2012 and 2016 decreased to USD 38.9 million with an absolute low in 2016 (USD 30.7 million). Most Cadmium is sold on long term contracts and only small amounts are freely available on the world market (USGS, 2018).

Considering trade and production numbers, China is the leading consumer of cadmium worldwide. In 2017, China imported 34% of available cadmium, followed by India with 28% (OECD, 2019). From a production perspective, the top-five cadmium suppliers in 2021 were China, South Korea, Japan, Mexico, and Canada (MC Group, 2022).

In 2021-2022, cadmium key players included: Korea Zinc, Nyrstar NV, Teck Resources, Young Poong Corp, Zhuzhou Smelter Group, Mitsui Mining and Smelting, Dowa Metals and Mining, Grupo México, Luoping Zinc and Electricity, Grupo Peñoles, Chelyabinsk Zinc Plant, Toho Zinc Co, Western Mining, and Yuguang Gold and Lead (MarketWatch, 2022).

EU TRADE

For this assessment, Cadmium is evaluated at both extraction and processing stage.

Table 4. Relevant Eurostat CN trade codes for Cadmium

Mining		Processing/refining	
CN trade code	**title**	**CN trade code**	**title**
		28259060 28303000 81072000	Cadmium Oxide Cadmium Sulphide Cadmium, Unwrought Cadmium and powders

EU is currently a net importer of cadmium oxide. There has been a trend reversal since 2020 as previously volume of exports was higher than import. Export volume has been falling consistently since 2007 and reached below 500 tonnes in 2021. Import volume, on the other hand, has been steadily growing in volume since 2012 and is on its way to reach 1000 tonnes in the coming years.

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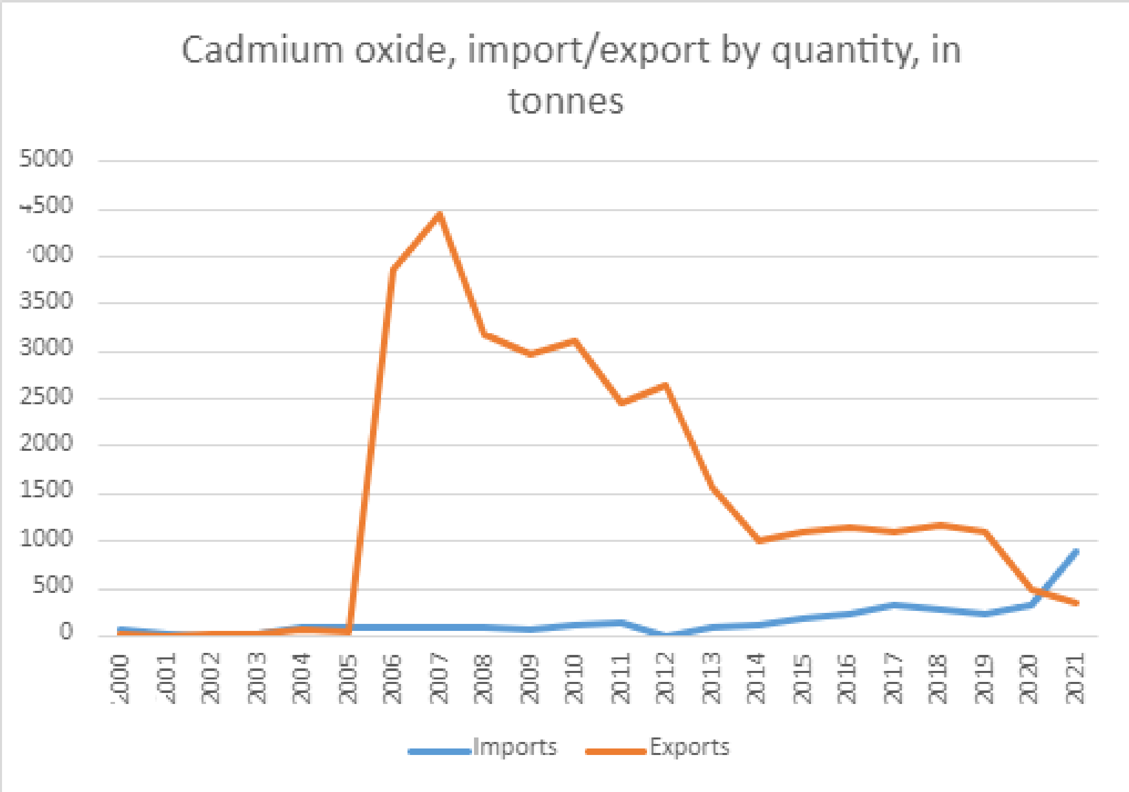

Figure 5. **EU trade flows of cadmium oxide (CN 28259060) from 2000 to 2021 (Eurostat, 2022)**

Growth in volume of import in the last few years has been primarily due to the Chinese supply. The growth rate has been significantly higher in the past 3 years with the import volume nearly tripling from 2020 to 2021.

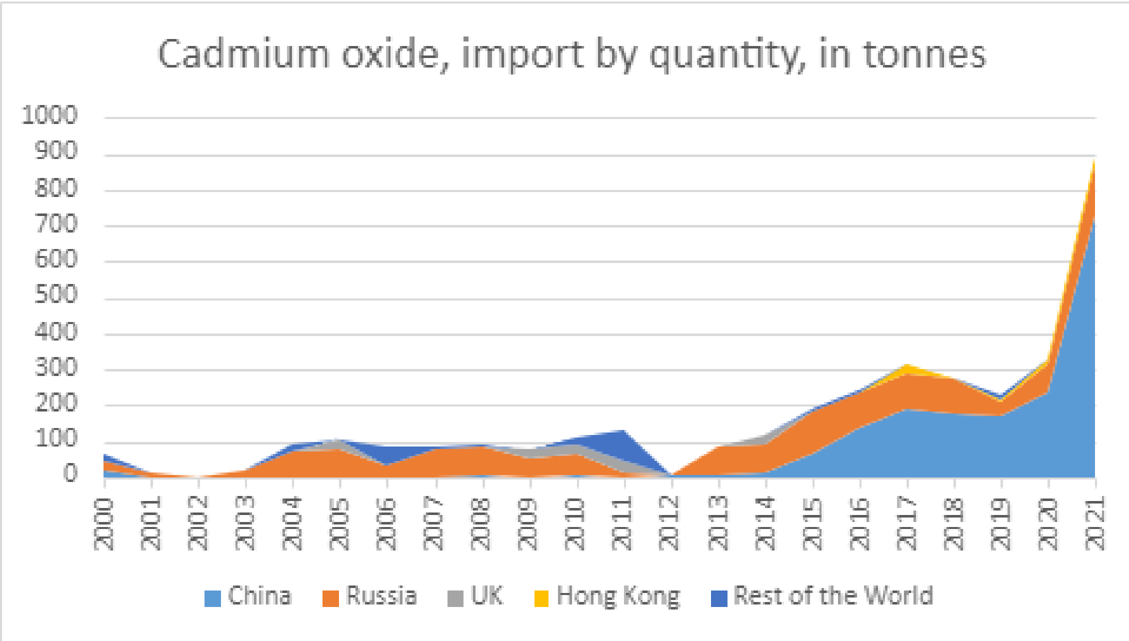

Figure 6. EU imports of cadmium oxide (CN 28259060) by country from 2000 to 2021 (Eurostat, 2022)

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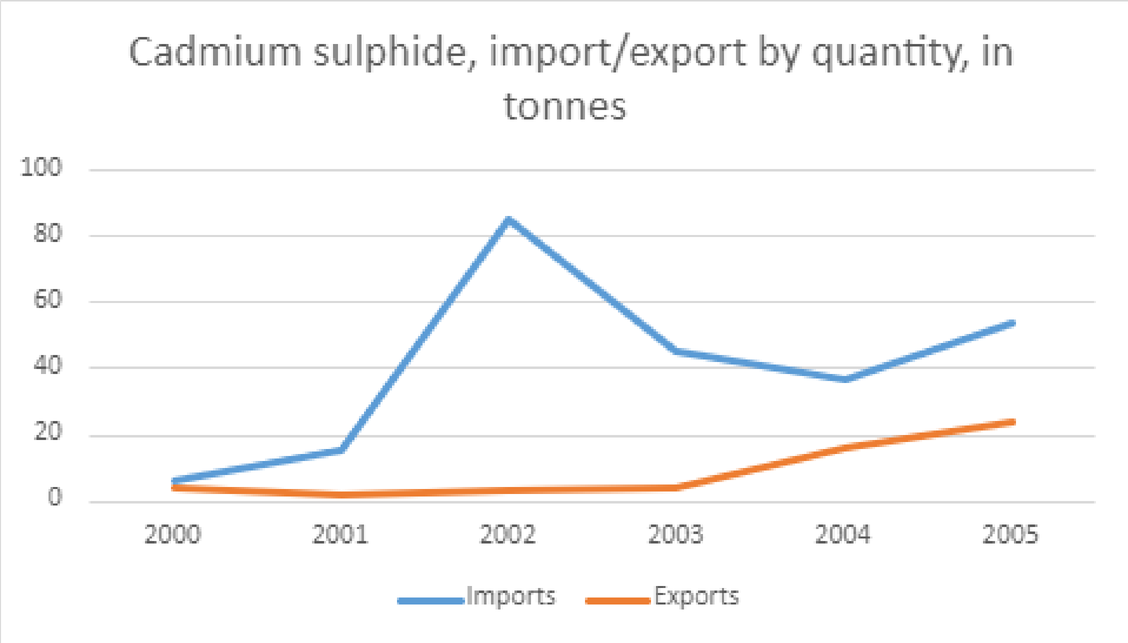

Figure 7. EU trade flows of cadmium sulphide (CN 283030) from 2000 to 2005 (Eurostat, 2022)

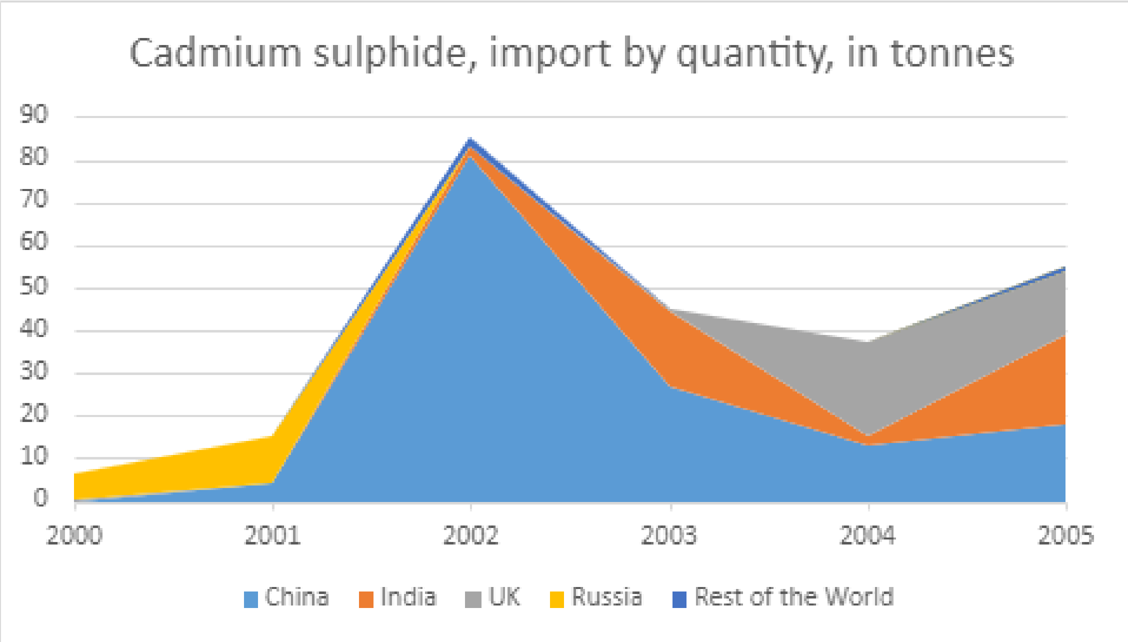

Figure 8. EU imports of cadmium sulphide (CN 283030) by country from 2000 to 2005 (Eurostat, 2022)

For cadmium articles including waste and scrap the volume of import and export has been nearly similar for the past few years. Historically imports have been higher than exports since 2010 but the volumes have been converging for a while now. 2010 – 2012 observed a steep fall in import volume. Currently, exports of cadmium articles are slightly higher than imports.

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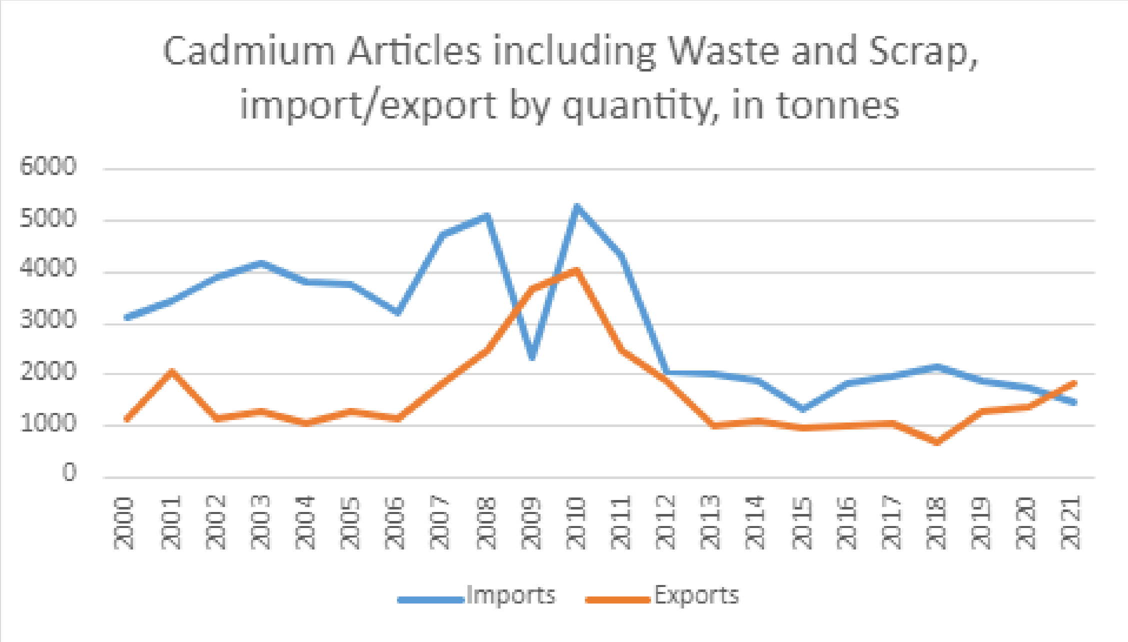

Figure 9. EU trade flows of cadmium articles including Waste and Scrap (CN 8107) from 2000 to 2021 (Eurostat, 2022)

Canada and Norway lead as the key destinations for supply of cadmium articles. Imports from Russia have nearly disappeared while from Mexico has significantly decreased in volume in the past few years.

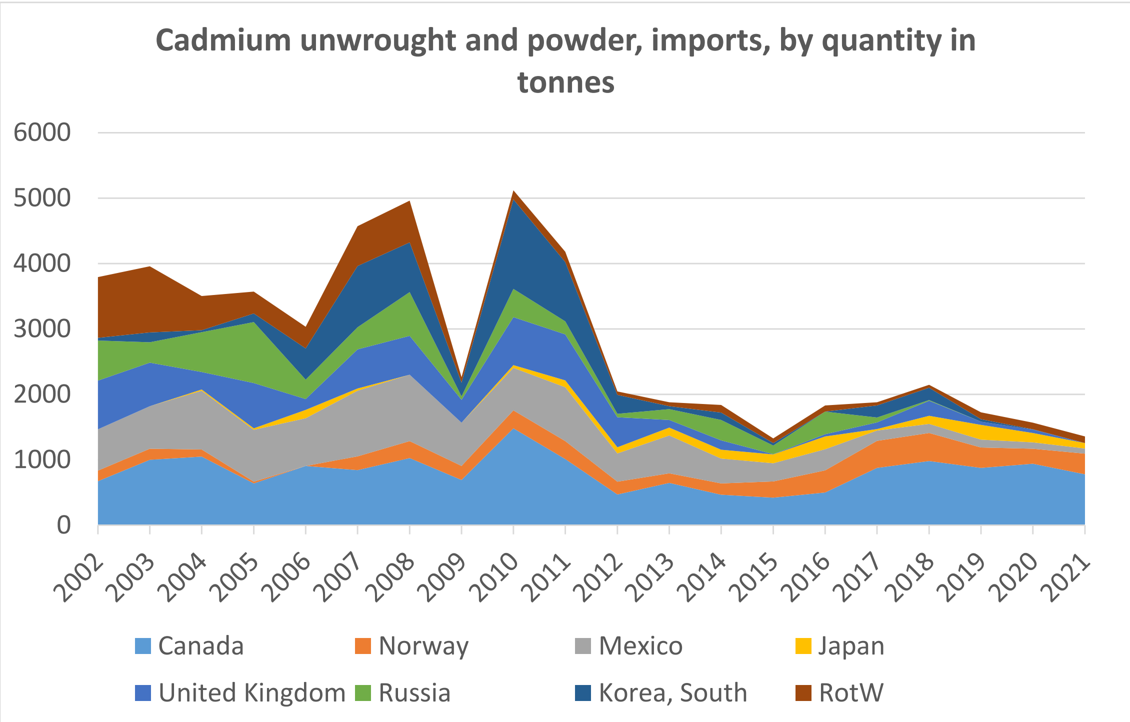

Figure 10. EU trade flows of cadmium articles including Waste and Scrap (CN 8107) from 2000 to 2021 (Eurostat, 2022)

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PRICE AND PRICE VOLATILITY

Price for cadmium has been fluctuating between 3000 USD/t to 2000 USD/t in the last few years. Highest price of cadmium in the past two decades was observed during 2007 when the price reached around 7700 USD/t in 2008. Although the price fell steeply post that to an all-time low in 2016.

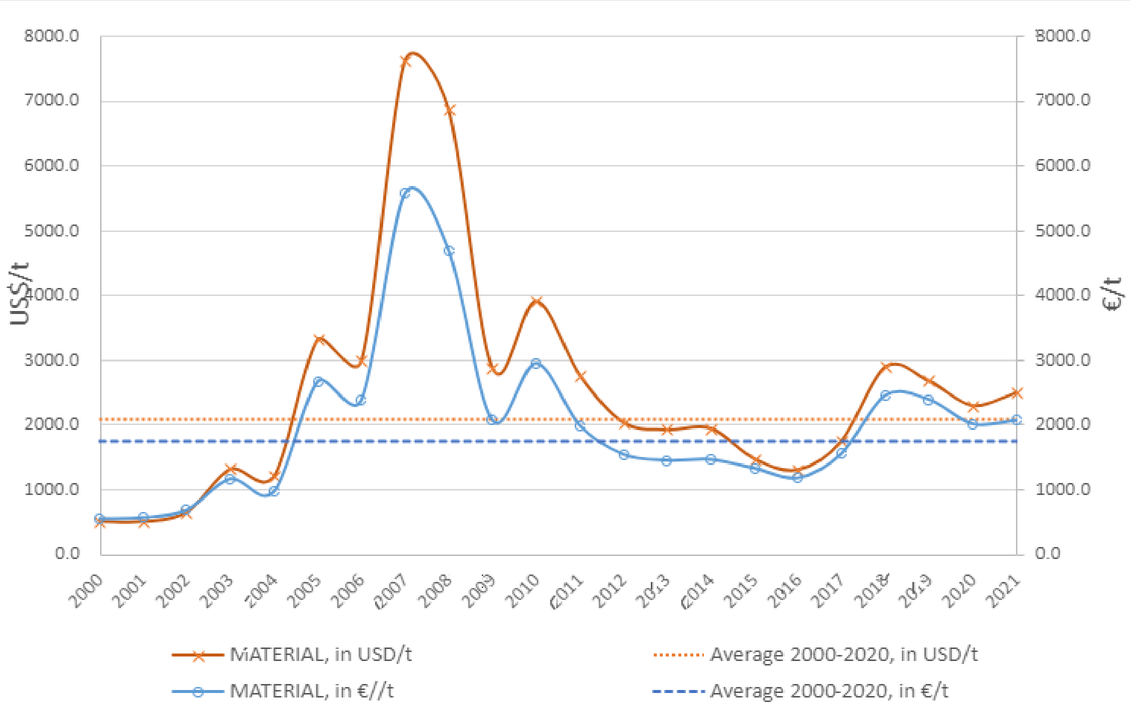

Figure 11. Annual average price of Cadmium between 2000 and 2020, in US$/t and €/t[3]. Dash lines indicate average price for 2000-2020 (USGS, 2022)

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

Annual average worldwide consumption of refined cadmium is about 23,500 tonnes for 2017-2021 (World Bureau of Metal Statistics, 2022). ICdA (2021) estimated worldwide cadmium consumption as 25,600 tonnes and EU-28 consumption as 2,500 tonnes for 2019. Cadmium consumption was calculated for processing stage only.

Cadmium processing stage EU consumption is presented by HS code CN 28259060 Cadmium oxide. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022).

[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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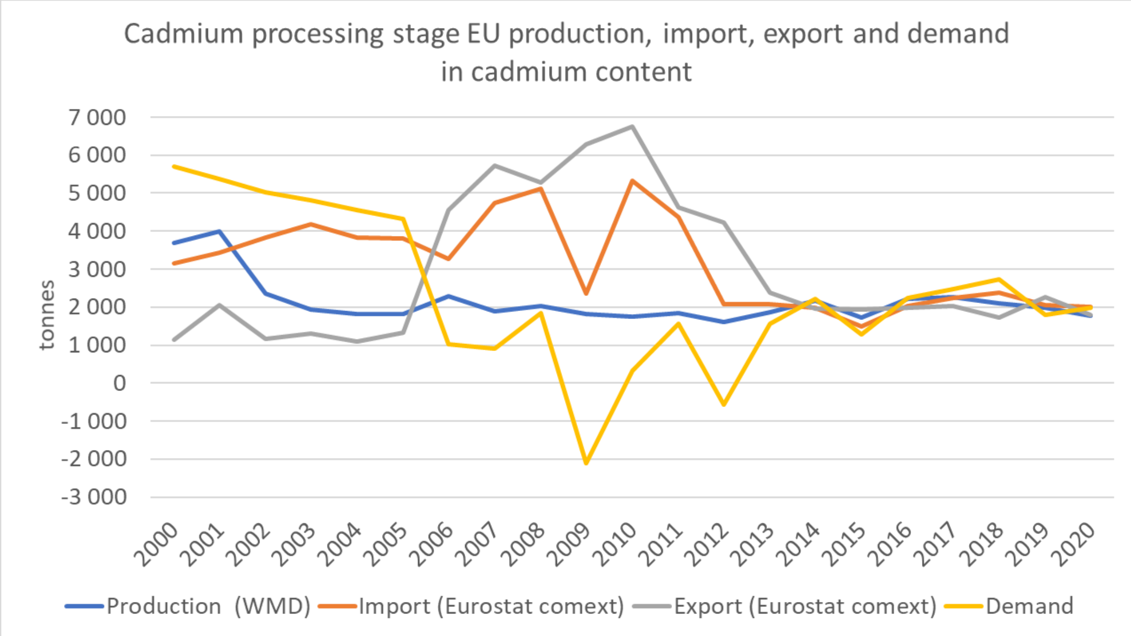

Figure 12. Cadmium (CN 28259060) processing stage apparent EU consumption. Consumption is calculated in cadmium content (EU production+import-export).

Average import reliance of cadmium at processing stage is 0 % for 2016-2020.

EU USES AND END-USES

APPLICATIONS OF CADMIUM IN THE EU:

In the EU, batteries account for most of the cadmium consumption, with the remainder used in alloys, coatings and solar applications (Cadmium Association, 2022).

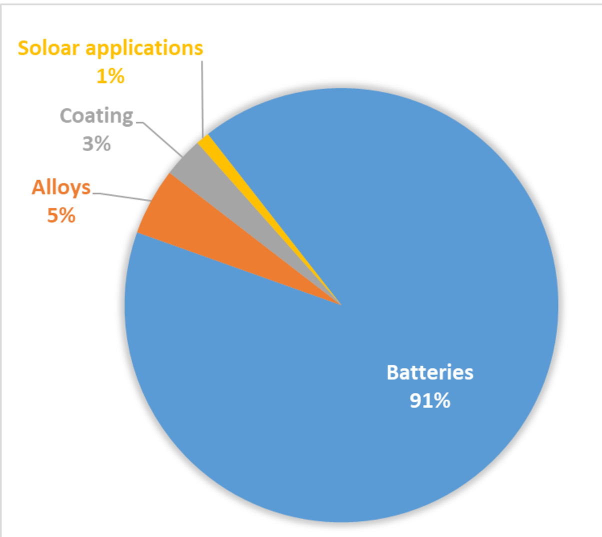

Figure 13. EU uses of cadmium 2020 (Cadmium Association, 2022; SCRREEN Experts 2022).

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Relevant industry sectors are described using the NACE sector codes (Eurostat 2022). The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (Table 1).

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

Applications	2-digit NACE sector	Value-added of sector (millions €)	Examples of 4-digit NACE sector
Batteries	C27 – Manufacture of electrical equipment	98,417.10	C2720 - Manufacture of batteries and accumulators
Pigments	C20 – Manufacture of chemicals and chemical products	117,093.2	C2030 – Manufacture of paints, varnishes and similar coatings, printing ink and mastics
Coatings	C25 – Manufacture of fabricated metal products, except machinery and equipment	183,015.50	C2561 – Treatment and coating of metals
Stabilisers	C20 – Manufacture of chemicals and chemical products	117,093.2	C2059 – Manufacture of other chemical products n.e.c.

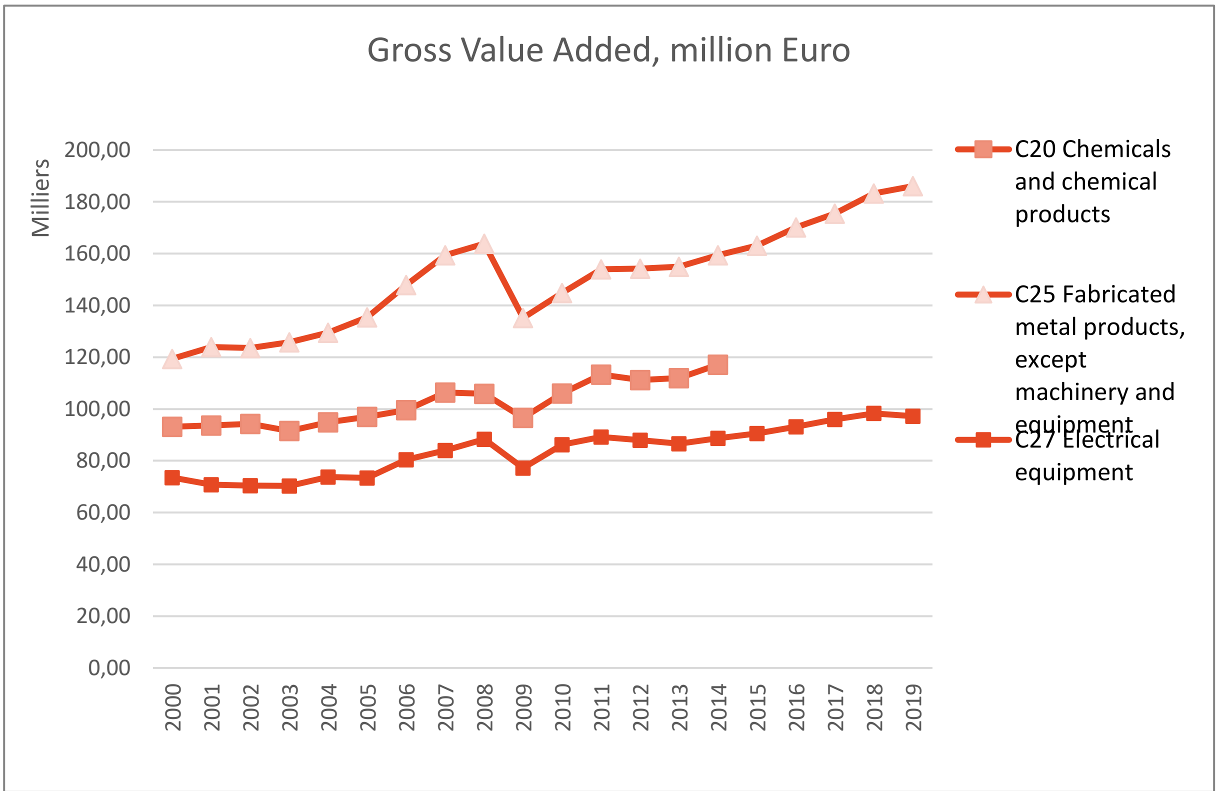

Figure 14. Value added per 2-digit NACE sector over time (Eurostat, 2022)

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BATTERIES

Industrial nickel-cadmium (NiCd) batteries are used by equipment manufacturers and operators to supply critical back-up power functionalities to ensure the safety of passengers in case of main power failure in underground metros systems, high-speed trains and commercial aircrafts (due to their reliability, sturdiness and operational temperature range).

They are also used to supply back-up power to mission-critical industrial assets, including nuclear power plants, steel mills, offshore platforms, refineries, emergency lighting and alarm systems in hospitals, and navigation assets such as lighthouses and buoys. (Eurometaux, 2019).

The use of NiCd batteries in the EU is restricted to industrial use, placing on the market of NiCd batteries in consumer goods is prohibited since 2017.

COATINGS

The high performance of cadmium coatings meets the needs of applications requiring high safety standards, such as aeronautical, aerospace, shipping, military (SCRREEN experts, 2022) mining, offshore and nuclear sectors where these coatings are applied to bolts, fasteners, connectors, landing gear and electrical connectors.

With high temperature resistance, cadmium pigments are used in applications such as thermoplastic, thermosetting powder coatings, enamels and glazes.

Their light and weather fastness makes them a preferred choice for artist paints and road markings.

The EU has restricted the use of cadmium pigments in most plastics to safety applications (Eurometaux, 2019).

Cadmium is used in the form of a stearate or laurate for stabilising PVC and are used in semi-rigid and flexible foil for products such as roofing membranes and in rigid applications for outdoor use such as window profiles.

ALLOYS

Cadmium is used in trolley wire (copper-cadmium) and other alloys (SCRREEN experts, 2022).

SOLAR APPLICATION

Cadmium is used in cadmium telluride (CdTe) thin film in solar applications (SCRREEN experts, 2022).

Owing to their unique combination of benefits, yellow, orange and red cadmium pigments are used in a range of demanding, high-performance applications and market segments where no colourants exist that can match their properties and value.

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SUBSTITUTION

Table 6. Uses and possible substitutes

Use	Share*	Substitutes	Sub share	Cost	Performance
Batteries	91%	Lithium-ion battery	60%	Very high costs (more than 2 times)	Similar
Batteries	91%	NiMH	10%	Slightly higher costs (up to 2 times)	Similar
Batteries	91%	Fuel cell	1%	Very high costs (more than 2 times)	Similar
Batteries	91%	No substitute	29%	No substitute	
Coatings	3%	Not assessed, below 10%			
Alloys	5%	Not assessed, below 10%			
Solar	1%	Silicon based	92%	Similar or lower costs	Similar
Solar	1%	Germanium	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Gallium phosphide (GaP)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Gallium arsenide (GaAs)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Gallium antimonide (GaSb)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Indium phosphide (InP)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Indium arsenide (InAs)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	Indium antimonide (InSb)	1%	Slightly higher costs (up to 2 times)	Similar
Solar	1%	No substitute	1%	No substitute	

* EU uses of cadmium 2020 (Cadmium Association, 2022; SCRREEN Experts 2022).

Except where the surface characteristics of a coating are critical (for example, fasteners for aircraft), coatings of zinc, zinc nickel, aluminium, or tin can be substituted for cadmium in many plating applications.

Cerium sulphide is used as a replacement for cadmium pigments, mostly in plastics. Barium-zinc or calcium-zinc stabilizers can replace barium cadmium stabilizers in flexible PVC applications.

BATTERIES

In small consumer electronics NiCd batteries can be substituted by lithium-ion and nickel-metal batteries. Cd batteries cannot be substituted in applications, where reliability and stability is of major importance, such as railway batteries for starting, braking, etc. Nickel-metal hydride batteries cab also substitute for NiCd batteries. They have a higher capacity than NiCd batteries and are less toxic. Nickel-metal hydride batteries, though, have limited service life, sensitivity to overcharge and high self-discharge.

COATINGS

Cadmium in pigments can be replaced by cerium sulphide, which is used mainly in the production of plastics. There are no alternatives for cadmium in artists' paints providing the same colour spectrum. Coatings using cadmium can be substituted by zinc, zinc-nickel, aluminium, or tin coatings, but only where the surface characteristics provided by cadmium (corrosion resistance, low friction coefficient, electric conductivity) are not of critical importance (USGS, 2022).

Substitutes for cadmium as a stabiliser in PVC production are barium zinc, or calcium zinc stabilisers. However, they are not very common an in the EU-PVC-industry, cadmium was completely replaced by Ba-Zn and Ca-Zn alternatives since 2007. (Eurometaux, 2019) (Cadex, 2018; USGS, 2018; USGS, 2019)

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SOLAR APPLICATIONS

For thin-film solar-cells, copper-indium-gallium-selenide and amorphous silicon photovoltaic cells can substitute for CdTe (USGS, 2022).

SUPPLY

EU SUPPLY CHAIN

The average annual production of cadmium in EU during the period 2016-2020, was 3957 tonnes. Netherlands, Germany, Bulgaria and Poland are the producer countries of Cd in EU. About 277 tonnes of cadmium products (CN code 28259060 88 wt% Cd) were annually imported in EU in the same period from China and Russia. At the same time, 1000 tonnes were annually exported mainly to India, South Korea and United Kingdom. The recycling rate of cadmium in EU is estimated at 30% (Eurostat, 2021).

Belgium is the largest consumer of cadmium in the EU with the company Flaurea Chemicals SA producing cadmium compounds for pigments, batteries, etc. (in 2016 and 2017 about 800 t per year) (Eurometaux, 2019). In 2016, Belgium imported 2,890 t of cadmium, mostly from France, Mexico, the Netherlands, and Poland (USGS 2016).

Belgium's main supplier (apart from EU sources) is China and in 2014 large amounts were imported from the United Kingdom.

The EU exported an average of 1,310 t of Cadmium per year in the period of 2012-2016 to 38 different countries. The main consumer of EU's cadmium is India (35%), followed by China (15%) (Eurostat, 2019; WMD, 2019).

Large volumes imported by Belgium reflect consumption by transformation industry to make. Cd compounds for export while imports by Sweden relate to important NiCd battery manufacturing activities. Observed variations in trade activities in the UK, Switzerland and Estonia are linked to actions from traders rather than to an actual cadmium consumption. Europe consumed 406 t more cadmium metal than it produced in 2018 (ICdA, 2021).

SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF CADMIUM

GEOLOGICAL OCCURRENCE:

Cadmium is a very rare element with an occurrence of 0.3 ppm in earth's crust. It can occur in its elemental form, but so far only five locations are known where elemental cadmium has been found.

- Russia: River Khann'ya, Jana river basin, Billeekh intrusion

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- US: Goldstrike mines in Lynn (Eureka County, Nevada)
- Kazakhstan: Burabaiskii massif

There are more than 20 different cadmium minerals, including greenockite (CdS), and Otavite ($CdCO_3$). These ores are not of economic importance due to their rarity. However, they usually occur together with zinc ores such as sphalerite (ZnS) and smithsonite ($ZnCO_3$). Moreover, cadmium can partly replace zinc in the crystal lattice of sphalerite as both have similar chemical properties. It can also be found as an impurity in lead and copper ores. (ICdA, 2010; ISE, 2019; USGS, 2019)

GLOBAL RESOURCES AND RESERVES:

Global cadmium resources and reserves are not reported separately, as cadmium is solely produced as a by-product from zinc, copper, or lead refining.

Quantitative estimates of reserves are not available. The cadmium content of typical zinc ores averages about 0.03%

Typically zinc concentrates contain an average of 0.2% cadmium and 52% zinc. (Eurometaux, 2019)

According to USGS worldwide zinc reserves are estimated at 230 million t, and there are about 1.9 billion t of zinc resources. It is more than likely that these zinc reserves and resources contain cadmium that can be recovered as a by-product.

EU RESOURCES AND RESERVES:

At the time of the Minerals4EU (2019) assessment only France reported cadmium resources with 520 t of cadmium content (Table 1). However, Germany and Bulgaria are believed to have resources as well. There were in total three exploration projects ongoing, one in Portugal and two in Slovakia, that are potential sources for cadmium.

Due to low demand for cadmium, only four EU zinc plants recover cadmium from zinc concentrates. They represent 37% of EU zinc refining. The other plants extract a cadmium concentrate which is stabilised for safe and environmentally approved disposal. This implies that only one third of all cadmium mined in the EU or entering the EU is recovered for sales and use (Eurometaux, 2019).

Table 7. Resource data for the EU compiled in the European Minerals Yearbook of the Minerals4EU website (Minerals4EU, 2019)

Country	Quantity	Unit	Grade	Code Resource Type
France	520	t (metal content)	-	Historic Resource, Estimates
Germany				Resources know or believed to exist
Bulgaria				Resources know or believed to exist

In the EU eight countries22 have reported zinc reserves and twelve23 zinc resources. These deposits are likely to contain cadmium. (Minerals4EU, 2019)

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WORLD AND EU REFINERY PRODUCTION

The global average annual production of refined cadmium between 2016-2020 is around 25000 t according to WMD and USGS that are in accordance (Figures 1,2). EU production in 2020 represented about the 7.2% of the global production. Netherlands, Germany, Poland and Bulgaria are the producer-countries in EU and their Cd production distribution can be seen in Figure 3.

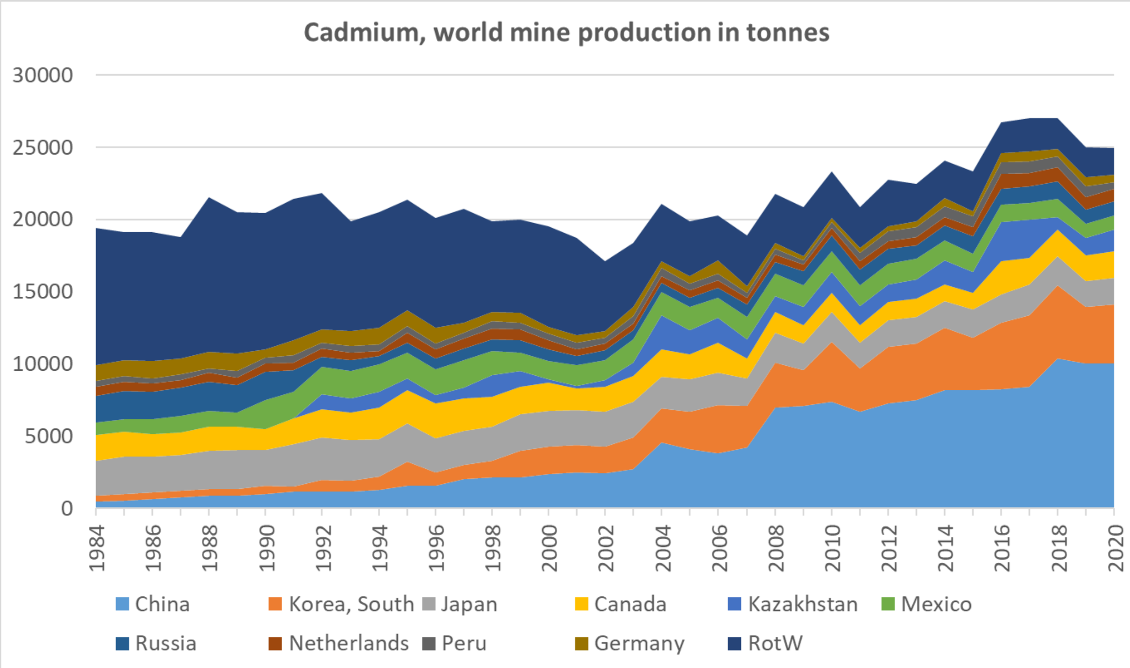

Figure 15. Global production of refined cadmium since 1984 according to WMD data (WMD, since 1984).

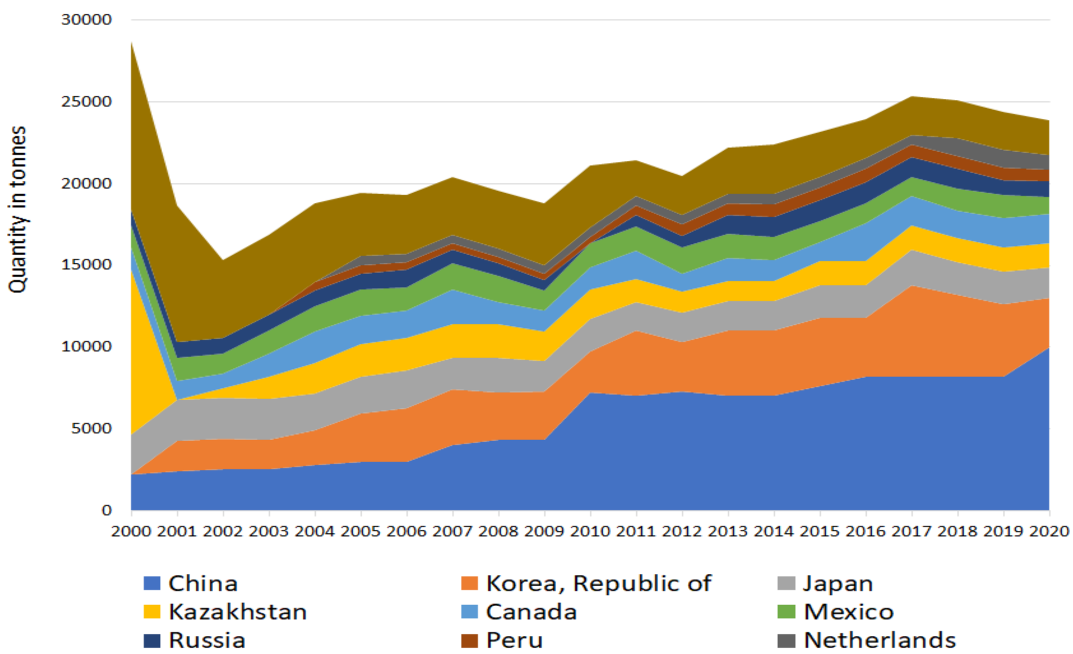

Figure 16. Global production of refined cadmium since 2000 according to USGS data (USGS, since 2000).

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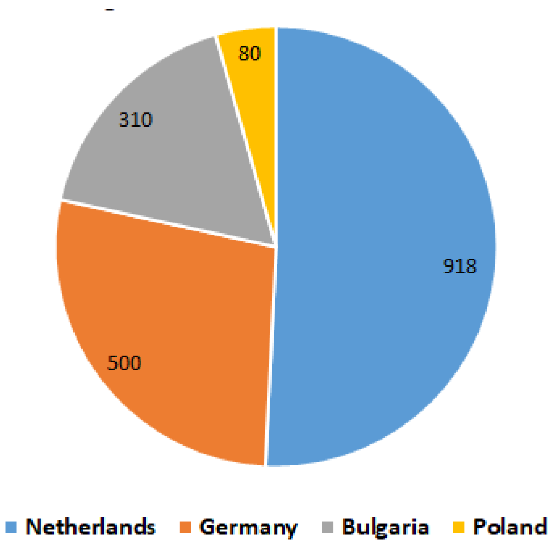

Figure 17. Cadmium production in EU in 2020 in tonnes (WMD, since 1984).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

Recycling of cadmium containing products is not only important to provide further raw material sources, but also to keep it out of the waste streams due to its toxicity.

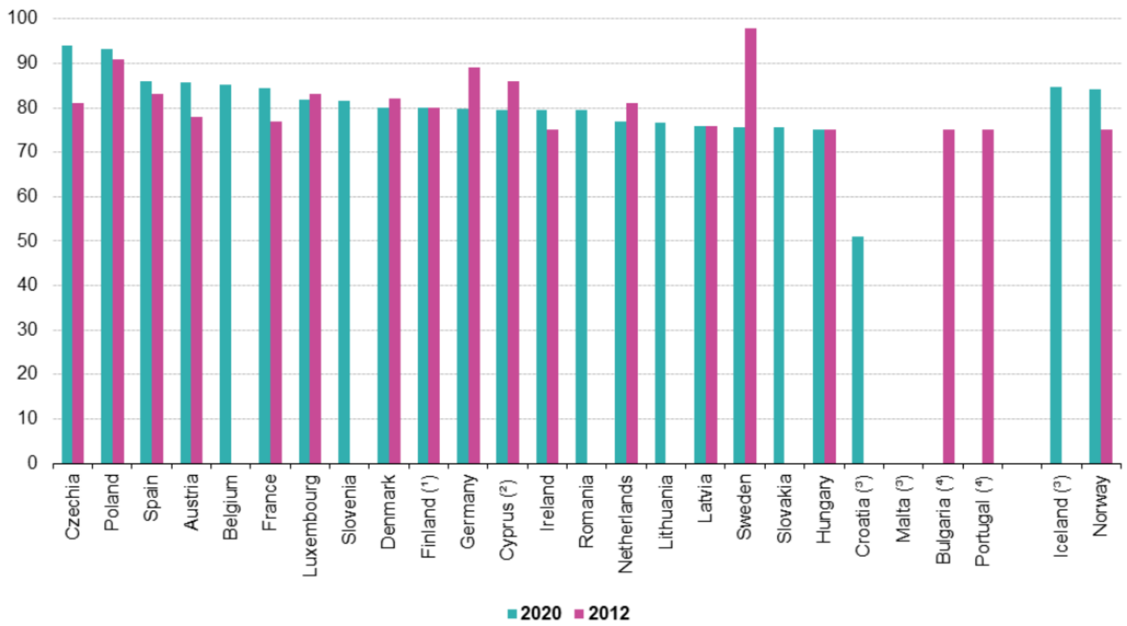

Figure 18. Recycling efficiencies for nickel-cadmium batteries (source Eurostat 2020).

Cadmium has a rather high global recycling rate of about 30% according to UNEP (2011) which remained stable in recent years (SCRREEN Validation Workshop, September, 2022). Secondary materials and end-of-life products include Nickel-Cadmium batteries and CdTe photovoltaic modules. Secondary or recycled cadmium now accounts for about 23% of total cadmium supply (ICdA 2023).

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The collection of NiCd batteries is well implemented particularly in Europe (Figure 4), North America, Australia, Japan and other OCDE countries, hereby improving overall recycling rates. Once collected, NiCd batteries are recyclable in excess of 75 wt%, similar to lead-acid batteries (Eurostat 2020). Cadmium makes up about 15–20 wt% of a Ni-Cd battery.

Worldwide recycling plants located in the United States, Europe and Asia have a total capacity of 20,000 t of industrial and consumer NiCd batteries and their manufacturing scraps. In the EU, there are currently six plants that recycle collected NiCd batteries. Over the past 5 years (reference year 2022), an average of 7,000 t per year NiCd batteries of EU origin were collected for recycling (ICdA 2023, SCRREEN Validation Workshop, September, 2022). Nickel-cadmium battery collection programs in Europe are now being organized and promoted by Eucobat which maintains a complete listing of national collection organizations and recyclers throughout Europe.

The materials in recyclable Ni-Cd batteries can be more than 99% recovered for reuse in the production of new Ni-Cd batteries.

Concerning CdTe photovoltain modules, current thin-film PV module recycling processes recover more than 90% of a CdTe PV module at the end of its useful life for reuse in new solar, glass and rubber products (ICdA 2023). This includes over 90% of the CdTe semiconductor material. However, recycled volumes of thin films are modest so the amount of Cd recovered does not represent a significant contribution to the total Cd recovered from secondary sources in Europe.

PROCESSING OF CADMIUM

The production of cadmium depends on the method used for zinc refining. Zinc can either be produced using the so called dry zinc extraction, or the wet zinc extraction.

In the dry zinc extraction cadmium and zinc are reduced. As cadmium has a lower boiling point it evaporates before the zinc components. It then reacts with oxygen to cadmium oxide and can be distilled. Fractional distillation is used to increase cadmium recovery.

Wet zinc extraction reduces and precipitates dissolved cadmium ions with zinc dust. It is then oxidised with oxygen and dissolved in sulphuric acid. The resulting cadmium sulphate is electrolysed with aluminium anodes and lead cathodes producing particularly pure cadmium. (ISE, 2019)

For recycling nickel-cadmium batteries, metallurgical processing can be performed in three different ways: pyrometallurgy, hydrometallurgy, or hybrid processes that combine pyro- and hydrometallurgy techniques for the production of metals or their compounds. Preparation stages based on typical ore enrichment operations, such as crushing, grinding, magnetic separation, electrostatic separation, and separation according to the densities of particles are also applied (Blumbergs 2021).

Three main pyrometallurgical processes are used for recovering cadmium (Barashev 2013): sublimation of cadmium oxide in an open furnace followed by its condensation in the form of a powder; distillation in the atmosphere of a closed furnace with the production of powdered metallic cadmium and an iron-nickel alloy;

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and chlorination of batteries by gaseous chlorine or hydrochloric acid, with cadmium chloride undergoing sublimation at 960°C. Nickel and cobalt remain stable. The companies Snam (France), Sab Nife (Sweden), and Inmetco (U.S.) all use large-scale pyrometallurgical processes for recycling nickel-cadmium batteries based on distillation of metallic cadmium in the atmosphere of a closed furnace. The distillation is usually carried out within the temperature range 850–900°C and the resulting cadmium is more than 99.95% pure.

Hydrometallurgical technologies are usually more complex and require more stages compared to the pyrometallurgical approach, however they are often more efficient, more flexible, and provided an increased selectivity during metal extraction (Blumbergs 2021). Batenus (Germany) and TNO (Holland) are typically applied hydrometallurgical processes for recycling nickel-cadmium batteries. These processes are based on solvent extraction followed by electrolysis, ion exchange, and membrane technology.

OTHER CONSIDERATIONS

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

The International Agency for Research on Cancer (IARC, 2012) includes cadmium and cadmium compounds in Group 1 carcinogens since they cause lung cancer. Moreover, the IARC mentions that a positive association has been observed between exposure to cadmium and kidney and prostate cancer. Consequently, cadmium use is severely restricted by the (REACH Regulation, 2006). Cadmium and cadmium compounds are listed in entry 23 of Annex XVII, which lists the polymer products in which cadmium cannot be used. Also, this provision stands that cadmium shall not be used in plating[4] for articles in several industrial branches such as freezing, cooling and food production, and limits the use of cadmium in jewellery accessories. Since cadmium and various cadmium compounds are known carcinogen elements, the (REACH Regulation, 2006) restricts the introduction in the European market of all the substances listed in Appendices 1, 2 3 and 4 to Annex XVII. Finally, since cadmium and its compounds are included in Appendix 12 to Annex XVII, their use in clothing, textile or footwear is prohibited in the European market by the (REACH Regulation, 2006).

Cadmium compounds are classified by the (Classification, Labelling and Packaging EU Regulation, 2008) for their acute toxicity to humans on the grounds of being harmful if inhaled (H332), harmful in contact with skin (H312), and harmful if swallowed (H302). The aforementioned EU Regulation also establishes that the mixtures containing cadmium (alloys), which are used for brazing or soldering, shall include in the label of the packaging the following statement: “EUH207 — ‘Warning! Contains cadmium. Dangerous fumes are formed during use. See information supplied by the manufacturer. Comply with the safety instructions”.

The concentration limit for cadmium in drinking water is 5 µg/l (Drinking Water EU Directive, 2020).

The government of Canada issued the (Guideline Technical Document 2020) on the Canadian Drinking Water, which includes a specific section dedicated to cadmium.

[4] Cadmium plating refers to any deposit or coating of metallic cadmium on a metallic surface.

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In 2008, Washington's Legislature passed the Children's Safe Products Act (or CSPA). This law applies to children's products sold in Washington State and limits the use of priority toxic chemicals, including cadmium.

ENVIRONMENTAL ISSUES

Cadmium compounds are classified by the (Classification, Labelling and Packaging EU Regulation, 2008) for their acute toxicity to the environment since they are very toxic to aquatic life (H400) and very toxic to aquatic life with long-lasting effects (H410). Animals exposed to cadmium in the environment suffer from cadmium-induced kidney damage. This substance is particularly dangerous due to its high potential for bioavailability and bioaccumulation. Furthermore, cadmium is toxic to various plants and microorganisms (UNEP, 2020).

A study conducted in China by (Buyun, D. et al., 2019) found high cadmium levels in two settlements living nearby an active lead-zinc mine and a copper smelter, respectively. Both sampled populations were in the city of Guixi, in the Jiangxi Province. Hair samples were collected, and cadmium presence was analysed. The results showed that 38 % of children and 5 % of adults living in the areas exceeded the health standard for cadmium in hair as reported by the Trace Element Research Council of China (0.5 mg/kg for children and 0.6 mg/kg for adults). Rice and vegetable ingestion were the two major pathways of cadmium exposure. Moreover, the samples collected from workers of the mine and the smelter contained higher levels of the element than the rest of the inhabitants, suggesting that the occupationally exposed population might be vulnerable to other routes of exposure, such as inhalation.

Cadmium from a zinc mine polluted the Jinzu River basin in Japan and caused the outbreak of the "Itai Itai" disease from 1912 on, which is till nowadays a well-known example of severe, lethal consequences of environmental pollution. (Kasuya et al. 1992)

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

The (UN Recommendations on the Transport of Dangerous Goods 2019) list the principal dangerous goods, the general packaging requirements, testing procedures, marking, labelling and transport documents for a set of elements considered dangerous, including cadmium.

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF CADMIUM FOR EXPORTING COUNTRIES

In 2021, there were no countries for which the economic value of cadmium product exports represented more than 0.1 % of the total value of their exports. (ComTrade 2023)

SOCIAL AND ETHICAL ASPECTS

The state-run Guangdong Dabaoshan Mining Corporation (GDMC) owns a currently active iron ore and copper mine in Southern China, in the Guangdong province, which pollutes the Hengshi River and affects the

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environmental quality of the region. Since the 1980s, people living in the area, especially in the Shangba village, claim that there has been an increase in cancer rate among the population, demonstrating that the high concentration of heavy metals in water was strongly affecting their health. Test results conducted by local authorities on the dwellers showed that the concentration of cadmium, a known human carcinogen, was 12 times higher than the standard levels. Despite the protests of the population, GDMC argued that the excess of cadmium in Hengshi River was mainly caused by the activities of illegal private miners and that it was not linked to their mining operations. The dispute ended in 2005 with a commitment by GDMC to build a water reservoir for the Shangba village, aiming at providing safe water for domestic and irrigation use. The construction was finished in 2015. Currently, the South China Agricultural University is working on the restoration of the ecological system of the region, which will take decades to be completed (EJA, 2019).

The use of cadmium to produce batteries is associated with human poisoning, and water bodies and soil pollution. Information about the topic is scarce, but some sources (Niewenhuis, L., 2017; BBC, 2012) reported on nickel-cadmium batteries factories in China and their detrimental effect on humans and the environment. (Niewenhuis 2017) reported that workers in battery production facilities such as in Henan Huanyu Power Source Company in the Henan province, will hardly find support in the Chinese justice system, as the battery companies are state-owned, and the Central Government prioritises their interests rather than the protection of the employees' health (Niewenhuis 2017).

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Black phosphorous as anode material in energy storage systems (TRL 2-3)

Black phosphorus (BP) is still in its early stage but is a promising anode material for lithium-, sodium-, potassium- and magnesium-ion batteries, as well as lithium-sulphur batteries, lithium–air batteries and supercapacitors. The high specific capacity may lead to a breakthrough in energy storage materials (C. Liu et al., 2020). The use of BP in energy storage systems provides a remarkable market potential in the foreseeable future (Li et al., 2021) in the strongly growing global market for lithium-ion battery anodes of expected USD 21.0 billion by 2026, at a CAGR of 19.9% from 2021 to 2026. (MarketsandMarkets, 2022).

OTHER RESEARCH AND DEVELOPMENT TRENDS

- SPECADIS[5] project: Speciation and bioavailability of heavy metal cadmium (Cd) in the soil-plant system: a novel approach combining stable isotope geochemistry and experimental spectroscopy (EU, 2019-2021)

The environmental pollution by ecotoxic heavy metals is an issue of increasing significance for ecological and human health reasons. Among these elements, cadmium (Cd) is of special concern due to its high mobility in the soil/plant system and its acute toxicity towards most forms of life, which requires monitoring of food products, especially crops. In this context, SPECADIS' overarching objective is to enhance our understanding

[5] https://cordis.europa.eu/project/id/794825

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of Cd bioavailability to crops and bring constraints on the mechanisms that govern the uptake and fate of Cd in the plants that feed the world.

- DyCLE[6] project: – Dynamics of Cadmium concentrations in Leaves in response to a challenging Environment (EU, 2019 – 2021)

Hyperaccumulators are unusual plants. Their ability to accumulate much larger amounts of heavy metals in their leaves than normal plants makes them useful for cleaning up contaminated land. The exact mechanism by which the plant facilitates hyperaccumulation remains a mystery. Is this attributed only to genetic mechanisms or could this be the result of being accustomed to the environment over the years? The EU-funded DyCLE project will study cadmium accumulation in populations of Arabidopsis 24elleri. This species exhibits the largest intrapopulation variation of this trait. Study outcomes will help find better methods of using hyperaccumulators for cleaning up metal-contaminated soils that are unsafe for agriculture.

- Does maternal low-dose cadmium exposure increase the risk of offspring to develop metabolic syndrome and/or type 2 diabetes? (Saedi et. al 2023)

Cadmium is a hazardous metal with multiple organ toxicity that causes great harm to human health. Cadmium enters the human body through occupational exposure, diet, drinking water, breathing, and smoking. Cadmium accumulation in the human body is associated with increased risk of developing obesity, cardiovascular disease, diabetes, and metabolic syndrome (MetS). Cadmium uptake is enhanced during pregnancy and can cross the placenta affecting placental development and function. Subsequently, cadmium can pass to fetus, gathering in multiple organs such as the liver and pancreas. Early-life cadmium exposure can induce hepatic oxidative stress and pancreatic β-cell dysfunction, resulting in insulin resistance and glucose metabolic dyshomeostasis in the offspring. Prenatal exposure to cadmium is also associated with increasing epigenetic effects on the offspring's multi-organ functions. However, whether and how maternal exposure to low-dose cadmium impacts the risks of developing type 2 diabetes (T2D) in the young and/or adult offspring remains unclear. This review collected available data to address the current evidence for the potential role of cadmium exposure, leading to insulin resistance and the development of T2D in offspring.

- Converting wastes to resource: Preparation of NiO@γ-Al2O3 sludge composite from aluminium-containing sludge for cadmium removal from wastewater (Chen et al. 2023)

Solid sludge waste and heavy metal water pollution have attracted great interest due to the adverse impacts on the ecological environment, which remains a significant challenge to environmental protection. Herein, with the concept of converting wastes to resources, this work presents a general procedure to fabricate NiO@γ-Al2O3 sludge composite derived from aluminium-containing sludge for efficient cadmium removal.

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