SCRREEN2

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958211.

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

TELLURIUM

AUTHOR(S):

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TELLURIUM

OVERVIEW

Tellurium (chemical symbol Te) is a chemical element with the atomic number 52. It is considered a semi-metal and has both metallic and non-metallic properties. Tellurium is very rare, its share in the earth's crust is about 0.01 ppm. It can be found in its native form, but usually it occurs in telluride minerals – tellurium compounds with lead and silver (most common), gold, selenium, or platinum. Native tellurium appears as a soft, silvery-white material, with a metallic shine. (Lenntech, 2019; ISE, 2019; USGS, 2015; GTK, 2019)

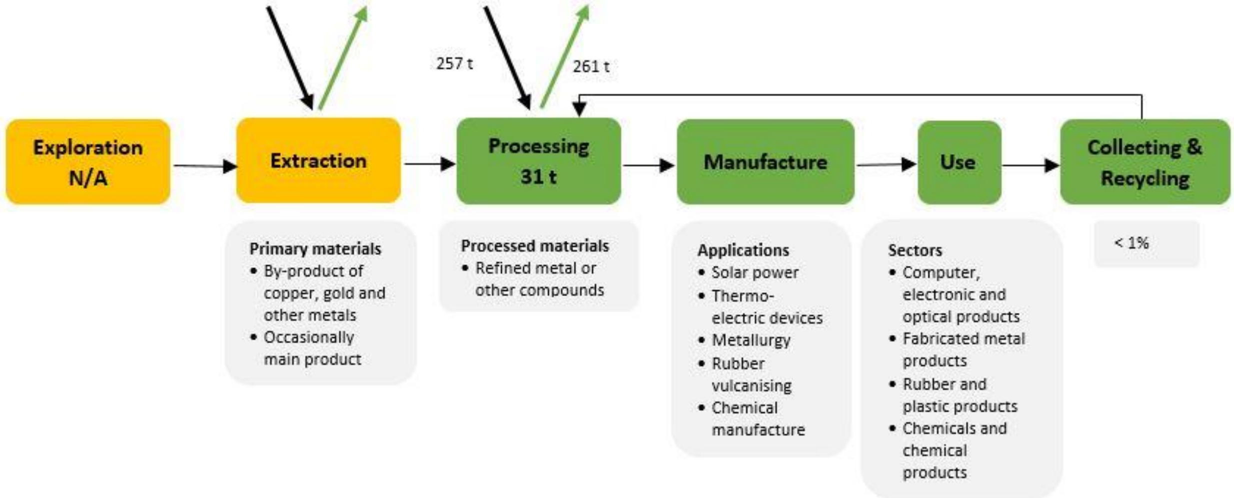

Figure 1. Simplified value chain for tellurium in the EU[1]

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
540	China 69% Japan 9% Russia 7% Sweden 7% Canada 4%	507	14%	Philippine 56% Canada 29%	80% (average 2019-2020 only)

Prices: Between 2008 and 2011 tellurium prices showed a significant increase to values almost 4 times higher than in the years before (maximum €259 per kg). From 2018 to 2021, tellurium prices remained stable, with a

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

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fluctuation between € 60 – 63 per kg. Prices in this period were mostly influenced by the production of the solar PV industry, electronics, semiconductors, and metal alloys (DailyMetalPrices, 2022).

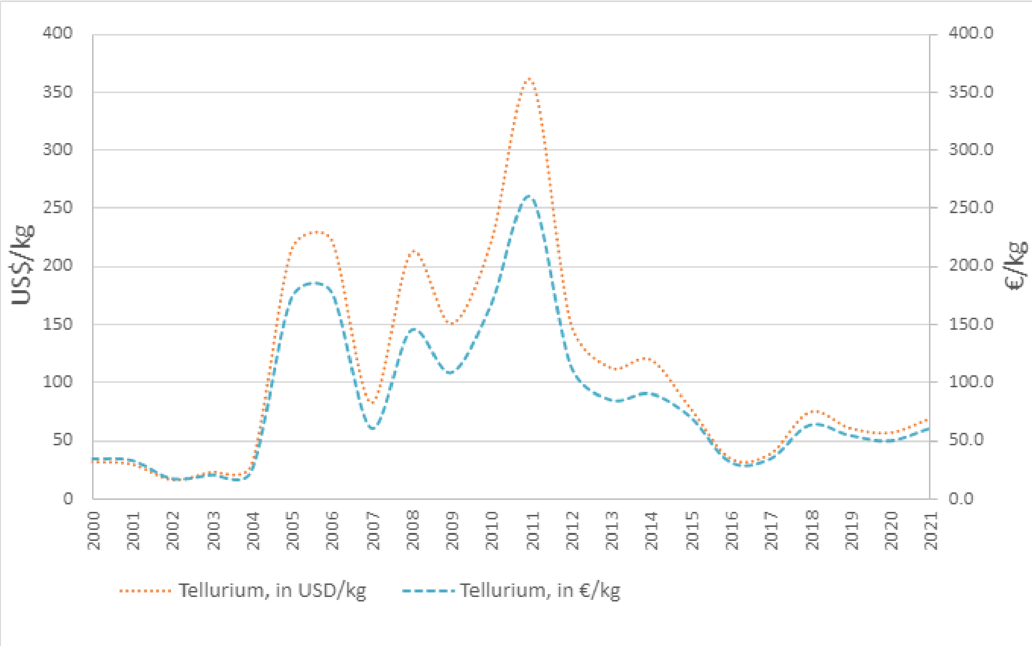

Figure 2. Annual average price of tellurium between 2000 and 2020 (USGS, 2021)[2].

Primary supply: The largest reserves are located in China, followed by Peru, and the USA. In total there are about 31,170 t of tellurium reserves worldwide. Resources are not documented, as the main source (90% of total production) for tellurium is anode slime from copper refining. However, potential sources include bismuth telluride and gold telluride ores. (USGS, 2019). The vast majority of the tellurium produced worldwide is as a by-product of electrolytic copper refining with smaller quantities extracted as a by-product of gold, lead or other metals. Within the EU, tellurium is mined as a by-product of gold at the Krankberg Mine in the Boliden Area of Sweden and it is also refined nearby at the Rönnskär Smelter (Boliden 2018).

Secondary supply: Many of the end uses of tellurium are dissipative, meaning that very little material becomes available for recycling. Tellurium contents in metallurgical applications are too small to be separated during recycling processes with the result that they become further dispersed rather than concentrated. A very small quantity is currently recovered from end-of-life electrical products. In the future, more significant quantities of tellurium are likely to become available for recycling from cadmium-tellurium photovoltaic solar cells but this is a relatively new technology and few of the cells have reached the end-of-life stage so far.

Uses: The main application of tellurium is in the production of cadmium telluride (CdTe) solar panels. These are the second most common type of solar cell (behind crystalline silicon) but represent only 5% of the global photovoltaic market.

Substitution: There are possibilities for some materials to replace tellurium in many of its uses, but usually with reduced efficiency and/or product characteristics. (USGS, 2022).

[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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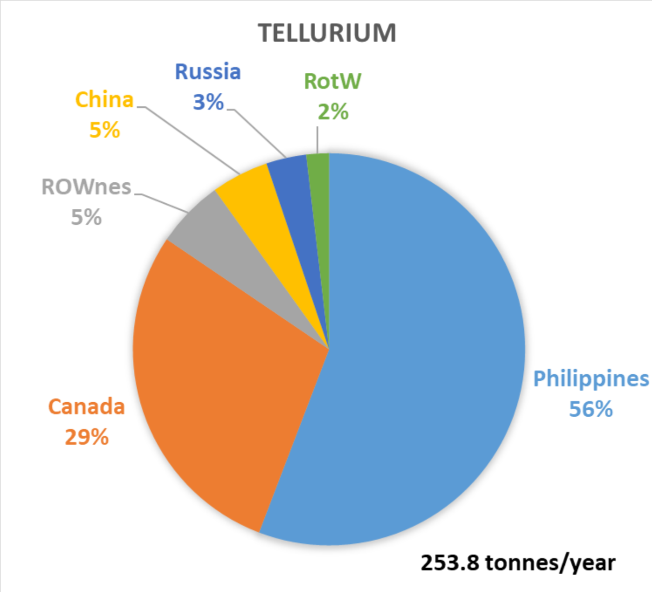

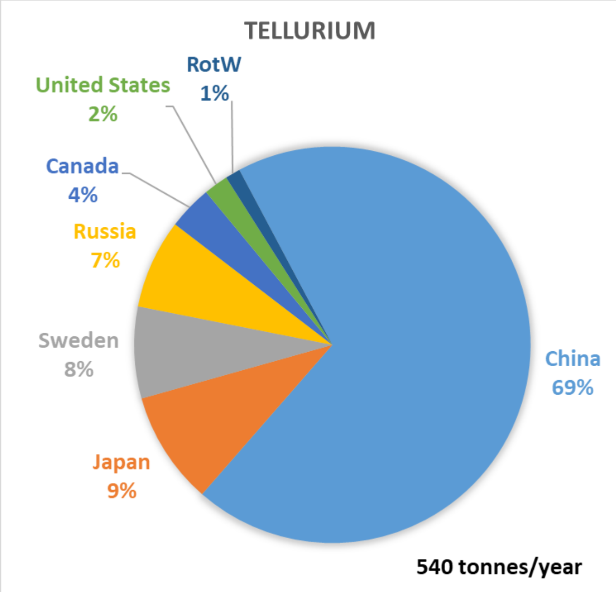

Figure 3. EU sourcing of tellurium and global mine production (update)

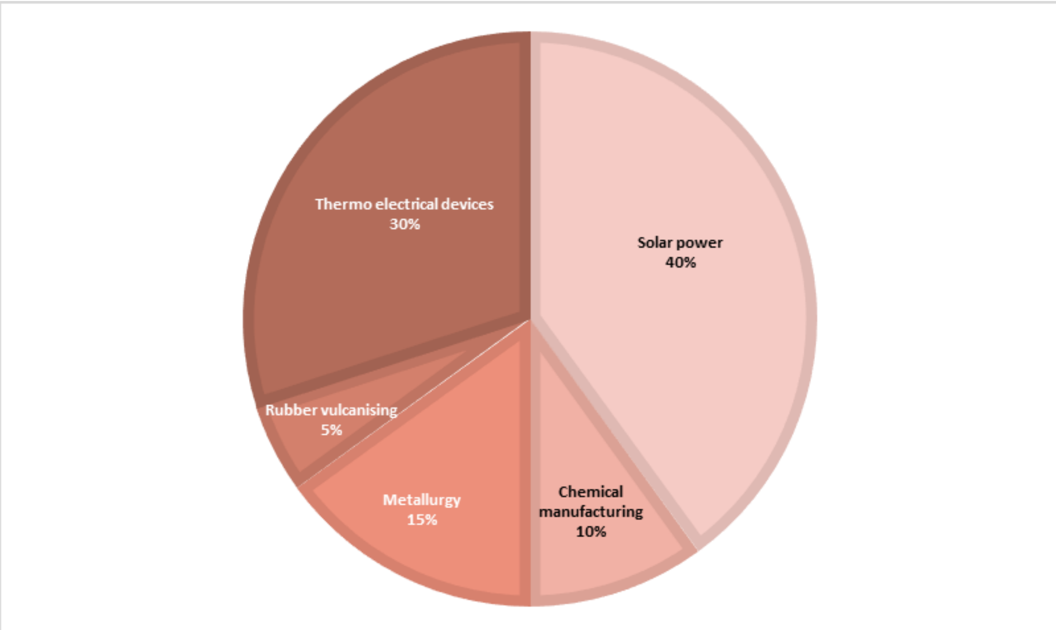

Figure 4: EU uses of tellurium

Other issues: Tellurium may damage fertility or the unborn child, is harmful if inhaled, causes allergic skin reactions, and may have long-lasting harmful effects on aquatic life (ECHA, 2021). Under the GESTIS international limit values with CAS No. 13494-80-9 states that Finland and Norway Tellurium exposure 8-hour limit is of 0.1 mg/m3 and Latvia's and Romania's is 0.01 mg/m3 and 0.05 mg/m3 respectively (IFA, 2021). This substance can be hazardous to the aquatic environment, being labelled as a Chronic Category 4; H413 and therefore its release to the environment should be avoided as indicated in the precautionary statement standards (P273) (IFA, 2022; PubChem, 2022). No information is available linking tellurium to particular social or ethical aspects.

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Table 2. Uses and possible substitutes

Use	Share*	Substitutes	Sub share	Cost	Performance
Thermo-electric modules	30%	Silicon-germanium	34%	Very high costs (more than 2 times)	Similar
Thermo-electric modules	30%	Bismuth selenide	10.0%	Similar or lower costs	Similar
Thermo-electric modules	30%	Organic polymers	10.0%	Similar or lower costs	Similar
Metallurgy	15%	Bismuth	8.0%	Similar or lower costs	Similar
Metallurgy	15%	Lead	8.0%	Similar or lower costs	Similar
Metallurgy	15%	Calcium	8.0%	Similar or lower costs	Similar
Metallurgy	15%	Phosphorus	8.0%	Similar or lower costs	Similar
Metallurgy	15%	Selenium	8.0%	Similar or lower costs	Similar
Metallurgy	15%	Sulphur	8.0%	Similar or lower costs	Similar
Rubber vulcanising	5%	Sulfur	25.0%	Similar or lower costs	Similar
Rubber vulcanising	5%	Selenium	25.0%	Similar or lower costs	Similar
Solar power	40%	Silicon wafer	94.9%	Similar or lower costs	Similar
Solar power	40%	CIGS thin film	1.0%	Slightly higher costs (up to 2 times)	Similar
Solar power	40%	Amorphous silicon thin film	0.1%	Similar or lower costs	Similar
Chemical manufacture	10%	various	50.0%	Similar or lower costs	Similar

*share for global estimates of tellurium end uses, 2019 (SDTA; SCRREEN, 2019)

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3 supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
540	China 69% Japan 9% Sweden 8% Russia 7% Canada 4%	507	14%	Philippine 56% Canada 29%	80% (average 2019-2020 only)

The global market for tellurium remains opaque, due to its small size and the confidential nature of supply agreements between producers and consumers of the material. China was the leading producer of refined tellurium, recovering tellurium from copper anode slimes and from residues generated during the lead, nickel, precious metals, and zinc smelting processes (USGS, 2022). Other important producers are Japan, Russia and Sweden. Recently, the Philippines seem to have started exporting non negligible amounts of mined Te but detailed data is not available (USGS, 2022). In 2022, Rio Tinto also began production of an expected 20 tonnes per year at a facility in the US (Rio Tinto, 2022).

Tellurium is sold in various forms, e.g. powder or granules, ingots or pieces, usually with a grade of 99.5% or higher. (MMTA, 2016). Demand for Tellurium is primarily driven by its application in thin film cadmium telluride solar panels and in thermoelectric applications. Major global producers of tellurium include: Umicore, Boliden, Grupo Mexico (via subsidiaries Asarco in the US and Southern Copper in Peru), Nornickel, Rio Tinto, 5N Plus, and II-VI Incorporated. The world's largest producer of Cd-Te solar panels is First Solar, though they do not provide public figures on the amount of Te they consume.

OUTLOOK FOR SUPPLY AND DEMAND

Between 2018 and 2022 the tellurium market was expected to grow by 3% per year, mainly due to its use in Cd-Te thin film solar panels, but also because of new applications that are currently being investigated (see Uses and end-uses of Tellurium in the EU). (Cleantech, 2018).

Demand for Te is expected to continue increasing in coming years. Notably, First Solar's plans to increase its annual production of Cd-Te solar panels to 16GW by 2024 will be a major driver of increased Te demand. Researchers estimate these production increases could see the company's demand exceeding total global Te supply in 2020 by up to 70% (Copley, 2021).

EU TRADE

For the purpose of this assessment, tellurium is evaluated at the processing stage. Figure 5 shows the EU trade in tellurium (CN 2804 50 90), in tonnes, between 2000 and 2021. The EU was a net importer of tellurium. Over the years 2016-2020, the annual import was 507.5 tonnes in average and export was 346 tonnes in average.

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Table 4 Relevant Eurostat CN trade codes for tellurium

Processing/refining	
CN trade code	**title**
2804 50 90	Tellurium

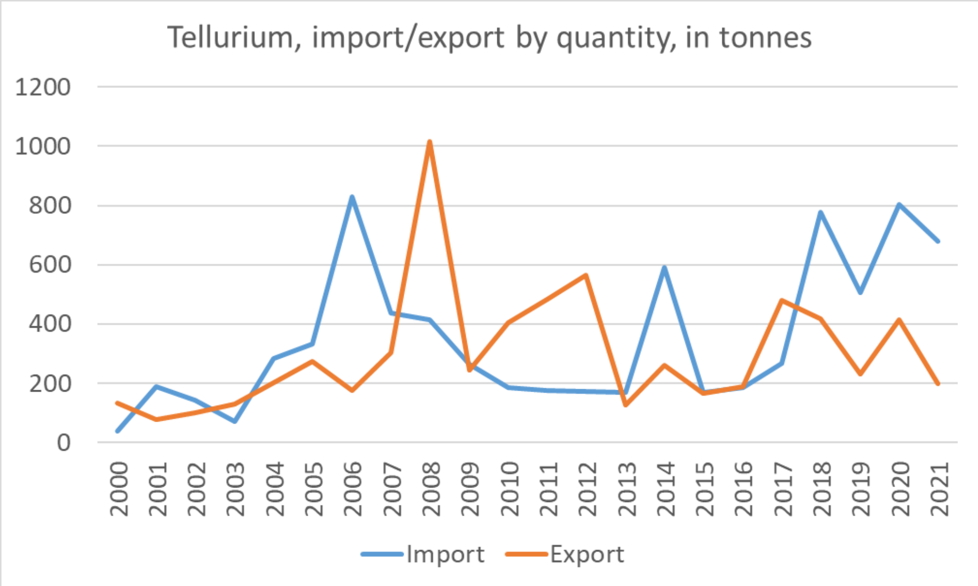

Figure 5 EU trade flows of tellurium (CN 28045090) from 2000 to 2021 (Eurostat, 2022)

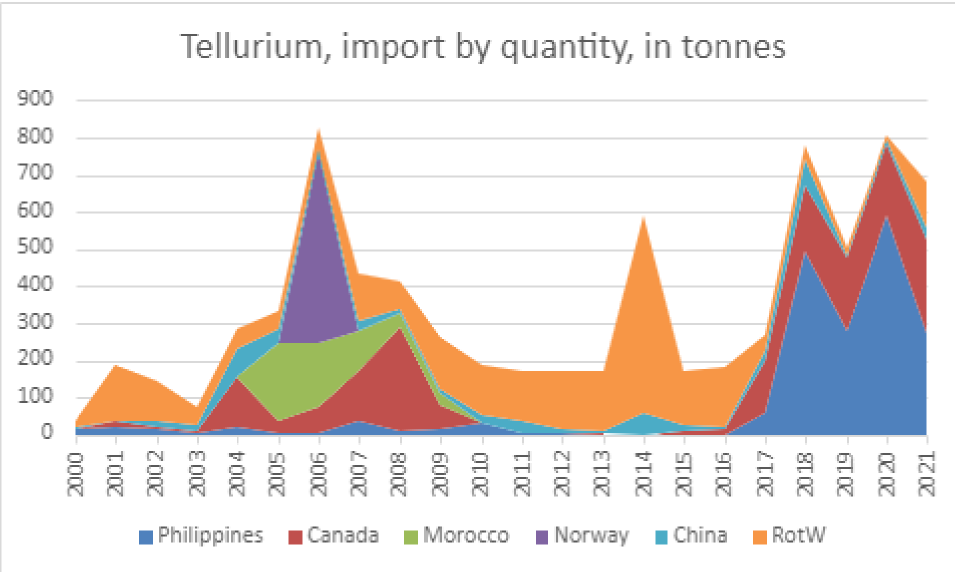

Figure 6 EU imports of tellurium (CN 28045090) by country from 2000 to 2021 (Eurostat, 2022)

Figure 6 present the average EU imports of tellurium by country for the period 2000-2021. The main supplier was the Philippines, which represents 25% of total EU imports in the period. This was mostly due to the increase of EU tellurium imports from the Philippines between 2018 and 2021. Canada, Morocco, Norway, and China followed with 23%, 7%, 7%, and 7% respectively.

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PRICE AND PRICE VOLATILITY

Between 2008 and 2011 tellurium prices showed a significant increase to values almost 4 times higher than in the years before (maximum €259 per kg). From 2018 to 2021, tellurium prices remained stable, with a fluctuation between € 60 – 63 per kg. Prices in this period were mostly influenced by the production of the solar PV industry, electronics, semiconductors, and metal alloys (DailyMetalPrices, 2022).

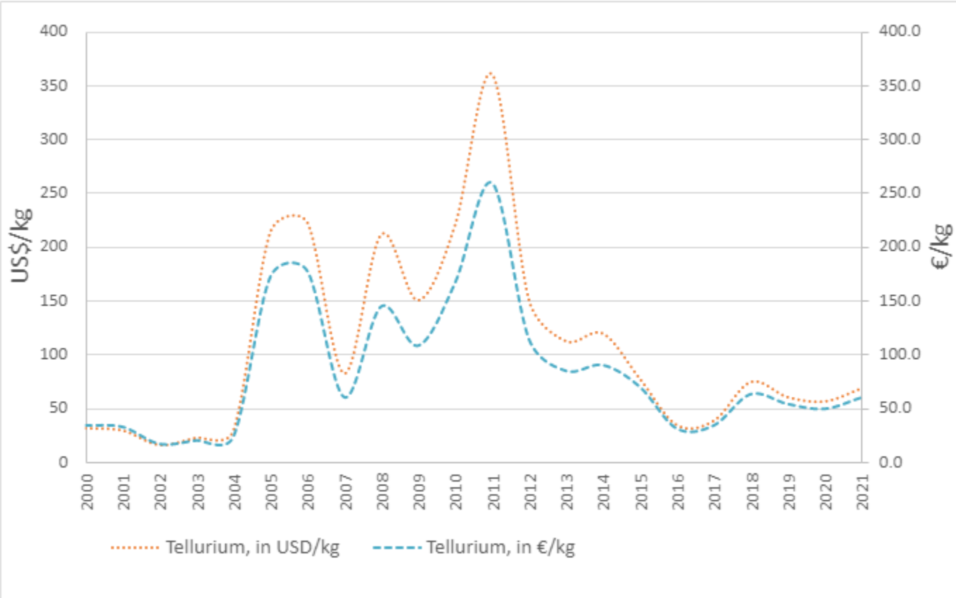

Figure 7 Annual average price of tellurium between 2000 and 2021, in US$/kg and €/kg [3]. (USGS, 2022)

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

The EU had an average apparent consumption of 27 tonnes per year in the period 2012-2016 (Eurostat, 2019a; WMD, 2019). For 2016-2020, the apparent average annual consumption is 206 tonnes (Eurostat Comext, 2022; WMD, 2022). Using production data from Eurostat Prodcom (2022) with PRCCODE 20132142 Tellurium results in a higher average apparent EU consumption of 507 tonnes in the period 2019-2020. The apparent consumption is calculated as EU-imports minus EU-exports plus EU production. Imports and exports were fairly balanced, except in 2008 and 2012, when exports were more than three times higher than imports. In 2006, the imports were three times higher than exports. Considering these numbers it can be assumed that the evaluated trade code might not record tellurium contained in other materials, for example intermediate copper products imported for further refining.

[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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Tellurium processing stage EU consumption is presented by HS code CN 28045090 Tellurium. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022).

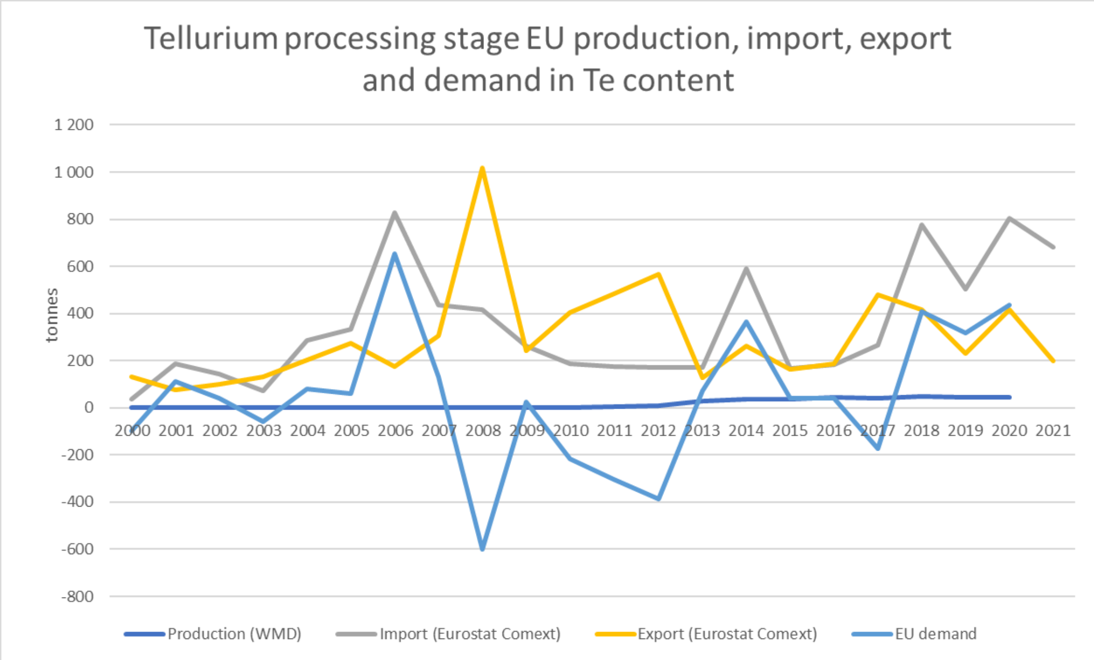

Figure 8. Tellurium (CN 28045090 Tellurium) processing stage apparent EU consumption. Production data is available fromWMD (2022). Consumption is calculated in Te content (EU production+import-export).

Based on Eurostat Comext (2022) and WMD (2022) average import reliance of tellurium at processing stage is 75.8% for 2016-2020.

EU USES AND END-USES

Figure 9 presents the main global uses of tellurium, as no EU-specific data is available.

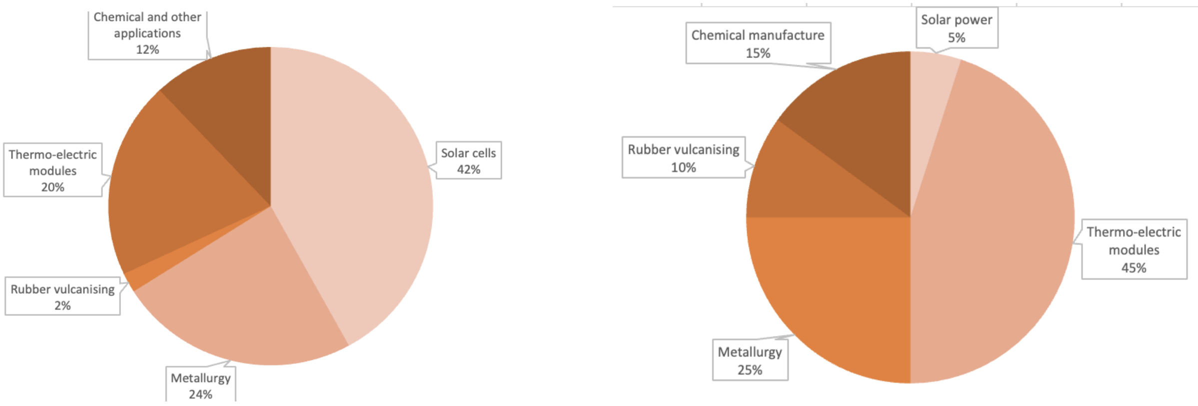

Figure 9 Left: Global end uses of tellurium (STDA, 2022) (validated by SCRREEN experts 2022); Right: EU27 end uses of tellerium 2022 (estimates by SCRREEN experts, 2022)

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Table 5 Tellurium applications, 2-digit and associated 4-digit NACE sectors, and value added per sector, 2019 (Eurostat, 2022)

Applications	2-digit NACE sector	Value added of NACE 2 sector (millions €)	Examples of 4-digit NACE sector(s)
Solar power	C26 – Manufacture of computer, electronic and optical products	84,074*	C2611 – Manufacture of electronic components
Thermo-electric devices	C26 – Manufacture of computer, electronic and optical products	84,074*	C2611 – Manufacture of electronic components
Metallurgy	C25 – Manufacture of fabricated metal products, except machinery and equipment	186,073	C2511 – Manufacture of metal structures and parts of structures; C2599 – Manufacture of other fabricated metal products n.e.c.
Rubber Vulcanising	C22 – Manufacture of rubber and plastic products	94,767	C2219 – Manufacture of other rubber products
Chemical Manufacture	C20 – Manufacture of chemicals and chemical products	117,150*	C2059 – Manufacture of other rubber products; C2012 – Manufacture of dues and pigments; C2059 – Manufacture of other chemical products n.e.c.

** data to 2014 only*

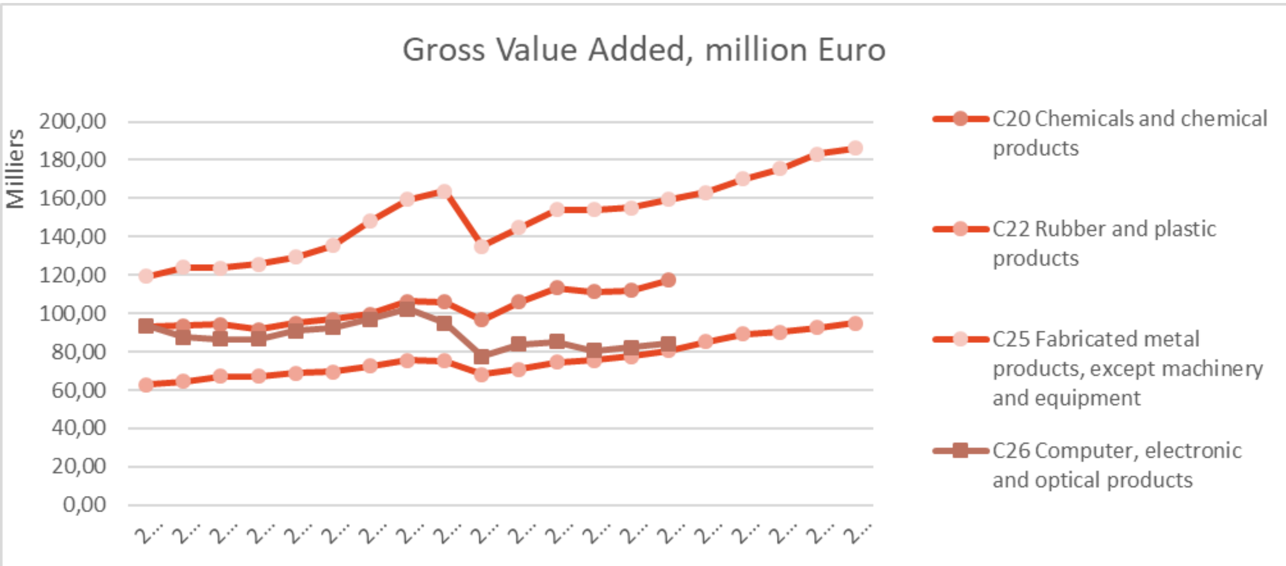

Figure 10 Value added per 2-digit NACE sector over time (Eurostat, 2022)

The global applications of tellurium have remained unchanged since the last criticality study in 2017.

APPLICATIONS OF TELLURIUM IN THE EU:

SOLAR POWER

The main application of tellurium is in the production of cadmium telluride (CdTe) solar panels. Within the solar power sector, the most significant material in use is currently silicon.

CdTe cells have the advantage of absorbing sunlight as close to the ideal wavelength as currently possible, meaning that they capture energy at shorter wavelengths for optimal sunlight to electricity conversion. CdTe panels can also be manufactured at low cost. The toxicity of CdTe has to be taken into consideration, especially regarding the end-of-life disposal of the panels.

Tellurium, combined with cadmium, forms the active layer in photovoltaic thin-film solar panels. These are the second most common type of solar cell (behind crystalline silicon) but represent only 5% of the global photovoltaic market.

THERMO-ELECTRIC DEVICES

Thermo-electric devices are semi-conductor electronic components that can turn a temperature variation into electricity or electricity into a temperature variation. These devices can be used for power generation or as a heat pump or for cooling.

This application sector also includes mercury-cadmium-telluride (MCT) used in infrared detectors and CZT (cadmium-zinc-telluride) semi-conductors for gamma- and x-ray detection (radiation mapping, nuclear medical imaging, astrophysics, and homeland security) (Fenixam, 2019).

METALLURGY

Tellurium is used as an additive in steel or copper alloys to improve machinability, and in lead alloys to improve strength, hardness, and resistance to vibration.

RUBBER VULCANISING

Tellurium is used as a vulcanising agent and accelerator in the processing of rubber.

CHEMICAL MANUFACTURING

Tellurium is used as a catalyst in the production of synthetic fibre or in oil refining, and as a chemical in photoreceptor devices.

Tellurium also adds blue and brown colours when used as a pigment in glass and ceramics.

It can also be used as a chemical in rewritable CDs or DVDs, and as an additive in lubricants. (European Commission, 2017).

SUBSTITUTION

There are possibilities for some materials to replace tellurium in many of its uses, but usually with reduced efficiency and/or product characteristics. (USGS, 2022).

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Table 6. Potential substitution options for Tellurium in main uses

Use	Share*	Substitutes	Sub share	Cost	Performance
Thermo-electric modules	30%	Silicon-germanium	34%	Very high costs (more than 2 times)	Similar
Thermo-electric modules	30%	Bismuth selenide	10.0%	Similar or lower costs	Similar
Thermo-electric modules	30%	Organic polymers	10.0%	Similar or lower costs	Similar
Metallurgy	15%	Bismuth	8.0%	Similar or lower costs	Similar
Metallurgy	15%	Lead	8.0%	Similar or lower costs	Similar
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Metallurgy	15%	Phosphorus	8.0%	Similar or lower costs	Similar
Metallurgy	15%	Selenium	8.0%	Similar or lower costs	Similar
Metallurgy	15%	Sulphur	8.0%	Similar or lower costs	Similar
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Solar power	40%	Silicon wafer	94.9%	Similar or lower costs	Similar
Solar power	40%	CIGS thin film	1.0%	Slightly higher costs (up to 2 times)	Similar
Solar power	40%	Amorphous silicon thin film	0.1%	Similar or lower costs	Similar
Chemical manufacture	10%	various	50.0%	Similar or lower costs	Similar

*share for global estimates of tellurium end uses, 2019 (SDTA; SCRREEN, 2019)

SOLAR POWER

There are three alternatives as thin film solar panels:

- *Amorphous silicon solar panels*. These use very little toxic material and are less liable to cracks compared to traditional panels.
- *Copper gallium indium diselenide (CIGS) solar panels*. These offer high efficiency, similar to traditional silicon panels and they use toxic cadmium at lower levels than CdTe panels. The main disadvantages of CIGS panels are high production costs.
- *Organic photovoltaic (OPV) cells.* OPV cells also struggle with the efficiency, but they offer a lot of benefits for the building-integrated photovoltaic market, as they can be coloured or made transparent to fit the purpose. (Energysage, 2019)

The criticality of the materials used in the alternatives should be considered. Silicon, indium and gallium were all assessed as being 'critical' in previous and/or current EU criticality assessments (European Commission, 2014, 2017, 2020).

Indium, gallium and selenium are like tellurium in that they are by-product metals.

THERMO-ELECTRIC MODULES

Bismuth selenide and organic polymers can be used to substitute for some BiTe thermal devices. (Bismuth Telluride (BiTe)

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METALLURGY

In free-machining steels several materials can be used instead of tellurium: bismuth, calcium, lead, phosphorus, selenium, and sulphur.

RUBBER VULCANISING

Selenides and sulphides can be used as substitutes for tellurium in the vulcanisation process in rubber production.

CHEMICAL MANUFACTURING

Tellurium as a catalyst can be replaced by other catalysts or non-catalysed processes. Alternatives for niobium and tantalum tellurides as electrical-conducting solid lubricants are selenides and sulphides of those metals.

SUPPLY

EU SUPPLY CHAIN

Tellurium is mined in one location in the EU, at the Krankberg Mine in the Boliden Area of Sweden as a by-product of gold mining. Boliden, also operates a smelter/refinery at Rönnskär in Sweden, which recovers tellurium in addition to other metals. Reported production of refined tellurium within the EU (i.e. from Sweden and Bulgaria) amounted to an average of 44 tonnes per year (averaged over the 2016-2020 period). The largest amount is produced in Sweden (around 40 tonnes annually). The annual production of 60 tonnes of copper telluride with a 15 wt.% tellurium content in Finland is referred by the Eurostat data. EU imported annually around 254 of tellurium during 2016-2020. Over the 86% of Te amount is imported by Philippines and Canada (Eurostat, 2021). The average imported amount of tellurium in EU in the same period was about 507 tonnes, while the respective exports of intermediate products containing tellurium reached 346 tonnes (Eurostat, 2020).

Aurubis operates copper refineries in Germany and Bulgaria and tellurium is known to occur in the anode slimes at these refineries. Although the company mentions that tellurium is a recovered by-product no details are provided as to what form it takes or what happens to it. Atlantic Copper operates a refinery in Spain that recovers copper telluride from its anode slimes. This material is then further refined elsewhere.

Metallo Chimique operates a copper refinery in Belgium, which is believed to have a small amount of tellurium in its anode slimes but these are sold as “tankhouse slimes” to other companies for treatment and recovery of those metals. One company that processes these kinds of anode slimes is Umicore, located in Hoboken, Belgium.

KGHM operate a copper refinery in Poland that may have a very small amount of tellurium in its anode slimes, but there is nothing on the company website to suggest that it is actually recovered. There are also copper refineries in Austria, Cyprus, Finland and Italy but there is no information available as to whether tellurium occurs in the anode slimes of those plants. Not all of these copper refining plants source the feed material from within the EU. Similarly not all copper that is mined in the EU is refined within Europe.

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Copper mines are known to exist in many European countries but it is not known whether these deposits contain any tellurium. Similarly gold is mined in Europe but, other than Sweden, it is not known whether any of these other mines contain by-product tellurium. Gold ores mined in Finland are known to contain small concentrations of tellurium (in the range of 1-10 ppm), but there is no information available indicating that any of tellurium is recovered (GTK, 2019).

SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF TANTALUM

GEOLOGY

Tellurium is one of the rarest elements in the earth's crust with an abundance of only 10 parts per billion (ppb). It is also widely distributed meaning that concentrations which are sufficient in size to allow economic extraction in their own right are rare. Tellurium rarely occurs as a native metal, it is more commonly found in compounds with precious or base metals, primarily as tellurides but other compounds also exits.

It is a chalcophile element, meaning it preferentially combines with sulphur rather than oxygen, but it cannot easily replace sulphur in a compound because it has a much larger ionic radius. Instead it preferentially forms tellurides with metals of large ionic radii such as gold, silver, bismuth, lead, mercury, and the platinum group elements.

Tellurium can occur in a wide range of deposit types including magmatic, metasomatic and hydrothermal types. It occurs especially in association with epithermal gold and silver vein deposits, which are formed by relatively low-temperature hydrothermal processes (<300°C) at shallow crustal depths, but it is also frequently present in copper or copper-gold porphyries, and sulphide deposits containing copper, nickel, lead, or iron.

GLOBAL RESOURCES AND RESERVES:

Global reserves are listed inTable 7. The largest reserves are located in China, followed by Peru, and the USA. In total there are about 31,170 t of tellurium reserves worldwide. Resources are not documented, as the main source (90% of total production) for tellurium is anode slime from copper refining. However, potential sources include bismuth telluride and gold telluride ores. (USGS, 2019).

Table 7. Global reserves of Tellurium in year 2021 (USGS, 2022)

Country	Tellurium Reserves (t)
United States	3,500
Canada	800
China	6,600
Sweden	670
Other countries	19,000
World Total (rounded)	*31,000*

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The reserves estimated by USGS include only tellurium contained in copper reserves assuming that more than half of tellurium contained in unrefined copper anodes is recoverable.

In 2018, a project by Deer Horn Capital Inc. moving towards pre-feasibility in Canada was reported, with indicated resources of 414,000 t containing 5.12 g/t gold, 157.50 g/t silver, and 160 ppm tellurium (66,000 kg Tellurium contained), as well as inferred resources of 197,000 t at 5.04 g/t gold, 146.50 g/t silver and 137 ppm tellurium (27 t Tellurium contained). (Cleantech, 2018; Deer Horn Capital, 2019)

EU RESOURCES AND RESERVES

According to Minerals4EU (2019) about 3,200,000 t reserves of tellurium ores are located in the EU and 2,100,000 t resources of tellurium ores, all of which are located in Sweden.

There is continuing exploration at Kankberg mine (Sweden) to explore further gold resources and reserves, but with this also tellurium resources are expanded as they are recovered as a by-product of gold production at Kankberg. (Geological Survey of Sweden, 2016)

Table 8. Resource and Reserve data for the EU compiled in the European Minerals Yearbook at Minerals4EU (2019)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Sweden	FRB-standard	0.11	Mt	149 g/t	Measured
Sweden	FRB-standard	0.15	Mt	205 g/t	Indicated
Sweden	FRB-standard	1.89	Mt	232 g/t	Inferred
Sweden	FRB-standard	0.88	Mt	172 g/t	Proven
Sweden	FRB-standard	2.39	Mt	185 g/t	Probable

Resources may also exist in other countries that did not respond to the survey. Copper resources are known to exist in at least 18 European countries and gold resources in 19 European countries, as well as Sweden, and it is likely that some of these resources also contain tellurium which is not reported as a resource because it is a by-product. (Minerals4EU, 2019)

GLOBAL AND EU MINE PRODUCTION

The vast majority of the tellurium produced worldwide is as a by-product of electrolytic copper refining with smaller quantities extracted as a by-product of gold, lead or other metals. Within the EU, tellurium is mined as a by-product of gold at the Krankberg Mine in the Boliden Area of Sweden and it is also refined nearby at the Rönnskär Smelter (Boliden 2018). The global tellurium production since 1984 according to WMD data and since 2000 according to USGS data is presented in Figures 2 and 3 respectively (WMD, since 1984; USGS, since 2000). Sweden produced 7.1% of world supply between 2016 and 2020. A minor production in Bulgaria, 0.7% of the global, is also reported among EU countries. The largest supplier is China providing 68% of available tellurium (years 2016-2020). Further suppliers include Japan (9%), and Russia (7.3%). US productions seems to have been significantly decreased between 2016 (50 tonnes) and 2020 (2 tonnes). A dramatic global tellurium increase has been taking place since 2015 due to beginning of production in China which the previous years was negligible.

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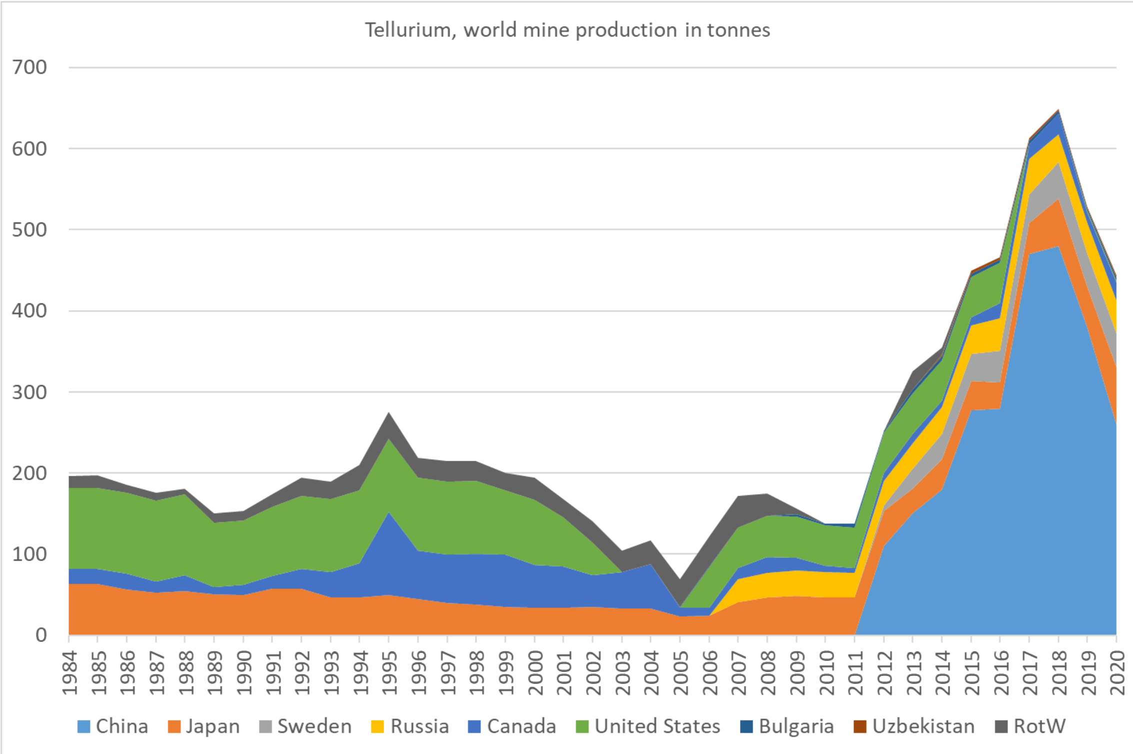

Figure 11. Global tellurium production since 1984 (WMD, since 1984).

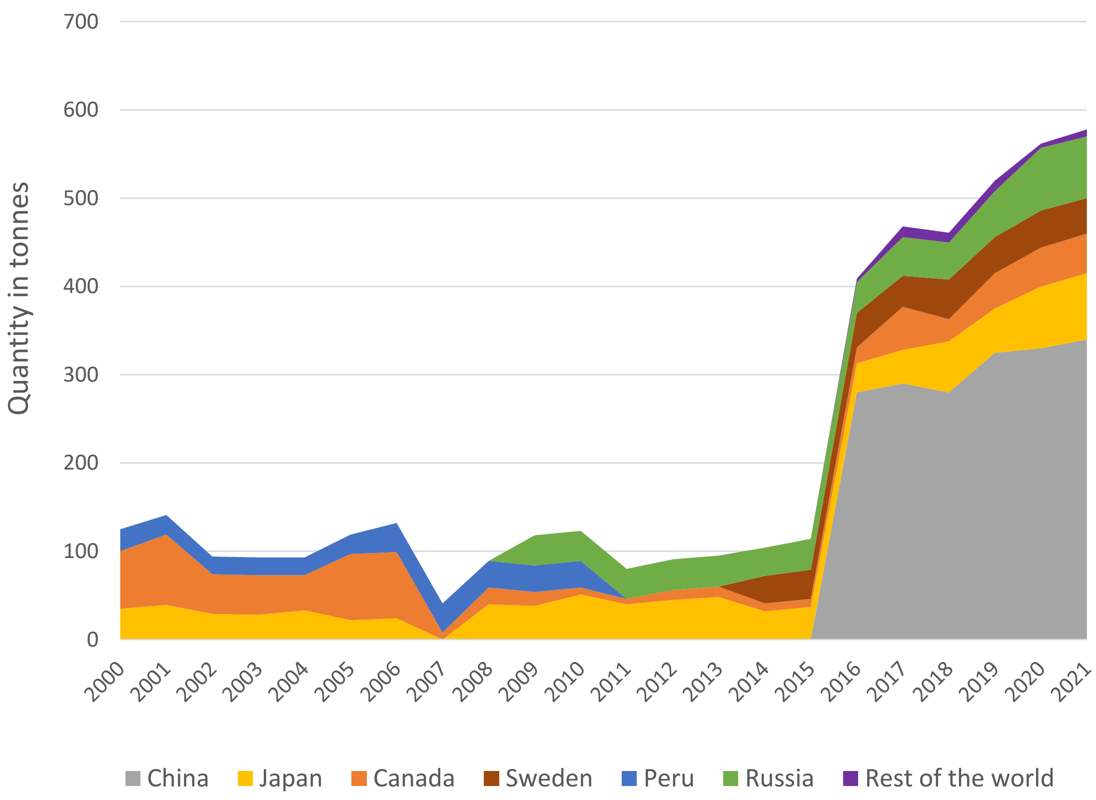

Figure 12. Global tellurium production since 2000 (USGS, since 2000).

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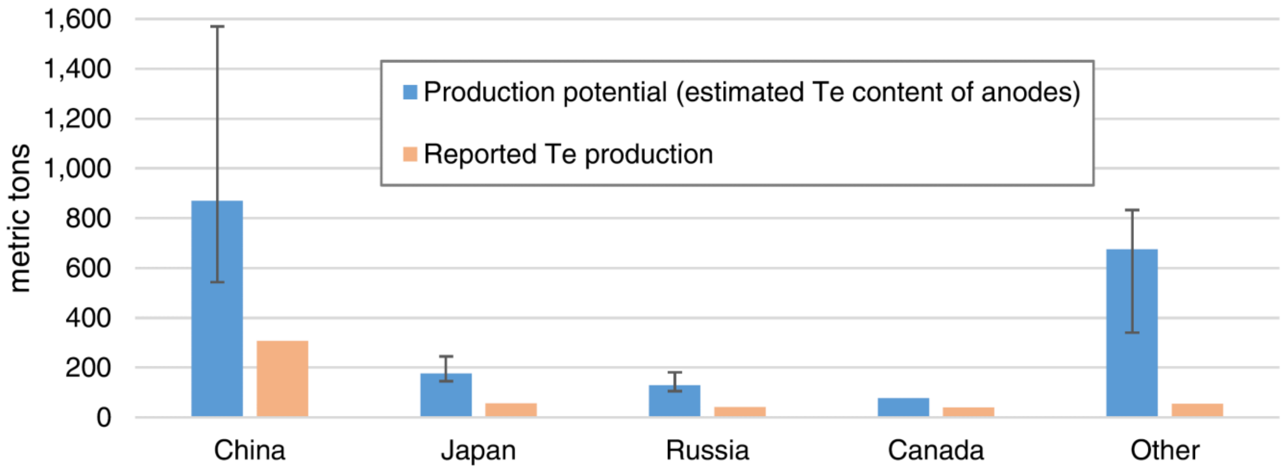

Figure 13. Current and potential Te production by country by Cu anodes (Nassar et al. 2022).

Over 90% of the world's Te supply is reportedly recovered from the anode slimes generated during electrolytic Cu refining, while the rest amount is produced lead (Pb) refineries and deposits enriched in Te minerals. Therefore, the supply of the metal is directly depended on the copper refining industry growth. It has been estimated that the potential of supply increase is high, since only the 26% of Te-containing anodes are metallurgically processed (Figure 14). However, the supply growth in short term is unknown taking into account: the closure of several refineries the past two decades in China and the gradual replacement of copper pyrometallurgical smelting and electrolytic refining with alternative techniques (i.e. solvent extraction-electrowinning) (Nassar et al. 2022).

PROCESSING

To reach the refining stage, copper, and its associated by-products including tellurium, undergo a number of processing stages. These include traditional mining techniques (either underground or from surface mines), crushing and grinding, froth flotation, roasting, smelting and the conversion of matte to copper blister. At each stage a proportion of the tellurium is lost in tailings or residues.

Electrolytic refining uses slabs of copper blister as anodes and pure copper or stainless steel as cathodes immersed in an electrolyte. An electrical current is passed through the electrolyte and as the anodes dissolve, copper atoms transfer to the cathodes. Tellurium is either insoluble during this process, settling to the bottom of the electrolytic cell into what is known as 'anode slimes' or muds, or is held in suspension in the electrolyte. These muds or liquids can subsequently be treated to recover tellurium and/or other metals such as silver, gold or platinum group metals using a variety of proprietary techniques. The resulting tellurium-containing products, such as crude tellurium dioxide (approximately 70% Te), copper telluride (20–45% Te) or low grade tellurium concentrates (approximately 10% Te), are subsequently further refined to produce tellurium metal.

The recovery rate during the initial concentration stages is as low as 10%, during the smelting and converting stages the recovery is 50%, and during the treatment of anode slimes as much as 90% of the available tellurium

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is recovered. This is a reflection of the degree of attention focused on tellurium at each stage. During the initial concentration phases, the focus is on recovering copper or other base metals which will be more economically rewarding due to the larger quantities available. In contrast, where recovery of tellurium is carried out the equipment used is optimised to ensure the highest possible recovery rate of tellurium as this has become the focus (European Commission, 2017).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

Many of the end uses of tellurium are dissipative, meaning that very little material becomes available for recycling. Tellurium contents in metallurgical applications are too small to be separated during recycling processes with the result that they become further dispersed rather than concentrated. A very small quantity is currently recovered from end-of-life electrical products. In the future, more significant quantities of tellurium are likely to become available for recycling from cadmium-tellurium photovoltaic solar cells but this is a relatively new technology and few of the cells have reached the end-of-life stage so far.

It is reported that metallic tellurium and tellurium dioxide are produced by secondary resources in EU (Finland, Belgium) by Umicore and Aurubis however the produced amounts and the pyrometallurgical methodology which is followed are not specified. The secondary resources from which tellurium is extracted are: anode slimes from the copper refining industry, scrap from BiTe manufacturing and defective and end of life solar panels (umicore. com; aurubis.com).

There are many different indicators that can be used to assess the level of recycling taking place for any material. The United Nations Environment Programme (UNEP) estimated the 'end-of-life recycling rate' of tellurium as <1% (UNEP, 2011). This is measured as 'old scrap' sent for recycling as a proportion of the 'old scrap' generated. The UNEP report was not able to source or calculate any other indicators with regards to tellurium. For this criticality assessment, a slightly different indicator was required: the end-of-life recycling input rate (EOL-RIR). This measures the quantity of end-of-life scrap (i.e. 'old scrap') contained within the total quantity of metal available to manufacturers (which would also include primary metal and 'new scrap'). For tellurium, insufficient data was found to enable the calculation of EOL-RIR but as UNEP (2011) estimated EOL-RR as <1%, it was concluded that EOL-RIR must be very low.

According to recent studies on the criticality of raw materials, (Graedel and Miatto, 2022; Graedel et al. 2022), the recycling rate of tellurium remains extremely low (around 1%), while an important amount (5%) is dissipated during its use. Nevertheless, the potential recyclability of the metal through the application of novel technologies is high (85%).

First Solar Company has developed a methodology for tellurium recycling by spent CdTe PV modules through mechanical and hydrometallurgical processing. The methodology comprises the following steps (Perez-Gallardo et al. 2018) (Figure 15):

1) Dismantling, shredding and milling. The collected PV modules are reduced in a shredder and crushed into small pieces from 4 to 5 mm.

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2) Extraction of tellurium via leaching using a mixture of sulphuric acid and hydrogen peroxide to obtain tellurous acid (H_2TeO_3).

3) Solid–Liquid separation. After extracting the semiconductor materials, the liquids are separated from solid materials (i.e. glass).

4) Precipitation and filtration. The extracted liquor is treated by a three-stage precipitation process with an increasing pH using sodium hydroxide for pH control. The thickened slurry is filtered consisting a semiconductor material rich in tellurium.

5) Laminate foil/glass separation and rinsing.

LCA study of the specific method proved about 20% energy saving in comparison to the production of new panels by primary raw materials (Perez-Gallardo et al. 2018).

At present, the recovery of tellurium metallurgy is relatively costly and at the same time produces a large amount of waste liquid pollutants. Most of the obtained tellurium does not meet industrial requirements and needs further purification, thereby increasing production costs. Kunming University has developed a vulcanization-vacuum distillation process for the separation of tellurium and cadmium through the recycling of CdTe PV modules. Taking into the account of the expansion of photovoltaic technologies and the optimization of recycling processes, it is expected that recycling technologies, such as those of First Solar and Kunming University, will be commercialized in short term (Zhang et al. 2020).

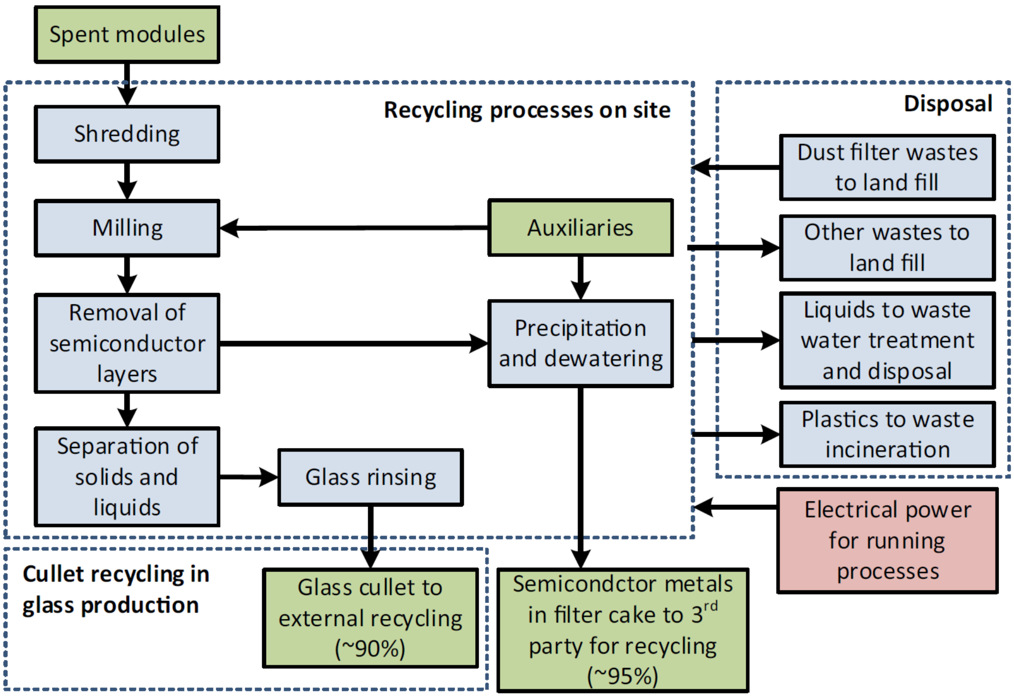

Figure 14. Simplified flowsheet of tellurium recycling by photovoltaic modules as developed by First Solar Company (Perez-Gallardo et al. 2018).

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OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Tellurium may damage fertility or the unborn child, is harmful if inhaled, causes allergic skin reactions, and may have long-lasting harmful effects on aquatic life (ECHA, 2021). Under the GESTIS international limit values with CAS[4] No. 13494-80-9 states that Finland and Norway Tellurium exposure 8-hour limit is of 0.1 mg/m^3 and Latvia's and Romania's is 0.01 mg/m^3 and 0.05 mg/m^3 respectively (IFA, 2021).

According to the Gestis substance database, tellurium when used has a risk of explosion when in contact with air (with tellurium dust) and bromine pentafluoride (with tellurium powder). In addition, tellurium can react dangerously with chlorine, fluorine, beryllium (rare), metal powder; chlorine fluoride; chlorine trifluoride; oxygen difluoride (heat); potassium (heat); lithium silicide; sodium (heat); silver bromate; silver iodate; zinc (heat); tin (heat). It has an LC_{50} inhalation value of > 2,42 mg/l/4 h and a LD_{50} oral value of > 5000 mg/kg (IFA, 2022; PubChem, 2022)

The National Institute for Occupational Safety and Health of the United States (NIOSH, USA) recommends a permissible exposure limit of 0.1 mg/m^3 in the air for Tellurium and compounds, and 0.2 mg/m^3 for tellurium hexafluoride for exposure for up to 10 hours' time-weighted average during a 40-hour week (NIOSH, 2020).

ENVIRONMENTAL ISSUES

This substance may be released into the environment as a result of industrial abrasion processing having a low release rate (e.g. cutting of textile, cutting, machining or grinding of metal). In addition, the low release rate of this substance can also occur from outdoor use in long-life materials (e.g. metal, wooden and plastic construction and building materials) and indoor use in long-life materials with low release rate (e.g. flooring, furniture, toys, construction materials, curtains, foot-wear, leather products, paper and cardboard products, electronic equipment) (ECHA, 2021).

This substance can be hazardous to the aquatic environment, being labelled as a Chronic Category 4; H413 and therefore its release to the environment should be avoided as indicated in the precautionary statement standards (P273) (IFA, 2022; PubChem, 2022).

NORMATIVE REQUIREMENTS RELATED TO THE USE AND PROCESSING OF THE MATERIAL

Technical rules for the use of Tellurium can be found in the GESTIS Substance database[5]. In addition, Tellurium is included under the German regulation of accident insurers[6] for the use of respiratory protective equipment published in November 2021.

[4] CAS Registry Number also referred to as CAS RN or CAS Number.
[5] See https://gestis-database.dguv.de/data?name=007520
[6] See https://publikationen.dguv.de/regelwerk/dguv-regeln/1011/benutzung-von-atemschutzgeraeten

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SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF TELLURIUM FOR EXPORTING COUNTRIES

No data is available.

SOCIAL AND ETHICAL ASPECTS

No information is available linking tellurium to particular social or ethical aspects.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

No research and development trends could be identified.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- BioMatCh[7] project (2014 – 2015, FP7, EU)

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