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**

GERMANIUM

AUTHOR(S):

TABLE OF CONTENT

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

GERMANIUM

OVERVIEW

Germanium is a chemical element with symbol Ge and atomic number 32. It is a lustrous, hard, brittle, crystalline and greyish-white metalloid in the carbon group, chemically similar to its group neighbours tin and silicon. It resembles a metal; however, it also displays non-metal characteristics, such as semi conductivity. Purified germanium is a semiconductor, with an appearance most similar to elemental silicon. Like silicon, germanium naturally reacts and forms complexes with oxygen in nature. Unlike silicon, it is too reactive to be found naturally on Earth in the free (native) state. Germanium was on the list of CRMs in 2011, 2014 and 2017.

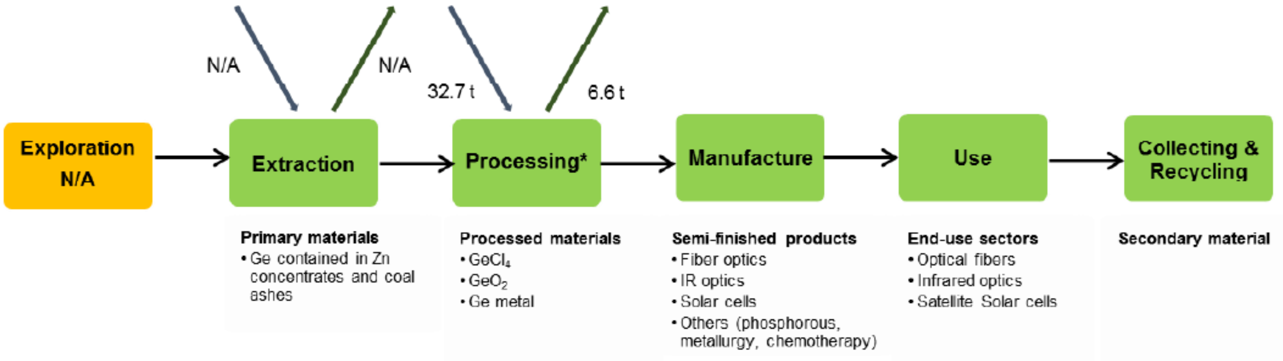

Figure 1: Simplified value chain for germanium for the EU, averaged over 2012-2016

Table 1. Germanium supply and demand in metric tonnes (processing stage), 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
111	China 83% Russia 5% Belgium 4% Germany 3% Japan 2% USA 2% Ukraine 1%	13.8	12.5%	China 45% Belgium 32% Germany 19% UK 2%	42%

Price: The annual price varied from 1357€/kg in 2003 to 877€/kg in 2020 (USGS, 2021a) with a minimum of 336€/kg in 2003 and a maximum of 1616€/kg in 2015. The price changes of germanium (metal and dioxide) have been influenced by supply and demand effects. For example, a partial force majeure on the Canadian production and the establishment of new environmental policies in China led to the increased price in 2018 (USGS, 2021).

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

Primary supply: Large uncertainties exist on germanium primary production. Between 100 (WMD, 2022) and 130 tonnes (USGS) of germanium were reported between 2016 and 2020. No EU production is reported by WMD and USGS however, DERA estimates EU production at 8 tonnes per year. China is the major producer with about 80% of the global production.

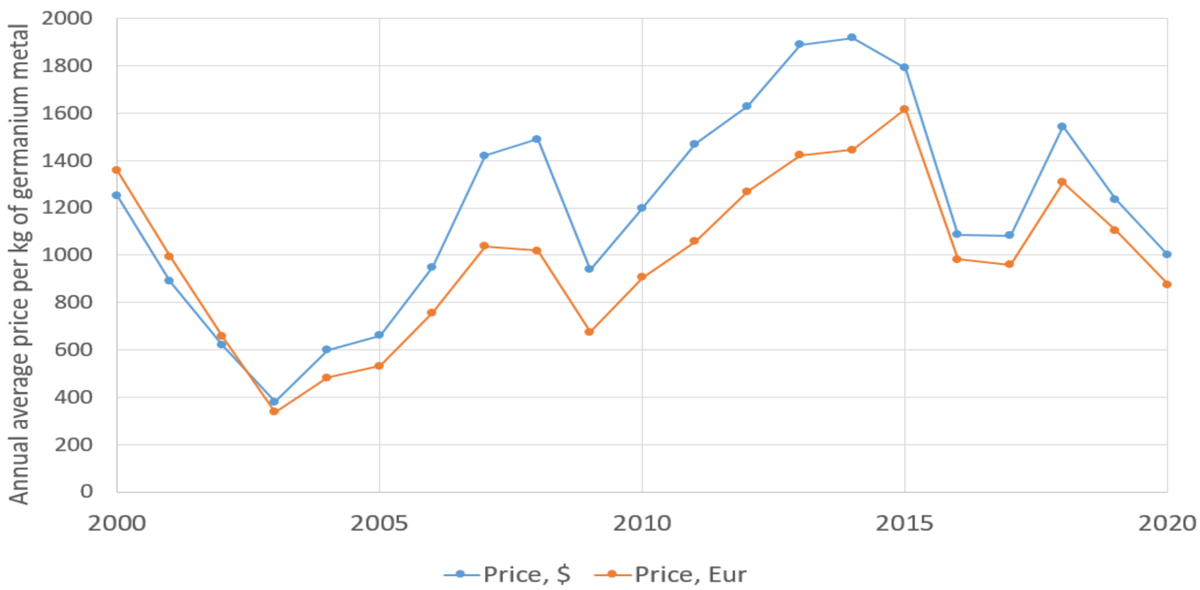

Figure 2. Annual average price of germanium metal between 2000 and 2020 (based on USGS, 2021a).

Secondary supply: USGS (2019) estimated that around 30% of global germanium production is supplied by recycling, mostly from scrap generated during the manufacture of fibre-optic cables and infrared optics. Due to the value of refined germanium, this scrap is reclaimed and fed back into the production process at a rate of 60%. There are two large global recyclers and refiners of zinc with combined germanium production in the EU (Melcher, F. and Buchholz, P., 2013).

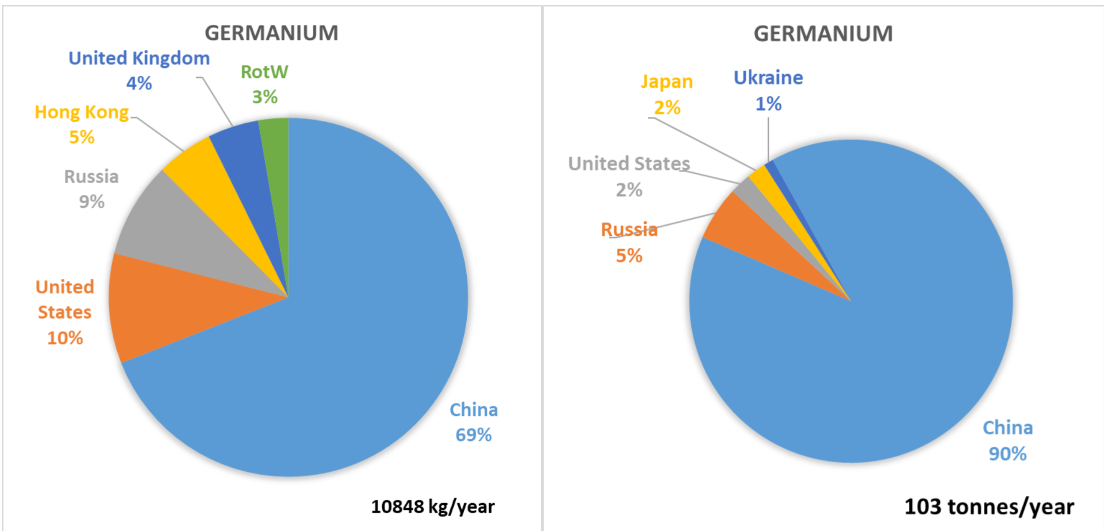

Figure 3. EU sourcing of germanium (Eurostat 2022) and global mine production (WMD 2022), average 2016-2020. According to DERA 8 tonnes could be added for EU production, i.e. about 7%

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

Uses: Germanium is used in several applications such as fibre optics, IR optics, wafers for satellites solar cells, IT applications, PET catalyst etc. Some of these end-uses, such as PET catalysts and IT applications, are not occurring in the EU (SCRREEN, 2022).

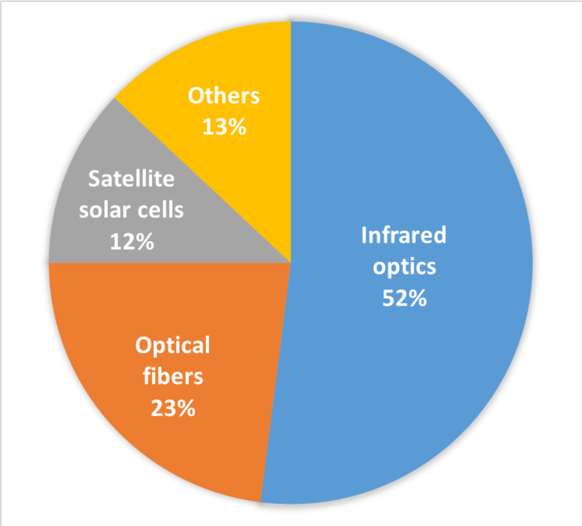

Figure 4: EU end uses of germanium (DG GROW 2023).

Substitution: Various alternatives are available for the substitution of germanium in some of its applications (mainly the IT applications and catalysts applications, not relevant for the EU scope). However, many of these substitutes result in a loss of performance.

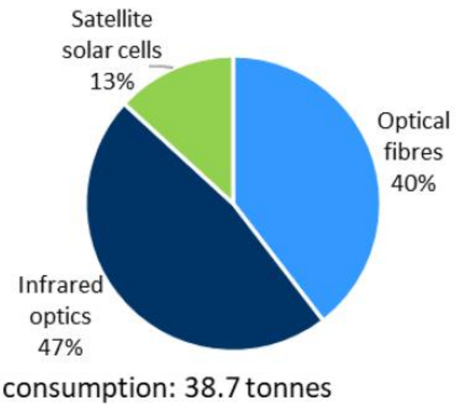

Figure 5: End uses with estimated quantity of EU consumption in 2012-2016 (SCRREEN, 2019)[1]

Other considerations: Germanium is a non-toxic element, except for a few compounds. Germanium in the ppm range, when dissolved in drinking water may cause chronic disease (Melcher, F. and Buchholz, P.,2013). Germanium and its compounds are suspected of damaging fertility or the unborn child, may cause damage to organs through prolonged or repeated exposure and is harmful to aquatic life with long-lasting effects (European Chemical Agency 2021; Gerber and Léonard 1997). With environmental regulations becoming more stringent, the ecological footprint of germanium recovery from coal starts to get more attention. An LCA study

[1] EU consumption is estimated and includes germanium oxides and germanium tetrachloride, based on the quantity of EU import for both products reported in criticality assessment 2017 EU import of unwrought and powder germanium

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

has demonstrated the ecological benefit of other sources, such as recycling of Ge from Zn-based ores (Robertz, Benedicte, Jensen Verhelle, and Maarten Schurmans, 2015). More than 40 years of coal mining and germanium processing in Lincang, West Yunnan have been causing releases of radionuclides into the environment affecting public health in the long-term. The average radiation of the natural radionuclide ^{238}U in the coal ores is 624 Bq/kg, while the maximum threshold limit is 2.17 kBq/kg. (Yang, 2005; Yu, 2007, Wang et al, 2022).

Table 2. Uses and possible substitutes

Application	Share	Substitutes	SubShare	Cost	Performance
Infrared optics	52	Zinc (selenide and sulphide)	25%	Similar or lower costs	Reduced
		Tellurium	25%	Similar or lower costs	Reduced
		Silicon	10%	Similar or lower costs	Reduced
		Fluorine	5%	Similar or lower costs	Reduced
		Selenium	5%	Similar or lower costs	Reduced
		Arsenic	5%	Similar or lower costs	Reduced
		No substitute	25%		No substitute
Optical fibers	23%	Phosphorus	3%	Similar or lower costs	Similar
		Aluminium	3%	Similar or lower costs	Reduced
		Photonic Crystal Fibers	2%	Similar or lower costs	Reduced
		Fluorine in cladding	3%	Similar or lower costs	Reduced
		Boron in cladding	3%	Similar or lower costs	Reduced
		No substitute	86%		No substitute
Satellite solar cells	12%	InGaP, AlGaInP, InGaAsP, InGaAs	0%	Similar or lower costs	Reduced
		Silicon	10%	Similar or lower costs	Reduced
		No substitute	90%		No substitute

Other considerations: Germanium is a non-toxic element, except for a few compounds. Germanium in the ppm range, when dissolved in drinking water may cause chronic disease (Melcher, F. and Buchholz, P.,2013). Germanium and its compounds are suspected of damaging fertility or the unborn child (European Chemical Agency 2021; Gerber and Léonard 1997). With environmental regulations becoming more stringent, the ecological footprint of germanium recovery from coal starts to get more attention. An LCA study has demonstrated the ecological benefit of other sources, such as recycling or Ge from Zn-based ores (Robertz, Benedicte, Jensen Verhelle, and Maarten Schurmans, 2015). More than 40 years of coal mining and germanium processing in Lincang, West Yunnan have been causing releases of radionuclides into the environment affecting public health in the long-term (Yang, 2005; Yu, 2007, Wang et al, 2022).

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

MARKET ANALYSIS, TRADE AND PRICES

Global Market

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
111	China 83% Russia 5% Belgium 4% Germany 3% Japan 2%	13.8	12.5%	China 45% Belgium 32% Germany 19% UK 2%	42%

The germanium market can be segregated into North America, Latin America, Europe, Asia Pacific, and Middle East & Africa. Asia Pacific dominated the germanium market in 2017. China, Russia, and the U.S. are the leading producers of germanium, with China contributing to a majority of the supply (86 out of 130 tonnes globally). Several events that took place in China have contributed to the change in price of germanium, such as the application of export tax on germanium dioxide, the closure of a Chinese germanium dioxide plant owing to environmental concerns, stockpiling activities, and the collapse of FANYA metal exchange (USGS, 2021). Primary germanium was also recovered from zinc residues in Belgium and Canada (concentrates shipped from the United States), zinc residues in Finland, and coal ash in Russia.

The germanium market is highly dependent on China. The government of Yunnan Province, a significant area of non-ferrous and minor metals production in China, created a stimulus plan directing companies to purchase and stockpile non-ferrous metals in response to lower demand caused by the COVID-19 pandemic.

Under the plan, the government had targeted a "commercial" stockpile of about 800,000 tonnes of metals, including 20 tonnes of germanium, and set aside $141 million to subsidise the interest on any loans taken out by companies to stockpile these metals. China's germanium exports in January through August 2020 increased by 18% compared to the same period of 2019. A leading Chinese producer of processed germanium products, based in Yunnan Province, reported that production of germanium wafers for satellites in January through June 2020 was more than seven times higher than wafer production in the first half of 2019 as production ramped up at its new germanium wafer production line.

China imposed a 5% export tax on germanium oxide throughout 2012-2016 (OECD, 2019). According to OECD database of export restrictions on Industrial Raw Materials, this restriction has been lifted in April 2015. A specific code for germanium tetrachloride in trade statistics is not available.

EU Trade

Figure 6 shows the EU trade flows of CN 81129295, unwrought germanium; germanium powders from 2000 to 2020. The trade balance figures (i.e., imports minus exports) showed that EU was a net importer of unwrought germanium. The annual EU imports of unwrought germanium was on average 10.870 t. It ranged from 8.768 t in 2016 to 6.956 t in 2020 with a peak at 21.237 t in 2018. EU exports were lower than imports, with average annual exports of 5.073 t.

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

Table 4. Relevant Eurostat CN trade codes for germanium

Processing/refining	
CN trade code	**title**
8112 92 95	Unwrought; waste and scrap; powders: Germanium
8112 99 40	Other: Germanium

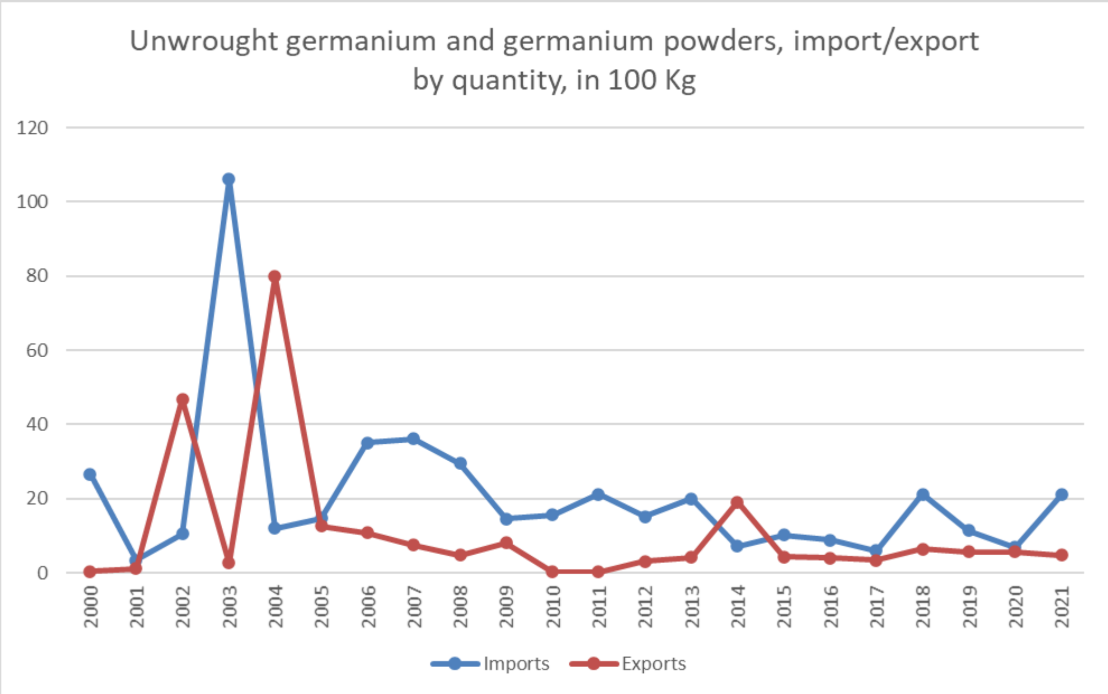

Figure 6. EU import and export of unwrought germanium and germanium powders by quantity (HS811230 (2000-2006) and HS81129295 (2007-2020)). Source: Eurostat, 2022

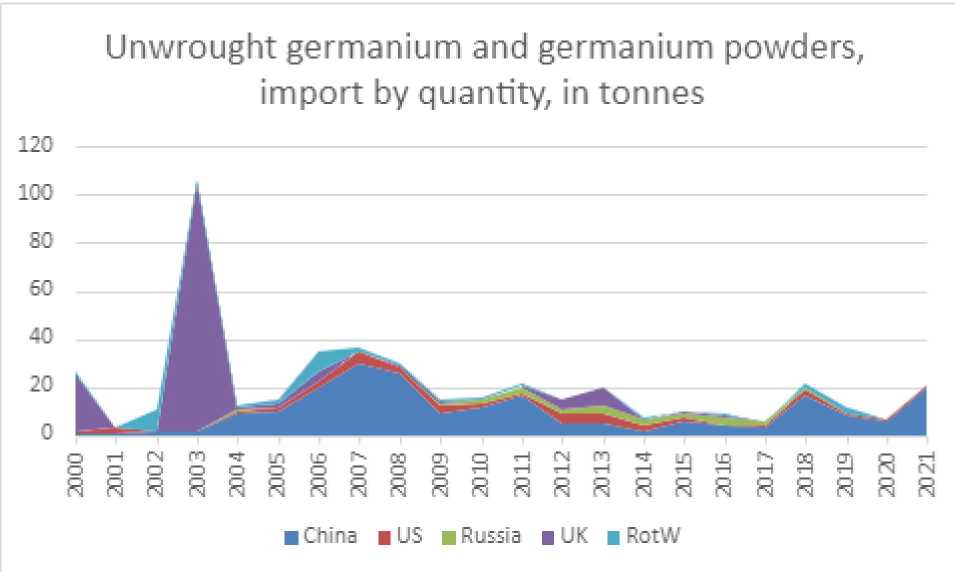

Figure 7. EU import of unwrought germanium and germanium powders by quantity (HS811230 (2000-2006) and HS81129295 (2007-2020)). Source Eurostat, 2022

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

Figure 7 shows the EU imports of unwrought germanium and powders by country of origin. China supplied a major part of germanium to the EU, accounting for 68% of total EU import. China was followed by the United States and Russia, with 10% and 8% of EU import subsequently.

There are no reports of EU trades for germanium ores and concentrates (HS code unknown), germanium waste, and scrap HS 1230 and 81123040). These categories are not currently accounted for in the EU trade flows. As well, germanium oxide is mixed with zirconium oxide in the reports (HS282560) and never alone (HS28256010). Therefore, HS282560 does not bring any added value in the analysis.

Price and Price Volatility

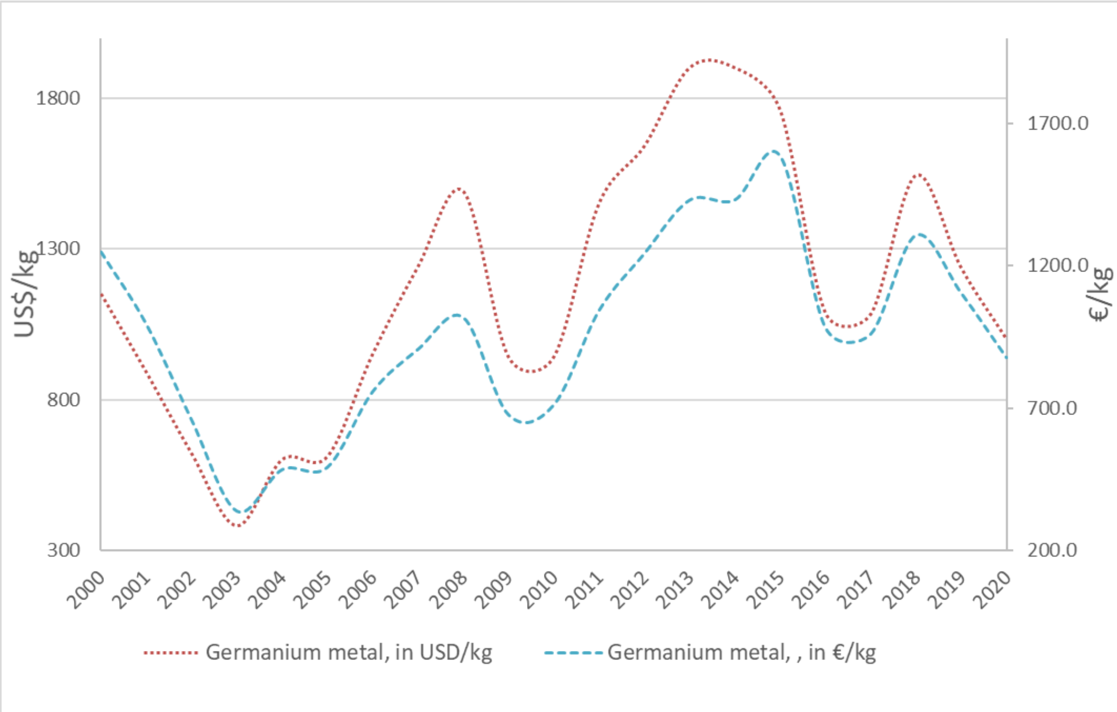

Figure 8. Annual average price of germanium metal between 2000 and 2020 (USGS, 2021)[2].

The price changes of germanium (metal and dioxide) have been influenced by supply and demand effects. For example, a partial force majeure on the Canadian production and the establishment of new environmental policies in China led to a price increase in 2018 (USGS, 2021; DERA, 2021). Regarding the demand impact, there was a decrease of demand for fibre-optic cable and related industries in the US as result of the COVID-19 pandemic in 2020 (USGS, 2021). However, the demand impact on germanium prices is expected to be indirectly offset by the US government through a plan for increasing broadband infrastructure in rural areas and the increase of remote work. Furthermore, the government of China's Yunnan province developed a stimulus plan to support business on stockpiling nonferrous metals as response to the decreasing demand due to COVID-19 pandemic (Daly, 2021). This plan influenced germanium exports from China, which increased by 18% in August 2020 compared to the same period in 2020 (USGS, 2021).

[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)

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

OUTLOOK FOR SUPPLY AND DEMAND

Since the market for germanium is small, it tends to be highly volatile. A higher price may result in increased interest shown by zinc refineries. According to experts, today's supply situation, which depends on China, is not a resource depletion issue, but the result of commercial terms (Umicore, 2019).

The development of germanium transistors has opened the door to countless applications of solid-state electronics, which has provided potential growth opportunities to the germanium market. The germanium market in Europe is anticipated to expand at a remarkable pace from 2018 to 2026 due to the rapid growth of the electronics industry. Latin America and Middle East & Africa also account for prominent shares of the global germanium market. This can be ascribed to the increase in demand for global germanium market in various end-user industries in these regions. The optical fibres segment is anticipated to dominate the global germanium market during the forecast period. Growth of the solar installation market is estimated to drive the global germanium market from 2018 to 2026.

It is worth noting that the COVID-19 pandemic has already had an impact on demand. For instance, demand for fibre-optic cable in the United States decreased during 2020 owing to decreasing demand from related industrial end use markets because of the COVID-19 pandemic. However, this decrease was partially offset by Federal funding to increase broadband infrastructure in rural communities and a nationwide increase in remote work. Domestic demand for fibre-optic cable was still expected to increase as wireless carriers continue to expand and upgrade their networks.

Figure 9. Global germanium market forecast in 2027. (https://www.globenewswire.com/fr/news-release/2022/02/03/2378561/28124/en/Insights-on-the-Germanium-Global-Market-to-2027-Featuring-5NPlus-Novotech-and-Umicore-Among-Others.html)

Demand forecast should also be balanced with the substitution potential of germanium. However, to date many of the substitutes for germanium result in a loss of performance and are therefore not optimal. Research on efficient germanium substitutes is currently in progress (Industrial-Player, 2016). Silicon can be a less-expensive substitute for germanium in certain electronic applications such as transistors (USGS, 2021). Some

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

metallic compounds can be substituted in high-frequency electronics applications and in some light-emitting-diode applications. Zinc selenide and germanium glass substitute for germanium metal in infrared applications systems, but often at the expense of performance. Antimony and titanium are substitutes for use as polymerization catalysts. There is currently no substitute for germanium in satellite solar cells, even if some researches are ongoing on semiconductor materials based on gallium and indium such as InGaP, AlGaInP, InGaAsP, InGaAs (Industrial-Player, 2016).

The Global Germanium Market size was estimated at USD 272.38 million in 2020, is expected to reach USD 280.23 million in 2021, and is projected to grow at a CAGR of 3.24% to reach USD 340.64 million by 2027.

Regarding trade restrictions, some countries (e.g., Russia and China) have imposed export taxes to germanium in the past decade, which limited the availability of EU trades for germanium (CRMAlliance, 2021). More recently, China has imposed non-automatic export licensing requirements for germanium, which means that the traders are required to obtain a prior approval in order to export germanium products. This measure also constrains the EU trade from the main supplier of germanium (OECD, 2021).

GERMANIUM DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

By taking into account the annual EU import of germanium unwrought and powders, EU domestic production and EU exports, the EU apparent consumption of germanium processed materials remained quite low until 2019 (between 5 and 15 tonnes per year during the last 10 years).

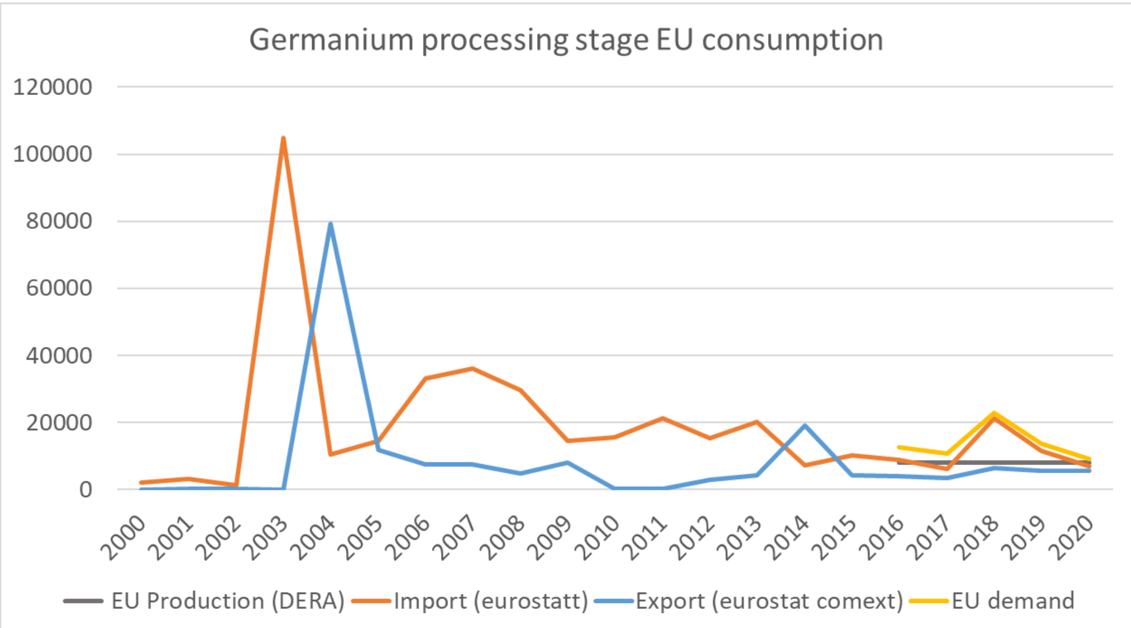

Figure 10. Germanium (HS codes 81129295 and 81123020) processing stage EU import, export, production and demand. Production data from DERA is only available for years 2016-2020 and therefore EU consumption is calculated only for 2016-2020. (Based on Eurostat Comext 2022). Consumption is calculated in Germanium content (EU production+import-export).

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

However, based on EUROSTAT (2022), in 2019 and 2020 there was a EU production of germanium (mainly in Germany) that increased the EU apparent consumption up to 136 tonnes in 2019 and 80 tonnes in 2020. These values were not considered in the criticality evaluation, the EU production being set at 8 tonnes per year according to DERA estimates. No other forms of germanium compounds are reported (oxide, chloride…)

In 2016-2022, the estimated EU consumption was 13.8 tonnes, approximately 12.5% of the world consumption. The import dependency was 42%

GLOBAL AND EU USES AND END-USES

According to Statista 2022, the global use of germanium in 2021 are the following: fibre optics 34%, infrared optic 22%, polymer catalysts for PET plastics 21%, and electronic and solar cells 17 %. The remaining 6% are used for illuminants, metallurgy, and chemotherapy. As shown in Figure 11, the applications of germanium remained quite stable along the last decade (USGS 2008, Curtolo et al. 2017, Buchholz, 2019).

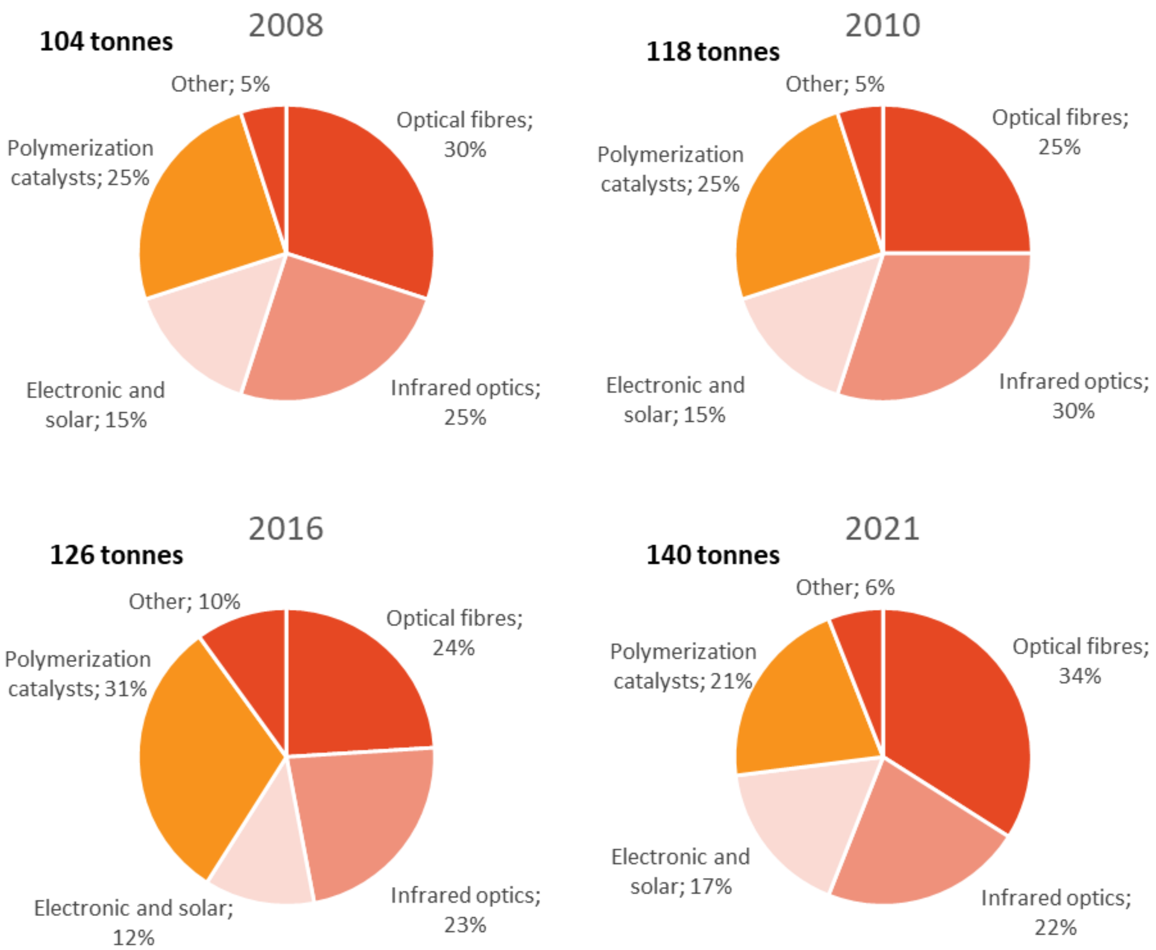

Figure 11: Global end uses of germanium (Statista 2022 and Buchholtz 2019).

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

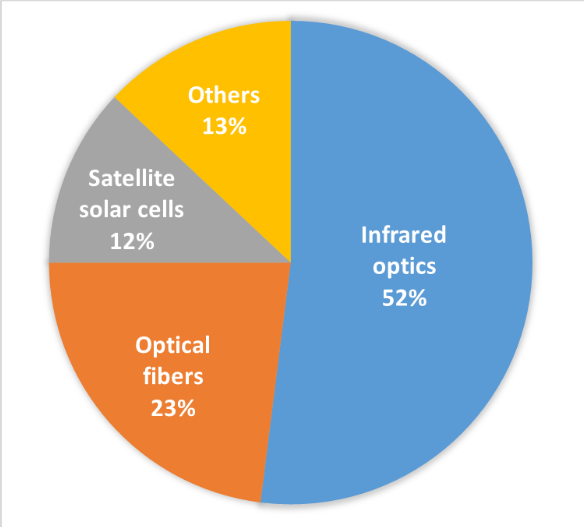

Figure 12: EU end uses of germanium (DG GROW 2023).

However, in the EU, germanium is used neither as PET polymerisation catalysts nor in the electronics industry. The main uses of germanium in the EU are infrared optics 52%, optical fibres 23% and satellite solar cells 12% as presented in Figure 12.

Relevant industry sectors in the EU for value added (up to 2019) are described using the NACE sector codes (Eurostat, 2022), presented in Table 5.

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

Applications	2-digit NACE sector	Value added (M€)	4-digit CPA
Optical fibres	C27 - Manufacture of electrical equipment	97,292	C2630- Manufacture of communication equipment; C2731 - Manufacture of fibre optic cables
Infrared optics	C26* - Manufacture of computer, electronic and optical products	84,074	C2670- Manufacture of optical instruments and photographic equipment
Satellite solar cells	C26* - Manufacture of computer, electronic and optical products	84,074	C2611- Manufacture of electronic components

* excludes value added from: Ireland; Cyprus, Latvia; Luxembourg; and Malta that have not declared values in recent years, although these will be relatively small compared to the overall total.

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

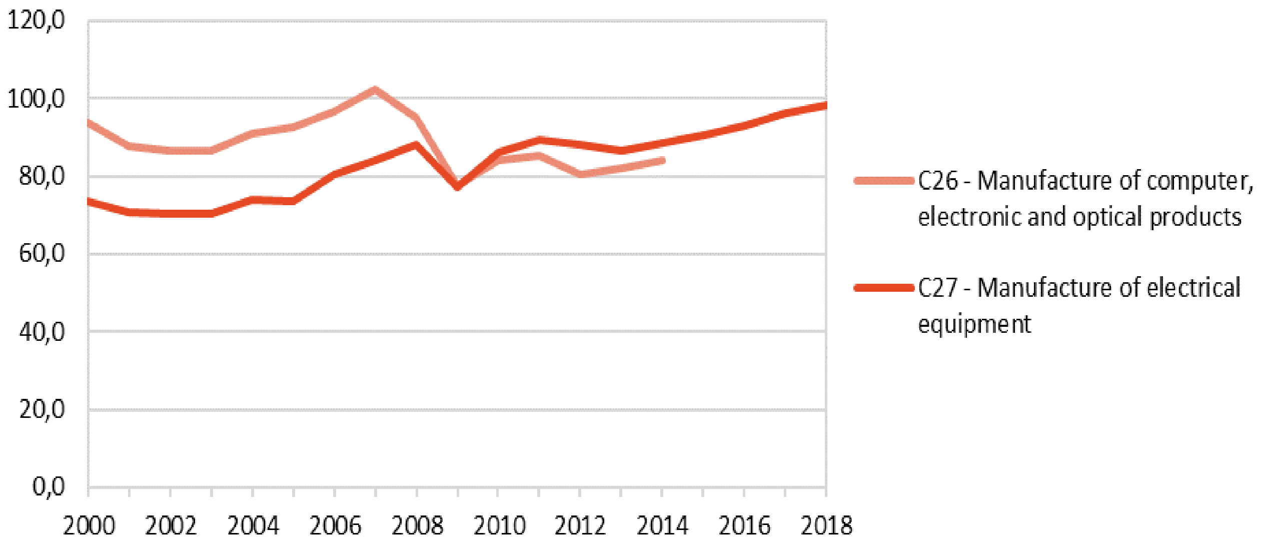

Figure 13. Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS OF GERMANIUM IN THE EU:

INFRARED OPTICS (47% OF SHARE)

Germanium is transparent to infrared radiation (IR) wavelengths, both as a metal and in its oxide glass form. For this reason, it is used to make lenses and windows for IR radiation. These are mainly used in military applications such as night-vision devices. Uses outside of the military are in advanced firefighting equipment, satellite imagery sensors and medical diagnostics.

FIBRE-OPTICS (40% OF SHARE)

Germanium oxide is used as a dopant in the core of optical fibres. Small quantities are added to the pure silica glass to increase its refractive index preventing light absorption and signal loss. This type of fibre is used for high-speed telecommunication. Over the past years, there has been substantial growth in this sector with increasing demand for more bandwidth.

SOLAR CELLS (13% OF END USE SHARE)

Germanium-based solar cells are mainly used in space-based applications but also in terrestrial installations. Demand for satellites has increased steadily from 2007 due to commercial, military, and scientific applications. The advantages of germanium substrates over the more common silicon-based solar cells are the smaller size and weight and higher efficiency (over 25%). These solar cells are not common in terrestrial applications because of the cost of their manufacture. However, since they are considerably more efficient at converting solar energy into electricity, fewer cells are required in a panel to produce equivalent amounts of power. It is thought that germanium-based cells will compete for a portion of the terrestrial market in the future.

Other uses in the EU include gamma-ray detectors and organic chemistry, phosphors, metallurgy, and chemotherapy.

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

FURTHER GERMANIUM USES OUTSIDE THE EU

POLYMERISATION CATALYSTS

Germanium dioxide is used outside the EU (and particularly in Japan) as a catalyst in the production of PET for plastic bottles, sheet, film and synthetic textile fibres. There is a drive to move towards different catalysts given the increasing price of germanium.

ELECTRONIC COMPONENTS

Germanium is used as a semiconductor in several electronic applications. Some examples are high brightness Light Emitting Diodes (LEDs) in devices such as cameras and smartphone display screens. Silicon germanium transistors have been replacing silicon-based components in high-speed wireless telecommunications devices due to the higher switching speeds and energy efficiency.

SUBSTITUTION

Various alternatives are available for the substitution of germanium in some of its applications (mainly the IT applications and catalysts applications, not relevant for the EU scope). However, many of these substitutes result in a loss of performance.

Table 6. Uses and possible substitutes

Application	Share	Substitutes	SubShare	Cost	Performance
Infrared optics	52	Zinc (selenide and sulphide)	25%	Similar or lower costs	Reduced
		Tellurium	25%	Similar or lower costs	Reduced
		Silicon	10%	Similar or lower costs	Reduced
		Fluorine	5%	Similar or lower costs	Reduced
		Selenium	5%	Similar or lower costs	Reduced
		Arsenic	5%	Similar or lower costs	Reduced
Optical fibers	23%	Phosphorus	3%	Similar or lower costs	Similar
		Aluminium	3%	Similar or lower costs	Reduced
		Photonic Crystal Fibers	2%	Similar or lower costs	Reduced
		Fluorine in cladding	3%	Similar or lower costs	Reduced
		Boron in cladding	3%	Similar or lower costs	Reduced
Satellite solar cells	12%	InGaP, AlGaInP, InGaAsP, InGaAs	0%	Similar or lower costs	Reduced
		Silicon	10%	Similar or lower costs	Reduced

IR OPTICS

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

The article "The Correct Material for Infrared (IR) Applications"[3], provides information on a range of IR material attributes and a comparison between materials and its uses (

Figure 14). Germanium is currently the only option for IR applications where the mix of high refractive index and hardness is crucial. However, increased research on the production of chalcogenide (CHG) could produce an alternative, but this is not currently available in the marketplace for commercial use.

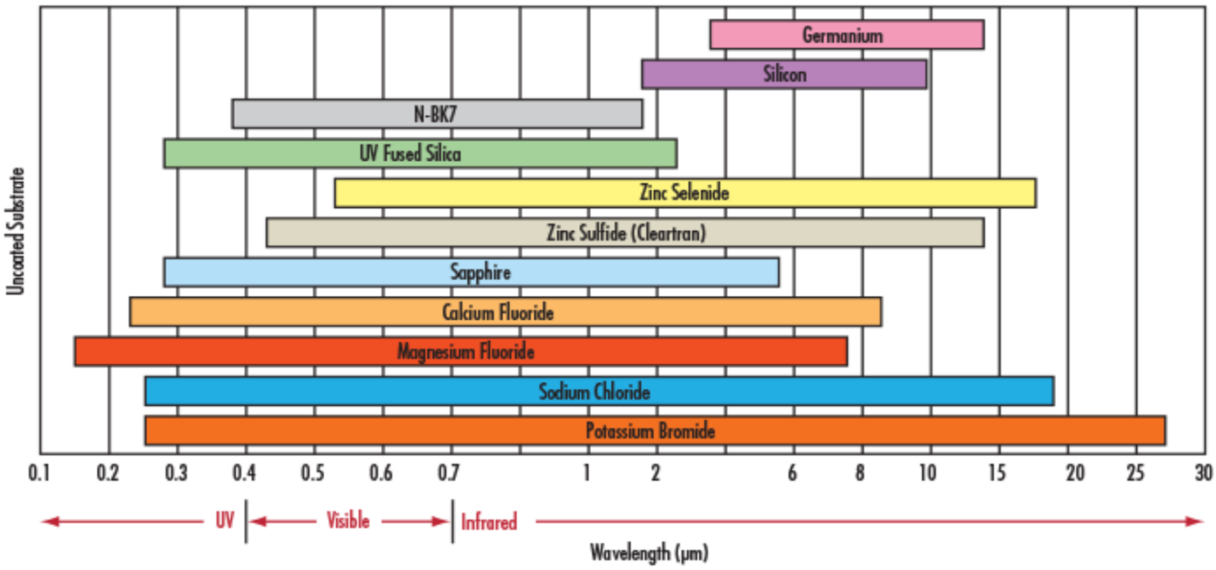

Figure 14. Range of properties for materials used in infrared optics[3]

FIBRE-OPTIC SYSTEMS

Germanium is required for the minimisation of losses in fibre-optics, and until now it has been considered that there are no alternatives that will keep losses to a minimum. Recent work is looking at the use of hollow core optical fibres that may have a similar or better performance.

Another option for substitution is to replace the use of fibre-optics entirely. In certain situations, the use of an open-air transmission system is being investigated. This is the use of open-air, or fibreless, optical transmission. In this system lasers, amplifiers, and receivers are used. The rate of transfer of data is higher than comparable radio or microwave systems and therefore could be considered as a replacement for optical fibre systems in the right conditions.

Another option for wireless transmission is the implementation of the wireless 5G standard. On the other hand, the effect is probably counteracted by 5G driving overall data traffic up and therefore requiring a stronger fibre-based backbone network (Allied Market Research, 2017; Fortune Business Insights, 2019; Mordor Intelligence, 2020).

[3] https://www.edmundoptics.co.uk/knowledge-center/application-notes/optics/the-correct-material-for-infrared-applications/

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

PET CATALYSTS

Although not used or manufactured in the EU, it is still important to consider potential substitutes as this may be a future opportunity for industry in Europe. There is continuing interest in identifying alternative catalyst systems for PET polymerisation. One such example is the use of titanate nanotubes. These are reported as having a lower cost of production, less toxic and having a high specific surface area, making them potential replacements.

A study has also looked at the use of group 14 dimetallenes and dimetallynes for catalysis (Lima et al. 2019, Hanusch et al. 2021). Germanium and tin catalysts are compared and suggestions for use of silicon-based catalysts are also considered.

SATELLITE SOLAR CELLS

This application currently has no substitution opportunities as germanium is used specifically for its performance, which makes the use for satellite solar panels unique. For earth based solar panels, the additional cost of germanium-based system is not economic as alternatives, although not as efficient, they are more cost effective.

ELECTRONICS

According to the US Geological Survey in the 2021 material summaries there remain the options for silicon to “substitute for germanium in certain electronic applications”. However, it remains the case that the electronic properties of germanium make it superior to silicon, and therefore only when these are non-critical would the substitution be appropriate.

GERMANIUM SUPPLY

EU SUPPLY CHAIN

Germanium production in EU, at the processing stage, is performed after 2019 at a small extent in Germany. The produced Ge amount in Germany was 114 kg and 72 kg in the years 2019 and 2020, respectively. The average annual imported amount of Ge in EU was 10.8 tonnes during the period 20116-2020, mainly by China. Around 4.6 tonnes of Ge were extracted during the same period mainly in Russia and United States (Eurostat, 2021).

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

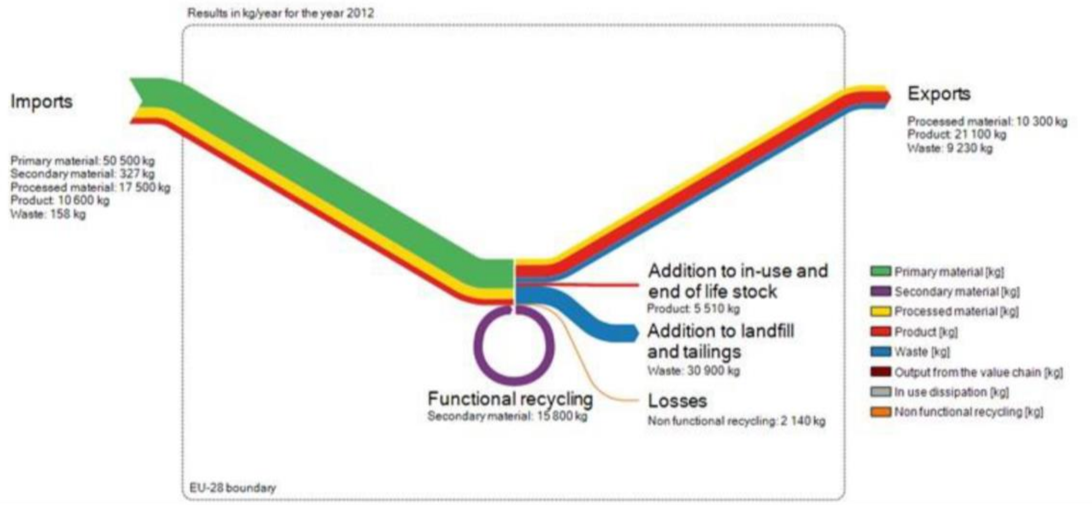

Figure 15. Simplified diagram of germanium MSA for 2012 (Bio Intelligence Service, 2015)

End-of-life recycling input rate (EOL-RIR) of Germanium, i.e. the recycled material fraction to the total production, is 2% (EIP Raw Materials, 2021).

In EU, germanium is recycled by Umicore from production scrap and waste streams from various industries such as fibre optics, solar cells, LEDs and infrared optics. Although end-of-life recycling presents significant challenges due to the dissipative nature of some of the applications, there is an increase in recycling opportunities by turning more and more complex waste streams to recycling flows (Umicore). Recent reports, describe a high recycling capability in US. The recycling rate is high in case of end-of-life devices used the military sector. Recycled germanium amount in US (2.2 to 3 tonnes) represents about the 10% of its total demands (defense.gov, 2022). Unfortunately, similar data are not available for EU.

EXTRACTION STAGE

Resources of germanium are known to exist in the EU. There were some very rich germanium mines in France and Austria but they all closed in the 1990's once empty (Bio Intelligence Service, 2015). However, there are no known reserves of germanium in the EU. In the past years, there was no germanium concentrates recovered neither from a European mine in activity, nor from coal ashes in the EU.

PROCESSING STAGE

World Mining Data reported that the production of germanium in Finland over the period of 2010-2015 was between 12 and 17 tonnes per year (World Mining Data, 2021). From 2012 to 2014, Finland produced some crude germanium dioxide (GeO2) from cobalt concentrates (mined in D.R. Congo by the owner of the Finnish refinery) with 80% of the final processed materials (GeO_2, $GeCl_4$ and Ge metal) exported outside the EU (Bio Intelligence Service, 2015). The Finnish plant stopped the production of germanium in 2015 (Bio Intelligence Service, 2015).

MANUFACTURING STAGE

The EU consumption of Ge processed materials are destined to the manufacturing of germanium processed products in the EU.

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

RECYCLING STAGE

Recylex in France with its subsidiary PPM Pure Metals Gmbh (Germany) and Umicore in Belgium are large global recyclers and refiners of zinc, both with combined germanium production. (Melcher&Buchholz, 2013).

SUPPLY FROM PRIMARY MATERIALS

Germanium is recovered from the leaching of zinc residues or coal fly ash and is precipitated into germanium concentrates and crude germanium dioxide (GeO_2). Crude GeO_2 is then converted into germanium tetrachloride ($GeCl_4$) and hydrolysed to produce high grade GeO_2. $GeCl_4$ is also partly used to produce high grade GeO_2. A fraction of high grade GeO_2 is then reduced and refined into germanium metal (Bio Intelligence Service, 2015).

Today, germanium is extracted as a by-product of zinc production and from coal fly ash. About 60% of worldwide production of germanium is sourced from zinc ores, mainly the zinc sulphide mineral sphalerite, and 40% from coal. China and Russia are the only countries recovering germanium from coal fly ash. The world production of primary germanium decreased after 2015 (>160 tonnes) and stabilized to less than 140 tonnes. This trend should be correlated to the respective zinc production which also has been decreased since 2015.

GEOLOGY, RESOURCES AND RESERVES OF GERMANIUM

GEOLOGICAL OCCURRENCE

Germanium is a rare metal, with an average concentration in the Earth's crust of 1.6-2 ppm, and 1.4 ppm in the upper crust (Rudnick, 2003).

As is the case for many minor metals, germanium does not occur in its elemental state in nature, but is found as a trace metal in a variety of minerals and ores. Only a few minerals of germanium have been identified, the major one being germanite ($Cu_{13}Fe_2Ge_2S_{16}$). This was the principal source of germanium in the past. However, no ore bodies with commercially viable contents of germanite are known at present.

GLOBAL RESOURCES AND RESERVES:

Global resources and reserve data for germanium are difficult to obtain, because details related to trace-metal concentrations in many sulphide and coal deposits are not readily available, or are of poor quality (Melcher, F. and Buchholz, P., 2013). The available resources of germanium are associated with certain zinc and lead-zinc-copper sulfide ores (USGS, 2016), as well as coal ashes. The amount of germanium potentially recoverable from coal ash is unlimited, but the commercial recovery is currently not viable except for germanium-rich coals from Russia and China (Melcher, F. and Buchholz, P.,2013).

Global known resources of germanium are estimated at 11,000 tonnes in zinc ores and 24,600 tonnes in coal in 2013 (European Commission, 2014). Approximately half of total known resources are located in Russia (17,500 tonnes, all from coal ashes) and one quarter is located in China (10,860 tonnes, including 4,200 tonnes in zinc ores and slag, the remaining in coal ashes) (European Commission, 2014). The USA and D. R. Congo also have significant resources of germanium in zinc ores (respectively 2,300 and 3,750 tonnes), while Canada,

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

Mexico, Namibia, Ukraine and Uzbekistan account for the rest of germanium resources (European Commission, 2014).

World known reserves for germanium are estimated at 8,600 tonnes in 2012, including 3,500 tonnes of proven reserves of germanium in China (Bio Intelligence Service, 2015).

Another source estimated 13,000 tonnes of germanium reserves and resources from sulphide deposits and 25,000 tonnes from germanium-rich coal (Melcher, F. and Buchholz, P.,2013).

EU RESOURCES AND RESERVES[4]

There is no Ge mine production in EU so far in 2021. No primary germanium ores have been reported in Europe. Germanium at relatively high concentrations (up several tens of ppm) have been recorded in sphalerite zinc occurrences in North Greenland which can be considered as potential Ge resources. Peary Land and Kronprins Christian Land are the main localities with Ge-containing sphalerite ores. According to Ge content in sphalerite, it has been estimated probably a zinc concentrate with around 500 ppm germanium could be obtained. This is comparable to values in zinc concentrates constituting the main source of germanium globally. According to geochemical and ore deposit data, minor Ge occurrences potentially exist in Nordic countries (Finland, Norway and Sweden) (Stensgaard et al. 2016; Lauri et al. 2018).

WORLD AND EU MINE PRODUCTION

Germanium is mainly (75% of the global production) recovered as a by-product from sphalerite zinc ores in which it is contained at concentrations up to 0.3 wt.%. More specifically, Ge is usually contained in low-temperature sediment-hosted, massive Zn–Pb–Cu(–Ba) deposits and carbonate-hosted Zn–Pb deposits (Frenzel et al. 2016). Coal fly ashes is the second resource of germanium (25% of the global production) (CRMAlliance).

Large uncertainties exist on germanium primary production. Between 100 (WMD, 2022) and 130 tonnes (USGS) of germanium were reported between 2016 and 2020. No EU production is reported by WMD and USGS however, DERA estimates EU production at 8 tonnes per year. China is the major producer with about 80% of the global production. According to the recent USGS report (USGS, 2021b), the global production of germanium in 2020 was 130 t, which is increased in comparison to 2017 (98 t) and 2000 (58 t). Also, as it can be seen, China became a major germanium producer after 2008, while at the same time, the production in United States presented a significant decrease (**Erreur ! Source du renvoi introuvable.**).

[4] For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for germanium. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for germanium, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for germanium the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU 2019).Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

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

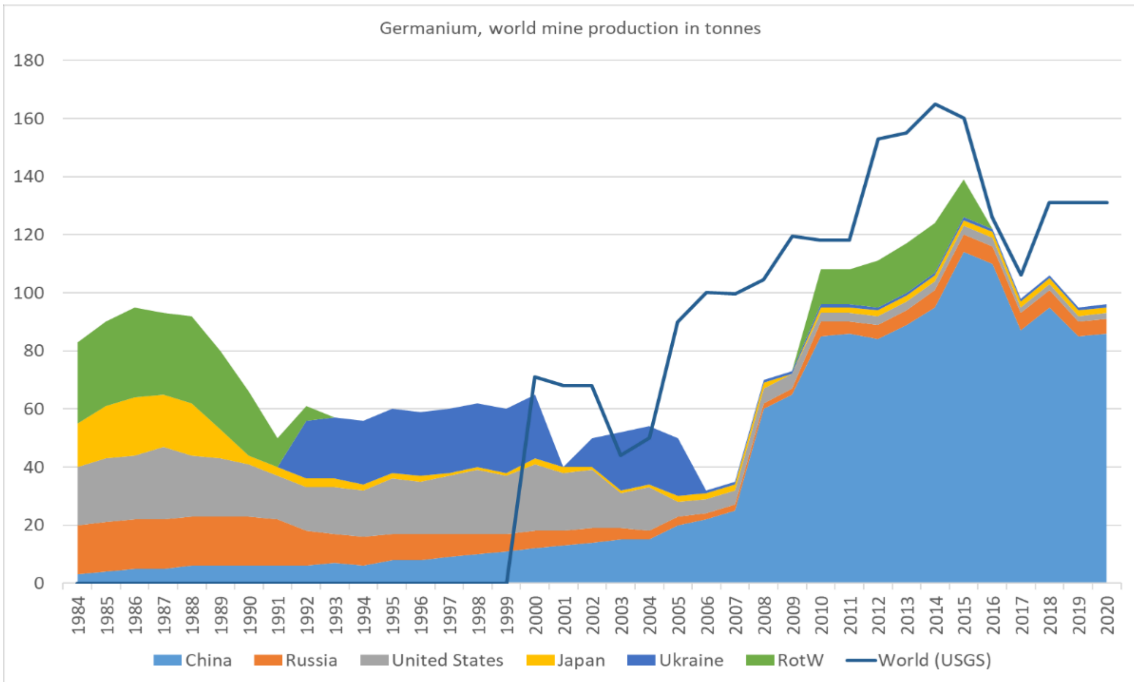

Figure 16. World production of germanium from 2000 to 2020 (stacked areas: WMD, lines: USGS)

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

It is estimated that around 30% of global germanium production is supplied by recycling, mostly from scrap generated during the manufacture of fibre-optic cables and infrared optics (new scrap). Due to the value of refined germanium, this scrap is reclaimed and fed back into the production process (European Commission, 2014). On the other hand, due to its high dispersion in most products and application in very low quantities, only a little quantity of germanium is recovered from post-consumer scrap (old scrap) (Melcher, F. and Buchholz, P.,2013).

INDUSTRIAL RECYCLING (NEW SCRAP)

As germanium products usually need to be of a very high purity, a lot of production scrap is generated all along the manufacturing chain. The high price of refined germanium encourages recycling. The majority of the new scrap generated during the manufacture of germanium processed materials and products is recycled by being fed back into the manufacturing process (Sundqvist Oeqvist, Pr. Lena et al. ,2018).

All the waste generated during the conversion of germanium dioxide (GeO_2) and the production of germanium tetrachloride ($GeCl_4$) and germanium metal is internally recycled (Bio Intelligence Service, 2015).

The manufacture of optical fibres generates about 75% of waste, and about 80% of this new scrap is reprocessed (Bio Intelligence Service, 2015). The effluents from optic fiber manufacturing process should be processed on site due to economic and environmental reasons (Ge recovery, chlorine gas disposal). The

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

specialists from Bell Technologies invented and then implemented to industrial practice the effective method for germanium recovery from optic fiber production effluents, with Ge recovery rate over 95% (Sundqvist Oeqvist, Pr. Lena et al. ,2018).

The waste produced during the manufacture of Infra-Red optics amounts to ca. 30% of the germanium input, of which 100% is internally recycled. The sawing (from large high purity mono-crystals) and grinding of germanium wafers during wafer manufacturing produces a lot of production scrap (e.g. germanium dust from sawing the wafers) - almost 50% of the germanium input - which is fully recycled internally (Bio Intelligence Service, 2015). Downstream producers of solar cells or infrared optics also generate a lot of production scrap on the way to the final product. About 50% of waste from this process is recycled (Melcher, F. and Buchholz, P.,2013).

POST-CONSUMER RECYCLING (OLD SCRAP)

Germanium is contained in various electronic devices for cutting edge applications at very low concentrations both with other metals and metalloids, therefore its efficient recycling treatment is challenging and only a little quantity of germanium is recovered from post-consumer scrap (old scrap) (Melcher, F. and Buchholz, P.,2013). Recycling of old scrap has increased over the past decade but is still low. The functional recycling rate has been estimated at about 12% (Bio Intelligence Service, 2015) and the end-of-life recycling input rate is assessed at 2% only. Very few used end-products are collected separately to be recycled: all used optical fibres go into non-functional recycling in C&D waste, solar cells for satellites are not recovered and only some germanium is recycled from old scrap of IR optics. According to experts, this situation will not improve in future due to dissipation and low grade uses, as well as extra-terrestrial applications (solar cells for satellites) that cannot be collected, etc. (Industrial player, 2016) Moreover, in most of the products and devices containing germanium the metal is present in trace amounts, making it technically and economically difficult to recover secondary germanium.

Despite the effective commercial recovery of germanium by end-of-life optical fibers and infrared optic devices, there is a little recycling progress concerning electronic scrap containing Ge at low concentrations (at the range of 0.2 ppm). The recovery of germanium by electronic scrap is challenging because of their dispersion in various products, which are neither designed nor assembled with recycling principles having been taken into account (Forti et al. 2020). The Ge concentration in relation to granulometric fraction in various end-of-life devices after their shredding, grinding and milling was found as following: Outdoor solar cells: 0.2 ppm at <0.1 mm, LED TV screens: 0.15 ppm at <0.1 mm, photoresistors: 14 ppm at 0.1-1 mm and photodiodes: 0.8 ppm at <0.1-1 mm (Willner et al. 2021).

PROCESSING AND REFINING

If refinery of germanium is mostly taking place in the producing countries, a minor refinery production of secondary resources is taking place in EU in Belgium and Germany (Reichl et al. 2019). Germanium was extracted from leaching of zinc refinery residues in Finland, from imported ore in significant amounts, up to 2015 when 13 t of Ge was produced from imported raw materials. Since 2016, Ge production in Finland has been minimal (BRGM, 2017; Lauri et al. 2018).

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

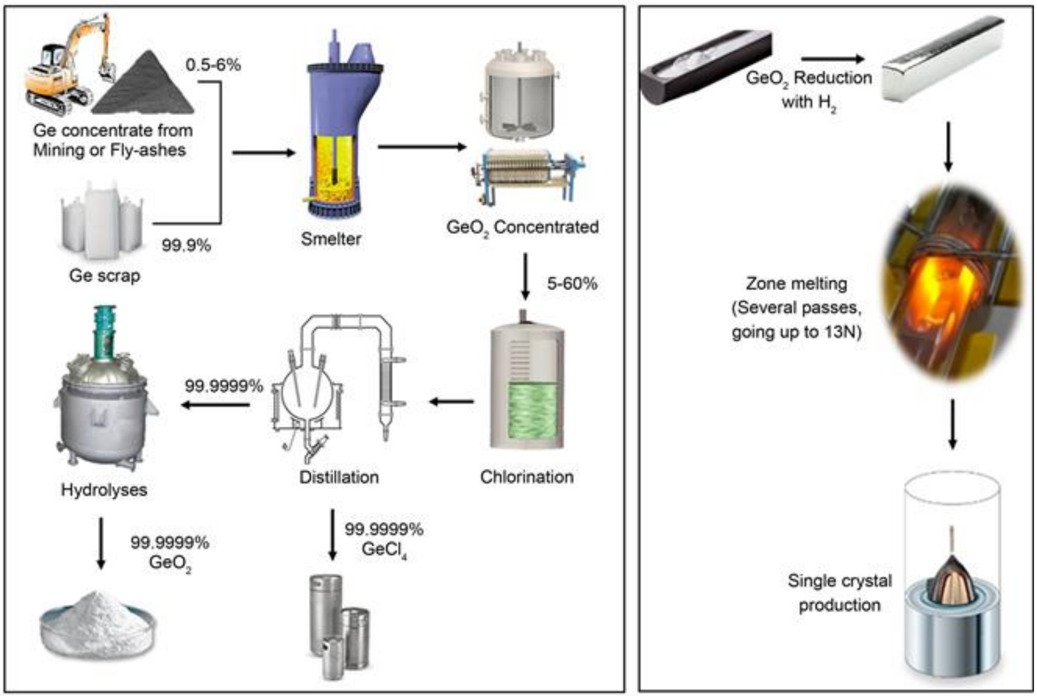

Figure 17. Simplified flowsheet of ultra-pure metallic germanium production by coal, fly ashes and scrap via pyrometallurgical route (Curtolo et al. 2017).

Germanium contained at low concentrations in two type of resources: sphalerite ores and coal fly ashes.. Germanium end concentrate, obtained from either zinc ore or coal fly-ashes presents a Ge concentration ranging between 0.5% and 6% Ge. The metallurgical processing starts with the production of germanium concentrate (germanium sulfide or oxide), followed by its chlorination and subsequent distillation/purification, producing ultra-pure germanium tetrachloride as end product, then germanium dioxide and subsequently the reduced metallic form. The latter will be further purified depending on its end-application as well as purity requirements (**Erreur ! Source du renvoi introuvable.**). Alternatively, Ge can be obtained by coal fly-ashes through a hydrometallurgical process. Including leaching using sulfuric acid and then an oxidization step of the precipitates back into GeO_2. (Curtolo et al. 2017).

OTHER CONSIDERATIONS

HEALTH AND SAFETY

Germanium is a non-toxic element, except for a few compounds. Germanium in the ppm range, when dissolved in drinking water may cause chronic disease (Melcher, F. and Buchholz, P.,2013). Germanium and its compounds are suspected of damaging fertility or the unborn child, may cause damage to organs through prolonged or repeated exposure and is harmful to aquatic life with long-lasting effects (European Chemical Agency 2021; Gerber and Léonard 1997). The germane gas (GeH4) is highly toxic at a level of 100 ppm and can cause death at 150 ppm from haemolysis and damage to the cardiovascular system, the liver and kidney (Merian and Clarkson 1991; Ferm and Carpenter 1970; Rosenberg 2008). The human intake of germanium can

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

happen unintentionally through food, water, inhalation and in certain industrial environments (Gerber and Léonard 1997). The American Chemical Association (CAS) registry includes in its database Germanium tetrahydride with a CAS 8 hr permissible exposure limits for chemical contaminants (PEL)[5] of 0.2ppm and 0.2 Recommended exposure limits (REL TWA[6])(Federal Advisory Council on Occupational Safety and Health (FACOSH) 2019).

Industrial exposures to germanium occur during the extraction and purification of the ore through inhalation of the fumes and dust (Rochow and Abel 2014; Langard, Norseth, and Friberg 1986).

ENVIRONMENTAL ISSUES

With environmental regulations becoming more stringent, the ecological footprint of germanium recovery from coal starts to get more attention. An LCA study has demonstrated the ecological benefit of other sources, such as recycling or Ge from Zn-based ores (Robertz, Benedicte, Jensen Verhelle, and Maarten Schurmans, 2015).

NORMATIVE REQUIREMENTS RELATED TO THE USE AND PROCESSING OF GERMANIUM

No relevant normative requirements could be identified.

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF GERMANIUM FOR EXPORTING COUNTRIES

According to COMTRADE (2022), the values of germanium exports remain below 0.1 % in each of the exporting countries.

SOCIAL AND ETHICAL ASPECTS

More than 40 years of coal mining and germanium processing in Lincang, West Yunnan have been causing releases of radionuclides into the environment affecting public health in the long-term. The average radiation of the natural radionuclide ^{238}U in the coal ores is 624 Bq/kg, while the maximum threshold limit is 2.17 kBq/kg. (Yang, 2005; Yu, 2007, Wang et al, 2022).

RESEARCH AND DEVELOPMENT TRENDS

- GeMiNi[7] project (2014 – 2017, EU)

The project introduces molecule-specific strong light-matter interaction at mid-infrared wavelengths through the engineering of plasmonic effects in group-IV semiconductors by a germanium-on-silicon material platform.

[5] California Code of Regulations, Title 8, Section 5155. Airborne Contaminants. Table AC-1 Permissible Exposure Limits For Chemical Contaminants: http://www.dir.ca.gov/title8/5155table_ac1.html
[6] NIOSH Pocket Guide to Chemical Hazards: http://www.cdc.gov/niosh/npg/pgintrod.html
[7] See https://cordis.europa.eu/project/id/613055

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

Sensing substrates containing infrared antennas and waveguides with antenna-enhanced detectors will be developed which will be made of heavily doped Ge to fully exploit plasmonic effects: high field concentration to increase sensitivity, resonant coupling to vibrational lines for chemical specificity, deeper integration to decrease costs. This allows for the complete substitution of metals with CMOS-compatible semiconductors in plasmonic infrared sensors, with enormous advantages in terms of fabrication quality and costs. Moreover, the mid-infrared range offers molecule specificity to target gases in the atmosphere, analytes in a solution or biomolecules in a diagnostic assay. Lab-on-chip disposable biosensors with integrated readout for medical diagnostics would radically cut healthcare costs. The possibility of tuning electromagnetic signals by electrical and/or optical control of the plasma frequency in semiconductors holds promises for dramatic opto-electronic integration. Finally, plasmonic semiconductor antennas will impact on photovoltaics, light harvesting and thermal imaging.

- Quantum computing with new qubits with holes[8] (2022)

The secret to a quantum computer's processing power lies in its use of quantum bits, or qubits – subatomic particles that are the basic units of quantum information. A potential new system for reliable qubits using the spin of so-called holes was developed to move two holes close to each other so that their spins would interact, creating a spin qubit. Notably, the qubit was created out of the two interacting hole spins using less than 10 millitesla of magnetic field strength, which is substantially weaker than the magnetic fields of other qubit set-ups, by using a layered germanium setup. The required magnetic field strength would allow the combination of this qubit with superconductors, usually inhibited by strong magnetic fields.

- Light-emitting silicon[9] (2022)

Computers transmitting data using photons instead of electrons would perform better and devour less power. A new light-emitting alloy of silicon and germanium, which is optically active, can be used in photonic chips to revolutionise computing.

REFERENCES

Allied Market Research (2017): Global Optical Fiber Market by Mode (Single Mode and Multi-Mode), Type (Glass Optical Fiber and Plastic Optical Fiber), and Industry Vertical (Telecom & IT, Public Sector, Healthcare, Energy & Utilities, Aerospace & Defense, Manufacturing, and Others): Opportunity Analysis and Industry Forecast, 2018 - 2025. Available at https://www.alliedmarketresearch.com/optical-fiber-market, accessed 22.02.2021.

360 Market updates, https://www.360marketupdates.com/global-zinc-selenide-market-17793415

BIO Intelligence Service. (2015). Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials.

BRGM, BGS, TNO, Deloitte (2017). Sustainability Study on the review of the list of Critical Raw Materials, Critical Raw Materials Factsheets. European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Directorate Industrial Transformation and Advanced Value Chains, Unit C.2 – Resource Efficiency and Raw Materials, Brussels. 515 p.

[8] See https://cordis.europa.eu/article/id/430392-quantum-computing-takes-a-step-forward-with-new-qubits-with-holes

[9] See https://cordis.europa.eu/article/id/418148-light-emitting-silicon-no-longer-a-holy-grail-for-computing

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

Brown, T.J., Idoine, N.E., Wrighton, C.E., Raycraft, E.R., Hobbs, S.F., Shaw, R.A., Everett, P., Deady, E.A. & Kresse, C. (2021). World mineral production 2015–2019. British Geological Survey, Nottingham. 89 p.

Buchholz, Peter. (2019). Consultation after Critical Raw Materials Validation Workshop in Brussels, September 2019.

Claeys, Cor, and Eddy Simoen. 2011. *Germanium-Based Technologies: From Materials to Devices*. Elsevier.

COM 2018_773 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=en

CRM 2020_ factsheet factsheet

CRMAlliance. (2021). *Germanium*. https://www.crmalliance.eu/germanium

Curtolo, D.C., Friedrich, S., Friedrich, B. (2017). High Purity Germanium, a Review on Principle Theories and Technical Production Methodologies, Journal of Crystallization Process and Technology, 7, pp. 65-84.

Daly, T. (2021). *China's Yunnan launches 800,000 T metals stockpiling drive*. Reuter. https://www.reuters.com/article/health-coronavirus-china-metals-idUSL3N2CE06R

DERA. (2021a). *Preismonitor*. https://www.deutsche-rohstoffagentur.de/DERA/DE/Produkte/Rohstoffpreise/Preismonitor/preismonitor_node.html;jsessionid=C82442B0885BD37607C415C49D402378.1_cid321

DERA. (2021b). *Volatilitätsmonitor*. https://www.deutsche-rohstoffagentur.de/DERA/DE/Produkte/Rohstoffpreise/Volatilitaetsmonitor/volatilitaetsmonitor_node.html

DG-GROW (2023), based on expert estimates

Eide, Mary, Phil Giles, Michael Simmons, and Warren Hendricks. 2005. 'Evaluation Guidelines for Air Sampling Methods Utilizing Spectroscopic Analysis'. 2005. https://www.osha.gov/sites/default/files/methods/spectroguide.pdf.

European Chemical Agency. 2021. 'ECHA- Germanium Information Card'. ECHA. 7 June 2021. https://echa.europa.eu/substance-information/-/substanceinfo/100.028.331.

European Commission (2011). Critical raw materials for the EU. [online] Available at: https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en

European Commission (2014) Report on critical raw materials for the EU - Critical raw materials profiles. Germanium profile, p67-76.

European Commission (2019). Negotiations and Agreements - Trade [online] Available at: http://ec.europa.eu/trade/policy/countries-and-regions/negotiations-and-agreements/

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

European Commission (2020b). Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474&from=EN

European Commission, EIP on Raw Materials (2021). Raw Materials Scoreboard 2021.

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

European Commission. (2017). *Critical raw materials factsheets 2017*. https://publications.europa.eu/en/publication-detail/-/publication/7345e3e8-98fc-11e7-b92d-01aa75ed71a1/language-en

European Space Agency. (2020). Reduce, Reuse, Recycle: Growing solar cells on nothing. https://www.esa.int/Enabling_Support/Space_Engineering_Technology/Shaping_the_Future/Reduce,_Reuse_Recycle_Growing_solar_cells_on_nothing

EUROSTAT (2020). Sold production, exports and imports by PRODCOM list (NACE Rev. 2) - annual data (DS-066341) and Total production by PRODCOM list (NACE Rev. 2) - annual data (DS-066342). Available: https://ec.europa.eu/eurostat/data/database.

EUROSTAT (2021) Annual detailed enterprise statistics for industry (NACE Rev. 2, B-E) Available: https://ec.europa.eu/eurostat/databrowser/view/SBS_NA_IND_R2__custom_1126320/default/table?lang=en

Eurostat Comext (2019). International Trade Easy Comext Database [online] Available at: http://epp.eurostat.ec.europa.eu/newxtweb/

Eurostat Comext. (2021). *Comext Database*. http://epp.eurostat.ec.europa.eu/newxtweb/

Federal Advisory Council on Occupational Safety and Health (FACOSH). 2019. 'Recommendations for Consideration by the U.S. Secretary of Labor on the Adoption and Use of Occupational Exposure Limits by Federal Agencies'. Occupational Safety and Health Administration (OSHA). 2019. https://www.osha.gov/sites/default/files/2019-12/Exhibit_9b.pdf.

Ferm, Vergil H, and Stanley J Carpenter. 1970. 'Teratogenic and Embryopathic Effects of Indium, Gallium, and Germanium'. *Toxicology and Applied Pharmacology* 16 (1): 166–70.

Forti V et al.(2020) The Global E-waste, Monitor 2020 Quantities, flows, and the circular economy potential Available at: file:///C:/Users/Michalis/Downloads/EN%20-%20Global%20E-waste%20Monitor%202020.pdf <Assessed July 12 th>.

Fortune Business Insights (2019): Fiber Optics Market Size, Share and Industry Analysis. Available at https://www.fortunebusinessinsights.com/fiber-optics-market-102904, accessed 22.02.2021.

Gerber, G. B, and A Léonard. (1997). 'Mutagenicity, Carcinogenicity and Teratogenicity of Germanium Compounds'. *Mutation Research/Reviews in Mutation Research* 387 (3): 141–46. https://doi.org/10.1016/S1383-5742(97)00034-3.

González Ruiz, P.Córdoba Sola, N. Moreno Palmerola «Germanium: Current and Novel Recovery Processes,» IntechOpen, 2018.

Hamilton, EI, MJ Minski, and JJ Cleary. 1972. 'Problems Concerning Multi-Element Assay in Biological Materials'. *Science of the Total Environment* 1 (1): 1–14.

Hanusch F. et al. (2021), Recent advances of group 14 dimetallenes and dimetallynes in bond activation and catalysis, Chem. Sci., 2021, 12, 2001-2015

Industrial-Player. (2016). *Communication during the workshop held in Brussels on 28/10/2016*.

Iris Winberg, Master's thesis of Åbo Akademi University "Techno-economic assessment of the process for recovery of indium, germanium and tin from alloys obtained as byproducts of zinc production", 2018

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

L. Wang, S.-J. Zhu, H.-Y. Wang, S.-N. Qu, Y.-L. Zhang, J.-H. Zhang, Q.-D. Chen, H.-L. Xu, W. Han, B. Yang, Common origin of green luminescence in carbon nanodots and graphene quantum dots, ACS Nano 8 (3) (2014) 2541-2547.

Langard, S, T Norseth, and L Friberg. 1986. 'Handbook on the Toxicology of Metals'. *Elsevier, Amsterdam*, 322–45.

Lauri, L.S., Eilu, P., Brown, T., Gunn, G., Kalvig, P. & Sievers, H. (2018). Identification and quantification of primary CRM resources in Europe. Deliverable 3.1 of the H2020 project SCRREEN. 63 p. Online at: http://scrreen.eu/wp-content/uploads/2018/03/SCRREEN-D3.1-Identification-and-quantification-of-primary-CRM-resources-in-Europe.pdf

Lima G.T. et al (2019), Evaluation of Sodium/Protonated Titanate Nanotubes Catalysts in Virgin and Post Consumer PET Depolymerization, Catalysis Letters (2019) 149:1415–1426 https://doi.org/10.1007/s10562-019-02724-8

Melcher, F. and Buchholz, P. (2013). Germanium. In Critical Metals Handbook, G. Gunn (Ed.). doi:10.1002/9781118755341.ch8

Melcher, Frank, and Peter Buchholz. (2012). Current and Future Germanium Availability from Primary Sources, 31.

Merian, Ernest, and Thomas W Clarkson. 1991. *Metals and Their Compounds in the Environment*. Vch.

Mordor Intelligence (2020): Fiber Optic Cable Market - Growth, Trends, COVID-19 Impact, and Forecasts (2021 - 2026). Available at https://www.mordorintelligence.com/industry-reports/fiber-optic-cable-market, accessed 22.02.2021.

OECD (2019). Export restrictions on Industrial Raw Materials. [online] Available at: http://qdd.oecd.org/table.aspx?Subject=ExportRestrictions_IndustrialRawMaterials [Accessed September 2019]

OECD. (2021). *Trade in raw materials*. https://www.oecd.org/trade/topics/trade-in-raw-materials/

Reichl, C., Schatz, M. (2019). World Mining Data 2019, Federal Ministry Republic of Austria, available at: https://www.world-mining-data.info/wmd/downloads/PDF/WMD2019.pdf, <Assessed July 12 th>.

Robertz, Benedicte, Jensen Verhelle, and Maarten Schurmans (2015). "The Primary and Secondary Production of Germanium: A Life-Cycle Assessment of Different Process Alternatives." JOM 67(2): 412–24.

Rochow, E. G., and E. W. Abel. 2014. *The Chemistry of Germanium: Tin and Lead*. Elsevier.

Rosenberg, Erwin. 2008. 'Germanium: Environmental Occurrence, Importance and Speciation'. *Reviews in Environmental Science and Bio/Technology* 8 (1): 29. https://doi.org/10.1007/s11157-008-9143-x.

Rudnick, R.L. and Gao. S. (2003). Composition of the Continental Crust. In: Treatise on Geochemistry, Volume 3. Editor: Roberta L. Rudnick. Executive Editors: Heinrich D. Holland and Karl K. Turekian. pp. 659. ISBN 0-08-043751-6. Elsevier, p.1-64

S. He, Y. Qian, K. Liu, C.W. Macosko, A. Stein, Modified-graphene-oxidecontaining styrene masterbatches for thermosets, Ind. Eng. Chem. Res. 56 (40) (2017) 11443-11450.

Santosh K. Tiwari, Sumanta Sahoo, Nannan Wang, Andrzej Huczko Graphene research and their outputs: Journal of Science: Advanced Materials and Devices 5 (2020) 10-29

Schroeder, Henry A, and Joseph J Balassa. 1967. 'Arsenic, Germanium, Tin and Vanadium in Mice: Effects on Growth, Survival and Tissue Levels'. *The Journal of Nutrition* 92 (2): 245–52.

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

SCRREEN (2019). Validation Workshop on Critical Raw Materials, 10-12 September 2019, Thon Hotel Brussels City Centre.

Stensgaard, B.M., Stendal, H., Kalvig, P. & Hanghøj, K. (2016): Review of potential resources for critical minerals in Greenland. Center for Minerals and Material (MiMa) rapport 2016/3, 74 pp.

Transparency-Market-Research. (2020). *Germanium*. https://www.transparencymarketresearch.com/germanium-market.html

Umicore https://eom.umicore.com/en/infrared-solutions/infrared-optics/

Umicore. (2019). *Consultation after Critical Raw Materials Validation Workshop in Brussels, September 2019*.

US Geological Survey. 2021. 'USGS.Gov | Science for a Changing World-Germanium'. Governmental. USGS-National Minerals Information Center. 2021. https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-germanium.pdf.

USGS (2016). Mineral Commodity Summaries: Germanium. [online] Available at: https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/germanium/mcs-2016-germa.pdf.

USGS (2021b). Mineral commodity summaries 2021. U.S. Geological Survey. 204 p. https://doi.org/10.3133/mcs2021

USGS. (2016). *Mineral Commodity Summaries: Germanium*. https://s3-us-west-2.amazonaws.com/prd-wret/assets/palladium/production/mineral-pubs/germanium/mcs-2016-germa.pdf

USGS. (2017). *Mineral Year book – Data Release: Germanium*. https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/myb1-2017-germa-adv.xlsx

USGS. (2019). *Mineral Commodity Summaries: Germanium*. https://prd-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-germa_0.pdf

USGS. (2021a). *Germanium Statistics and Information*. https://www.usgs.gov/centers/nmic/germanium-statistics-and-information

Willner, J., Fornalczyk, A., Jablonska-Czapla, M., Grygoyc, K., Rachwal, M. (2021), Studies on the Content of Selected Technology Critical Elements (Germanium, Tellurium and Thallium) in Electronic Waste, Materials, 14, 3722.

World Mining Data (2019). Bundesministerium für Nachhaltigkeit und Tourismus. Austrian Federal Ministry of Sustainability and Tourism. [online] Available at: www.en.bmwfw.gv.at/Energy/WorldMiningData/Seiten/default.aspx

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