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A handbook by the Technology
and Policy Assessment theme of
the UK Energy Research Centre

Energy Materials Availability Handbook

Introduction

Welcome to the Energy Materials Availability Handbook (EMAH), a brief guide to some of the materials that are critical components in low carbon energy technologies. In recent years concern has grown regarding the availability of a host of materials critical to the development and manufacturing of low carbon technologies.

In this handbook we examine 10 materials or material groups, presenting the pertinent facts regarding their production, resources, and other issues surrounding their availability. Three pages of summary are devoted to each material or material group. A ‘how to use’ guide is provided on the following pages.

The UK Energy Research Centre, which is funded by Research Councils UK, carries out world-class research into sustainable future energy systems.

It is the hub of UK energy research and the gateway between the UK and the international energy research communities. Our interdisciplinary, whole systems research informs UK policy development and research strategy.

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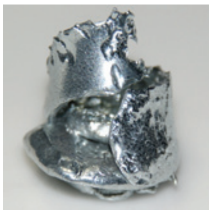
Selection of Materials

Concern over the availability of low carbon materials is increasing, with numerous materials highlighted throughout the debate. Identifying which materials are most important is therefore a complex and potentially subjective process. To select the 10 materials presented here we first systematically reviewed the literature on materials criticality assessment, focusing on materials with particular relevance to low-carbon energy technologies. We then normalised the results of these assessments. We also excluded any base metals on the basis that they were potentially better understood than other materials. Finally we selected the 10 materials or material groups with the highest normalised results. These are:


1. Cobalt


2. Gallium


3. Germanium

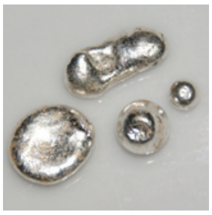

4. Indium


5. Lithium


6. Platinum Group Metals (PGMs)


7. Rare Earth Elements (REEs)


8. Selenium


9. Silver


10. Tellurium

Click images to go to material fact sheet.

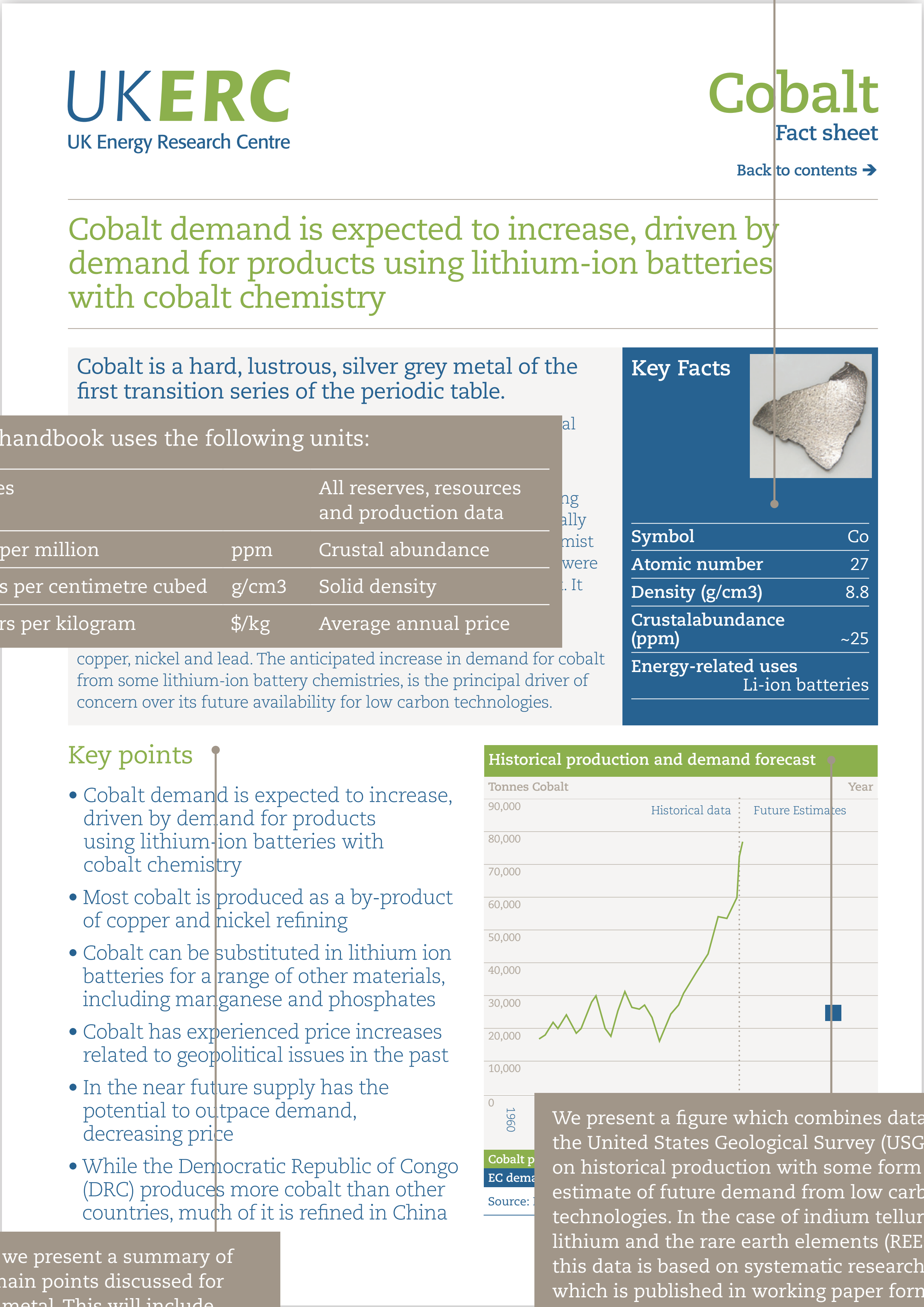
A working paper which details the systematic review of criticality methodologies and the selection of materials can be found on the **UKERC website.**

This handbook was first written in October 2012. The information contained is likely to change on an annual basis. Up to date information can be sought from the original sources of this data, **which can be found at the back of this report.**

How to use this handbook

The following pages provide a guide to the layout of the handbook. Description of the different sections of the handbook can be found in the grey boxes.

Useful summary information on each of the 10 materials or material groups.



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Cobalt
Fact sheet

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Cobalt demand is expected to increase, driven by demand for products using lithium-ion batteries with cobalt chemistry

Cobalt is a hard, lustrous, silver grey metal of the first transition series of the periodic table.

copper, nickel and lead. The anticipated increase in demand for cobalt from some lithium-ion battery chemistries, is the principal driver of concern over its future availability for low carbon technologies.

Key Facts

Symbol	Co
Atomic number	27
Density (g/cm3)	8.8
Crustalabundance (ppm)	~25
Energy-related uses	Li-ion batteries

Key points

- Cobalt demand is expected to increase, driven by demand for products using lithium-ion batteries with cobalt chemistry
- Most cobalt is produced as a by-product of copper and nickel refining
- Cobalt can be substituted in lithium ion batteries for a range of other materials, including manganese and phosphates
- Cobalt has experienced price increases related to geopolitical issues in the past
- In the near future supply has the potential to outpace demand, decreasing price
- While the Democratic Republic of Congo (DRC) produces more cobalt than other countries, much of it is refined in China

Historical production and demand forecast

The handbook uses the following units:

Tonnes		All reserves, resources and production data
Parts per million	ppm	Crustal abundance
Grams per centimetre cubed	g/cm3	Solid density
Dollars per kilogram	$/kg	Average annual price

Here we present a summary of the main points discussed for each metal. This will include the most pertinent details on production, resources, geopolitics and other market issues.

We present a figure which combines data from the United States Geological Survey (USGS) on historical production with some form of estimate of future demand from low carbon technologies. In the case of indium tellurium lithium and the rare earth elements (REEs) this data is based on systematic research, which is published in working paper format at www.UKERC.ac.uk. These figures also include estimates of future supply. For all other materials the future demand data is based on European Commission (EC) or Fraunhofer estimates.

This table represents 2011 production and reserves data presented in tonnes. Data is compiled from the United States Geological Survey (USGS) in order to give context to the current scale of production, and the geographical distribution of key producers.

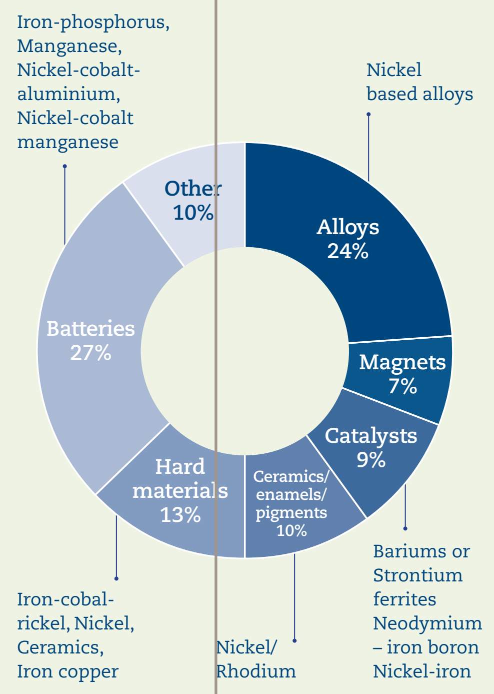
Here we present a simplified flow diagram representing the various stages of production and refining. This is compiled from the available literature and represents the most commonly used processes.

2011 Data (Tonnes)

Country	Production	Reserves
United States	–	33,000
Australia	4,000	1,400,000
Brazil	1,700	87,000
Canada	7,200	130,000
China	6,500	80,000
DR Congo	52,000	3,400,000
Cuba	3,600	500,000
Morocco	2,500	20,000
New Caledonia	2,000	370,000
Russia	6,300	250,000
Zambia	5,700	270,000
Other	7,000	990,000
World Total	**98,000**	**7,500,000**

Source: USGS (2012)

End uses and substitutes

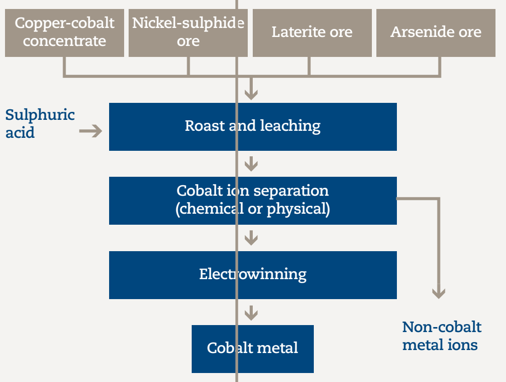


Source: GCC 2011; USGS (2012)

Production, extraction and refining

Although cobalt is found in several ores (e.g. linnaeite, Co_3S_4 and cobaltite, CoAsS), industrially it is produced as a by-product from the production of copper, nickel and lead.

Hydrometalurgical extraction of cobalt from ore concentrate



Source: Ullman & Bohnet (2012)

In the case of copper, concentrates are roasted in air to convert sulphides to oxides, then crushed and milled to a powder. To extract cobalt the oxide ore can be leached with sulphuric acid which dissolves metals more reactive than copper, particularly iron, cobalt and nickel, to form sulphates. Iron is separated from the liquor by the addition of lime which precipitates iron oxide, after which cobalt can be precipitated with sodium hypochlorite as hydroxide $Co(OH)_3$. The hydroxide is roasted to the oxide which is then reduced to cobalt metal with charcoal or hydrogen gas.

The Democratic Republic of Congo (DRC) produces the largest share of cobalt globally (~50%), with a host of other countries contributing the balance of production, including Australia, Brazil, Canada, China, Cuba, Morocco, Russia, Zambia and New Caledonia. However, much of the raw ore extracted from the DRC is exported to China, where it is refined, making China the largest producer of refined cobalt.

The 'End-uses and substitutes' figure describes the current types of end-uses for a particular material, along with the relative proportion of those uses and, where appropriate, the available substitutes.

Issues of material production including extraction and refining are often highly pertinent to questions of availability. Many of the materials discussed in the following pages are recovered with other materials, and the route to their production may provide information key to assessing availability.

Here we present an indication of the current reserves, wider resources, and their geographical distribution.

Estimates of resources and their geographical distribution are clearly important in assessing the availability of a material. One of the principal issues of resources is in their definition. Considerable confusion can be created by a lack of clear resource definition, or in comparing two definitions of resources incorrectly. To avoid this confusion this handbook refers to two broad resource definitions only: reserves, meaning those resources that can be recovered under today's economic and technological conditions; and resources, meaning all potential resources including those defined as reserves, and other identified or anticipated resources not currently economically or technologically producible.

For each material we include current USGS reserve estimates alongside production estimates providing the current scale of reserves, some context of the balance between production and reserves, some indication of the geographical distribution of reserves, and how that distribution compares to the distribution of production.

The geographical distribution of reserves and resources is important from two perspectives: physical access, and geopolitical availability. With the materials discussed in the handbook it is the geopolitical constraints which currently cause most concern.

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Resources and geography

Global reserves of cobalt are currently estimated at 7.5 million tonnes, with approximately half of these reserves existing in copper deposits in the DRC.

Substantial reserves also exist in Australia (1.4 million tonnes) with the balance of reserves existing in a wide range of different countries including the United States, Brazil, China, Canada, Cuba, Morocco, New Caledonia, Russia and Zambia.

The USGS also identify other resources equal to currently estimated reserves. These are thought to exist mostly in nickel-bearing laterite deposits and nickel-copper sulphide deposits, and are found in the United States (~1 million tonnes) Australia, Canada, Russia, DRC and Zambia. In addition to these resources it is thought that around 1 billion tonnes of cobalt exists in manganese nodules and crusts on the ocean floor, though this resource is highly speculative.

The wide range of countries with existing reserves offsets to some extent the significant concentration of reserves in the DRC. However, geopolitical issues have caused cobalt supply concerns in the past, and the price spike in the late 1970's was driven by political unrest in DRC at that time, and the resulting closure of cobalt production in the region.

Source: USGS (2012)

Market factors

Future demand for cobalt is anticipated to increase significantly, driven by demand for cobalt chemistry lithium ion batteries. However, low carbon vehicles are unlikely to use cobalt based batteries, favouring instead more modern chemistries with advantageous performance characteristics.

Consumer electronics will continue to use cobalt chemistries for some time, with growth in consumer electronics markets contributing to increases in cobalt demand. However, substitute lithium ion chemistries may also displace cobalt in these markets.

Cobalt price has responded to supply constraints in the past and the very high price seen in the late 1970's is widely acknowledged as a response to geopolitical pressures. However, the USGS suggest that in the near future, supply is more likely to outpace demand, creating negative pressure on the cobalt price.

metal, with 24%
om scrap in 2011.

Cobalt average yearly price

Source: USGS (2011)

A host of other issues also play a significant role in the assessment of availability, including the assessment of future material demand, the potential for future recycling markets, and the future material price conditions which influence these markets. We discuss these issues here.

Here we present historical price, inflated to 2011 dollars per kg

Cobalt
Fact sheet

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Cobalt demand is expected to increase, driven by demand for products using lithium-ion batteries with cobalt chemistry

Cobalt is a hard, lustrous, silver grey metal of the first transition series of the periodic table.

Cobalt does not occur naturally as metal and is found in chemical compounds often associated with sulphur and arsenic.

Cobalt has been used since ancient times for the blue colour it gives to glass and ceramics and has been found in artefacts dating back to the third millennium BC. However, the colour was originally attributed to the element bismuth until 1735 when Swedish chemist George Brandt discovered that the blue-pigment producing ores were reducible to a previously undiscovered metal later named cobalt. It was the first new metal to be discovered since prehistory.

Cobalt is commonly produced as a by-product of the refining of copper, nickel and lead. The anticipated increase in demand for cobalt from some lithium-ion battery chemistries, is the principal driver of concern over its future availability for low carbon technologies.

Key Facts

Symbol	Co
Atomic number	27
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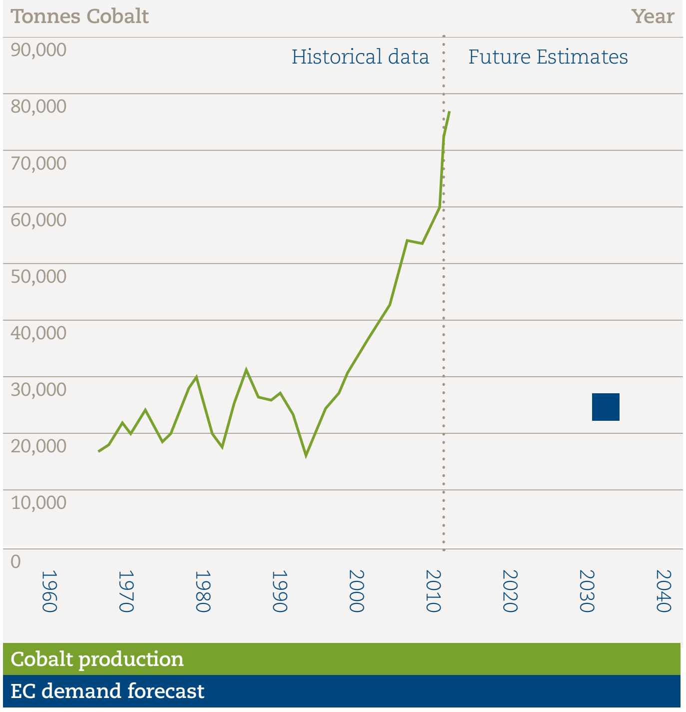
Historical production and demand forecast



Source: EC (2010); USGS (2012)

2011 Data (Tonnes)

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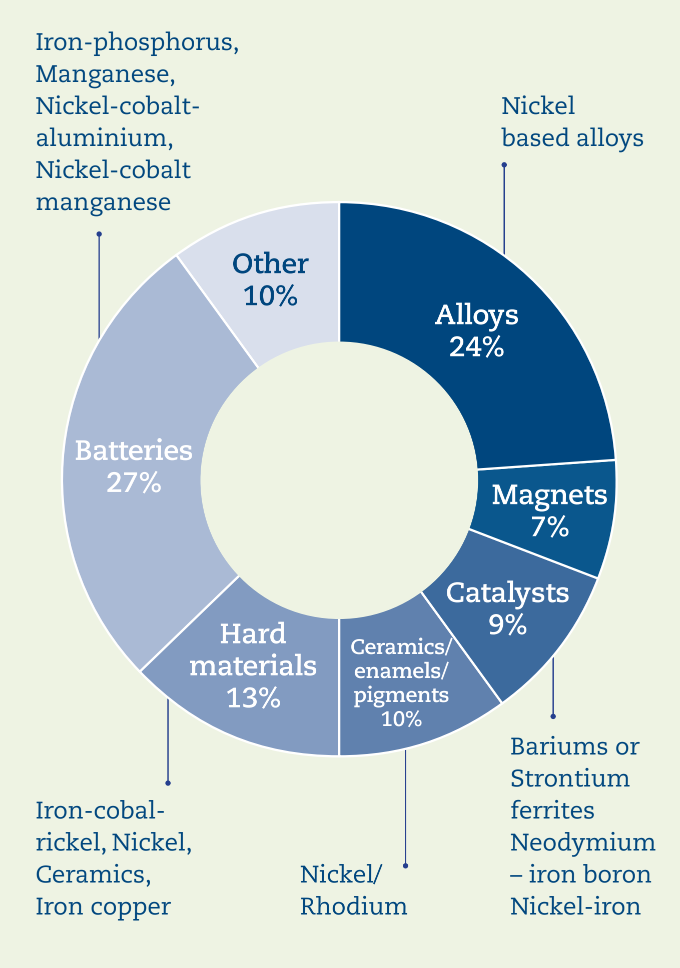
Source: USGS (2012)

End uses and substitutes



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Production, extraction and refining

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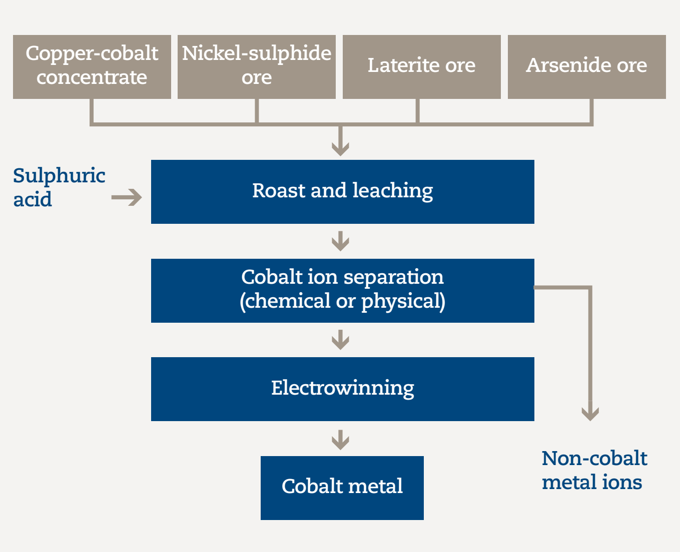
Hydrometalurgical extraction of cobalt from ore concentrate



Source: Ullman & Bohnet (2012)

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Resources and geography

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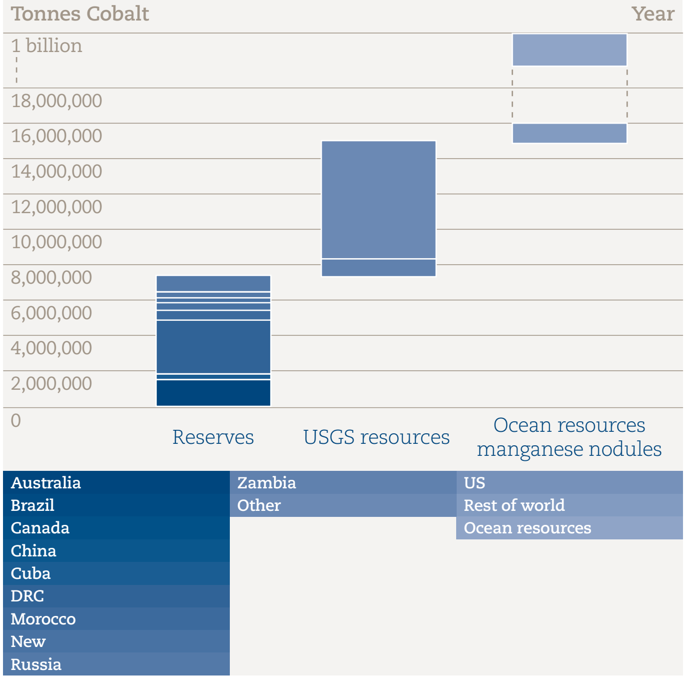
Cobalt reserves and resources



Source: USGS (2012)

Market factors

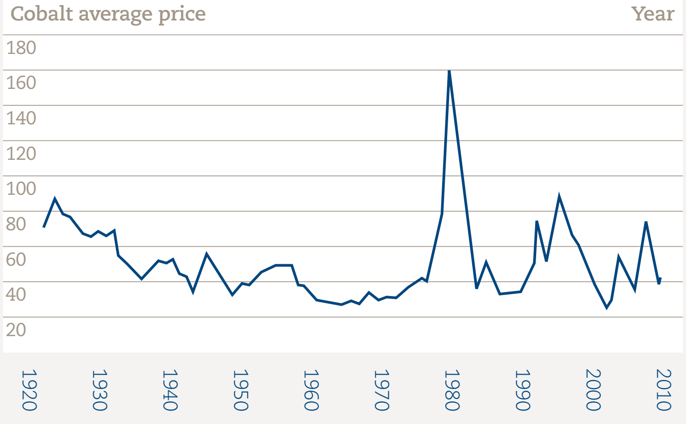
Future demand for cobalt is anticipated to increase significantly, driven by demand for cobalt chemistry lithium ion batteries. However, low carbon vehicles are unlikely to use cobalt based batteries, favouring instead more modern chemistries with advantageous performance characteristics.

Consumer electronics will continue to use cobalt chemistries for some time, with growth in consumer electronics markets contributing to increases in cobalt demand. However, substitute lithium ion chemistries may also displace cobalt in these markets.

Cobalt price has responded to supply constraints in the past and the very high price seen in the late 1970's is widely acknowledged as a response to geopolitical pressures. However, the USGS suggest that in the near future, supply is more likely to outpace demand, creating negative pressure on the cobalt price.

Cobalt is widely recycled from scrap metal, with 24% of US cobalt consumption sourced from scrap in 2011.

Cobalt average yearly price



Source: USGS (2011)

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Gallium
Fact sheet

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Expected increases in demand for gallium are in part a result of demand for thin-film PV driven by global decarbonisation goals

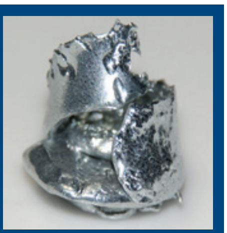
The main resource of gallium is as a by-product of aluminium production from bauxite ore.

The existence of gallium was predicted in 1871 by the Russian chemist Dimitri Mendeleev in his periodic table of the elements. He also predicted some of its properties such as density and melting point. The metal was discovered in 1875 by Paul Emile Lecoq from examination of the spectrum of a sample of sphalerite (a zinc sulphide material with varying iron content). In the same year he obtained gallium metal by electrolysis of alkaline leach solution from sphalerite in potassium hydroxide. Lecoq named the element Gallia from the Latin word for Gaul (France).

Gallium is too reactive to exist as metal in nature. It exists as compounds, particularly in trace quantities in bauxite and sphalerite. The main resource of gallium is as a co-product of aluminium production from bauxite ore.

Concern over availability of gallium for energy technologies has arisen due to perceived future demand associated with Copper Indium Gallium diSelenide (CIGS), a thin film PV technology.

Key Facts

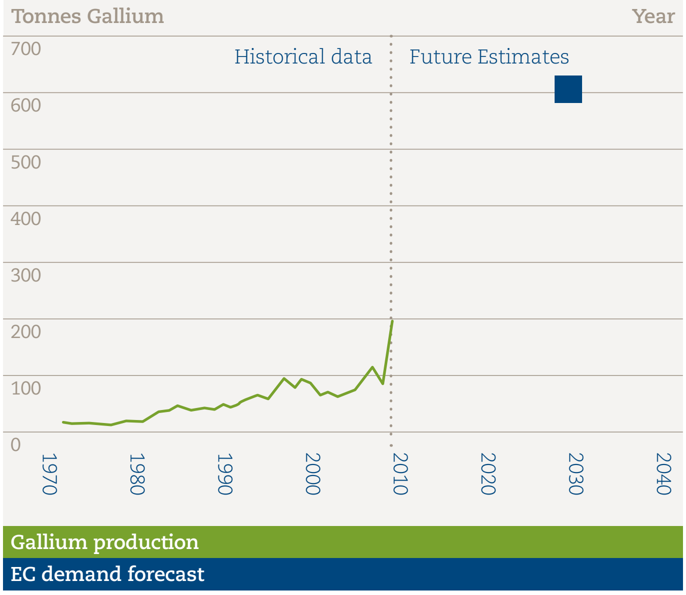


Symbol	Ga
Atomic number	31
Density (g/cm3)	5.91
Crustalabundance (ppm)	19
Energy-related uses	Thin-film PV (CIGS)

Key points

- Expected increases in demand for gallium are in part a result of demand for thin-film PV driven by global decarbonisation goals
- Gallium is produced as a by-product of aluminium, and possibly zinc in the future
- Data on gallium reserves and production are relatively scarce, making analysis problematic
- High purities are needed for semiconductor applications
- Semiconductor uses account for 95% of gallium demand

Historical production and demand forecast



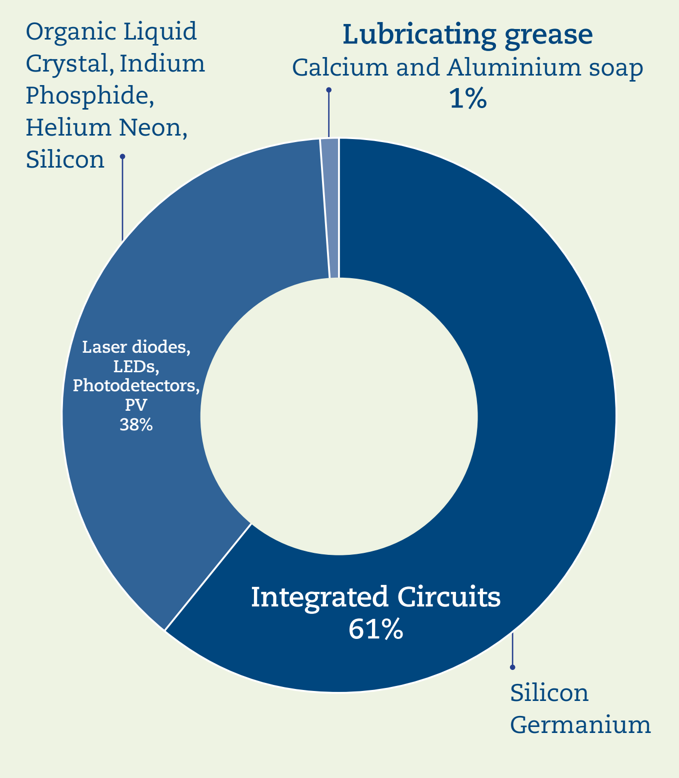
Source: EC (2010); USGS (2012)

Production data

The USGS typically present production and reserves figures disaggregated by country, for each metal covered in the Minerals Commodity Summaries. However, gallium data is not presented in the same way, providing only text with a limited amount of information. Primary gallium production in 2011 was estimated at 216 tonnes, 34 tonnes greater than the estimate for 2010. Major producers were China, Germany, Kazakhstan and Ukraine; minor producers were Hungary, Japan, the Republic of Korea and Russia.

No reference is made to reserve data.

End uses and substitutes

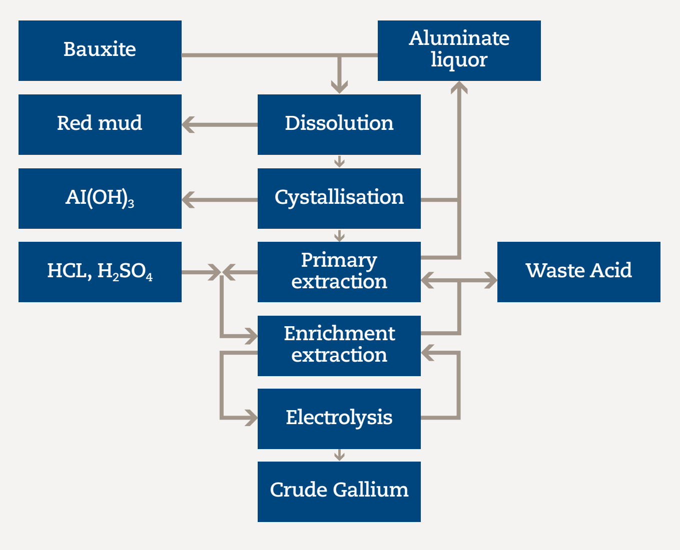


USGS (2012)

Production, extraction and refining

The USGS reports that in 2011 world primary production of gallium was estimated to be 216 metric tonnes.

The Rhône-Poulenc process for extracting gallium from sodium aluminate liquor



Source: Ullman & Bohnet (2012)

Refined production was estimated to be 310 tonnes, higher than gallium production estimated at 216 tonnes. The larger figure includes both primary production and refining of scrap and low purity gallium.

The main source of gallium is bauxite. Bauxite is often shipped as ore to be processed in other countries. The countries that are reported as producers of aluminium or gallium are therefore not necessarily the countries that hold the resource of these metals.

In the aluminium production process, bauxite is treated with hot concentrated caustic soda solution (Bayer process). Aluminium is extracted as sodium aluminate while traces of gallium are extracted as sodium gallate. Gallium is separated by selective precipitation. Gallium metal is produced by electrolysis of alkaline sodium gallate solution. The metal produced can be purified by melting in temperature controlled vessels. The temperature is reduced to and held at slightly below the freezing point of gallium. The metal bath is seeded with small single crystals of gallium placed on the surface (solid gallium is less dense that the liquid). The crystals grow and when of sufficient size are removed from the vessel and remelted. Repeated recrystalisation produces metal of >99.9999%. This purity is normally required where it is to be used for semiconductor compound production.

Resources and geography

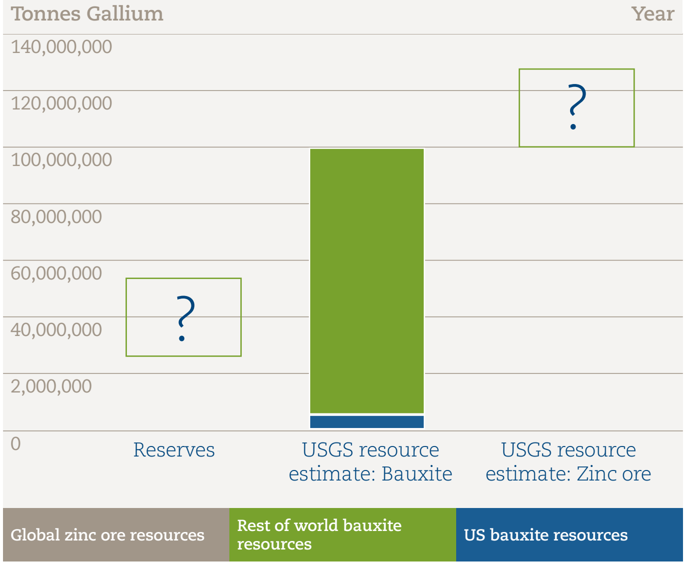
The USGS estimates that world gallium resources exceed one million tons. This estimate is based on its average concentration in known bauxite ore, 50ppm.

Until 2011 the USGS estimated that 15,000 tons of this resource existed in the bauxite of the United States, though this position changed in 2012, where the USGS state that recovery of gallium from these deposits is unlikely given their high silicon content which adversely affects the economic cost of extraction.

Gallium is also present in the zinc ore sphalerite. Though it is acknowledged that a significant gallium resource may be present in these zinc ores, no estimate of resources is given.

No official reserve figure is presented since much of the gallium associated with sphalerite and bauxite may never be economically producible.

Gallium reserves and resources

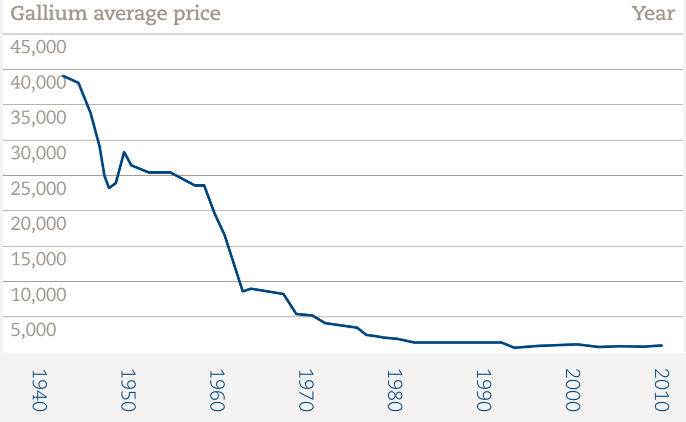


Source: USGS (2012)

Market factors

Over 95% of gallium is now used in semi conductors. A large proportion of semi conductor gallium is used in integrated circuits for example in the manufacture of high speed logic chips in mobile phones.

Gallium average yearly price



Source: USGS (2011)

A significant proportion is used in optoelectronics in a variety of infra red applications. AlGaAs is used in infrared laser diodes. Bright LEDs are used in lamps and back lighting for flat screen televisions.

Gallium III/V intermetallic compounds gallium arsenide (GaAs), gallium nitride (GaN) and gallium phosphide (GaP) have the property of changing electricity directly into light. Of these light emitting diodes (LED's) GaAs produces green light, GaN blue light and GaP red light. A combination of these different LED's are therefore used to produce full-colour LED displays. LED flat screen televisions working at low voltages have therefore largely replaced the bulky cathode ray tube monitors (CRT). Gallium has a potential application in photovoltaics, where it can be used as a component of a thin film coating of copper indium gallium selenide (CIGS) on solar panels.

Gallium price appears to have decreased significantly since the 1940's. The USGS note that gallium price in recent years has fluctuated, driven up by increasing demand, and back down again by the supply response to high price.

In-use gallium was not recorded as recycled, but recycling within the manufacturing process is thought to be significant.

Germanium

Fact sheet

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Future demand for germanium is expected to increase significantly, driven largely by PV demand

Germanium is a hard, lustrous greyish white metalloid.

In 1871 Dmitri Mendeleev predicted the existence of an element between silicon and tin in the periodic table.

In 1886 Clemens Winkler isolated a new element which exhibited properties remarkably similar to those predicted by Mendeleev. He named it germanium after his native country. It is a hard, lustrous greyish white metalloid.

Germanium does not exist in the elemental form in nature, but is found in a relatively small number of mineral ores. Historically germanium has been recovered from germanite and renierite, though currently, the majority of germanium is recovered from certain zinc ores. Germanium is also present in certain types of coal and it is concentrated in the fly ash from coal fired power stations. Such coals are found in parts of Russia and China, where the fly ash is used as a source of germanium.

Early uses of germanium were almost exclusively electronic, though modern uses include catalysts, optics and metallurgy. Future availability of germanium is of particular concern given expected future demand in PV manufacturing, where germanium is used as a substrate.

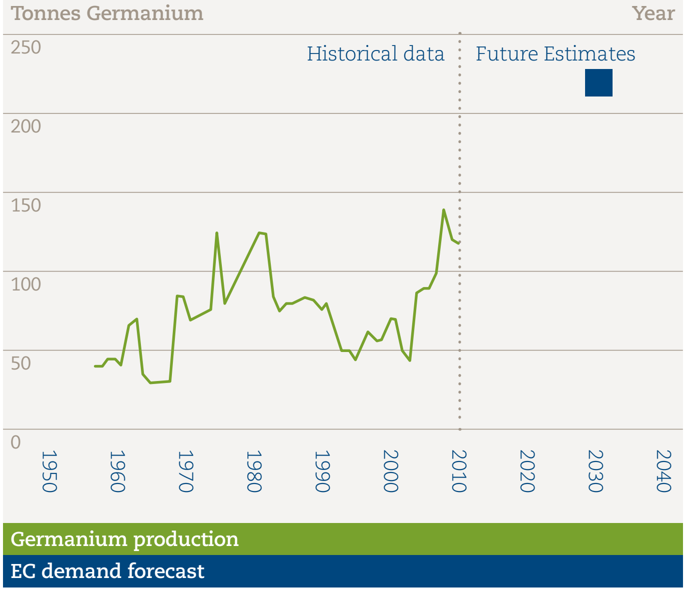
Key Facts

Symbol	Ge
Atomic number	32
Density (g/cm³)	5.32
Crustal abundance (ppm)	1.6-6.7
Energy-related uses	Thin-film PV

Key points

- Future demand for germanium is expected to increase significantly, driven largely by PV demand
- The majority of new germanium supply is as a by-product of zinc production
- Currently ~30% of global supply is provided through recycled material
- Recycling occurs both at the manufacturing/ new scrap and end-of-life stages
- Silicon can be used as a substitute for germanium in solar applications, with an associated loss in efficiency

Historical production and demand forecast



Source: EC (2010); USGS (2012)

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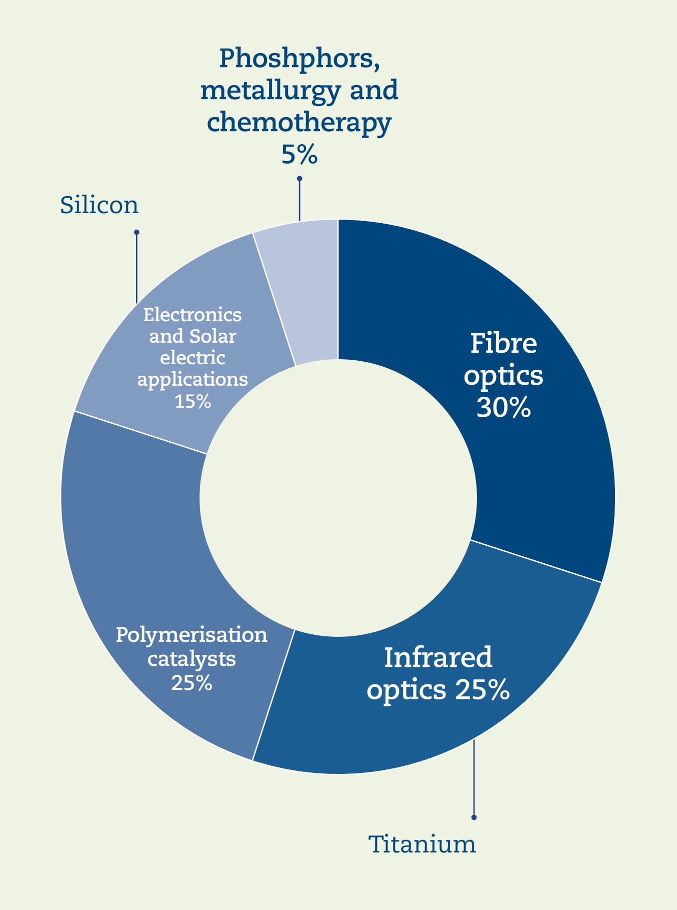
2011 Data (Tonnes)

Country	Production	Reserves
Russia	5,000	–
China	80,000	–
United States	3,000	450
Other	30,000	–
World Total	**118,000**	**450**

Source: USGS (2012)

End uses and substitutes

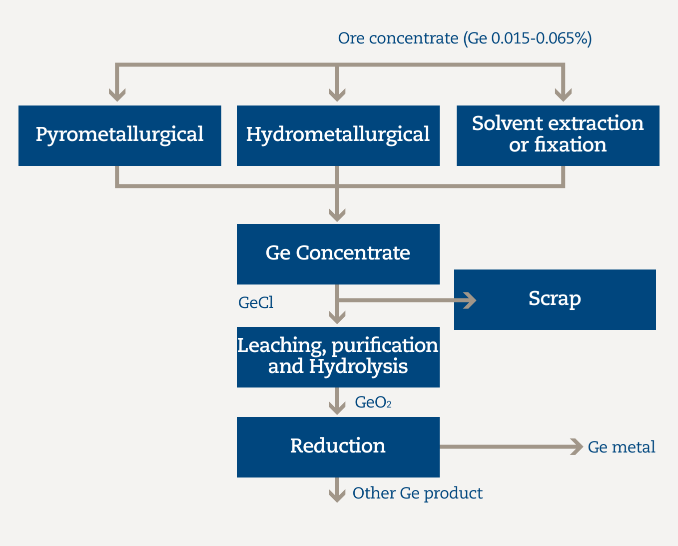


Source: USGS (2012)

Production, extraction and refining

Globally the majority of germanium is produced as a by-product of zinc extraction.

Germanium production from Metal ore concentrate



Source: Ullman & Bohnet (2012)

The ore is first crushed and ground to a powder. Froth floatation is then used to separate the ore minerals from other material. Germanium content of the concentrate is up to 0.3%.

The ore is then converted to oxide by roasting, after which either pyrometallurgy or hydrometallurgy can be used. In the hydrometallurgical process the oxidised ore is leached with sulphuric acid. The solution is then neutralised.

The zinc stays in solution while germanium and other metals are precipitated as hydroxides and oxides. After further processing, the germanium contained is converted to germanium dioxide and then to germanium tetrachloride either using chlorine gas or hydrochloric acid. The tetrachloride is volatile so can be separated by distillation then hydrolysed to the oxide (GeO_2) or purified by fractional distillation then hydrolysed. The purified oxide is reduced to metal with hydrogen.

In recent years world production has been in the range 100 to 120 tonnes per year, including recycled material. The vast majority of this production is concentrated in China.

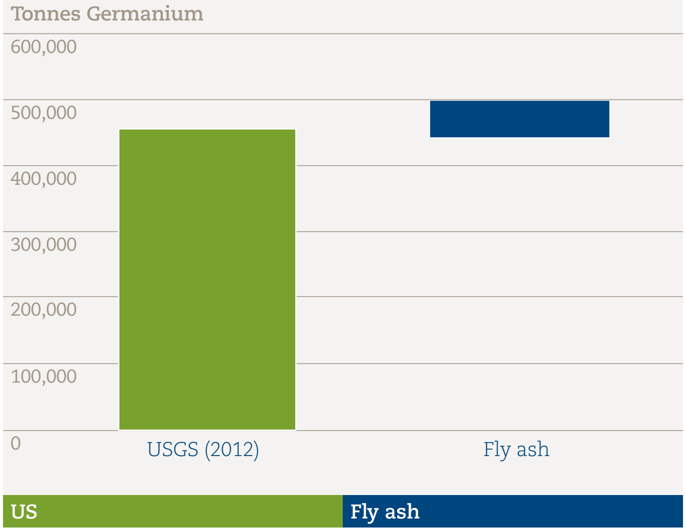
Resources and geography

Crustal abundance is 1.6-6.7 ppm. However, it is widely dispersed and only a few mineral deposits containing germanium have been produced economically.

United States reserves are estimated by the USGS at 450 tons. The USGS do not report reserve figures for other countries. Though the USGS recognise that there are germanium resources in zinc ores, lead-zinc-copper sulphide ores and in the fly ash produced by coal fired power stations, no estimate is published.

Ullmans Encyclopedia of Industrial Chemistry presents estimates of the concentration of germanium in various zinc concentrates, copper ores and coal fly ash. These resources exist in a range of countries including in zinc deposits in the United States, Canada, Namibia, France, Italy and Austria, in copper deposits in the United States and in coal in the United Kingdom. While this gives an indication of geographical location, reserve or resource estimates are not given.

Germanium reserves



Source: USGS (2012)

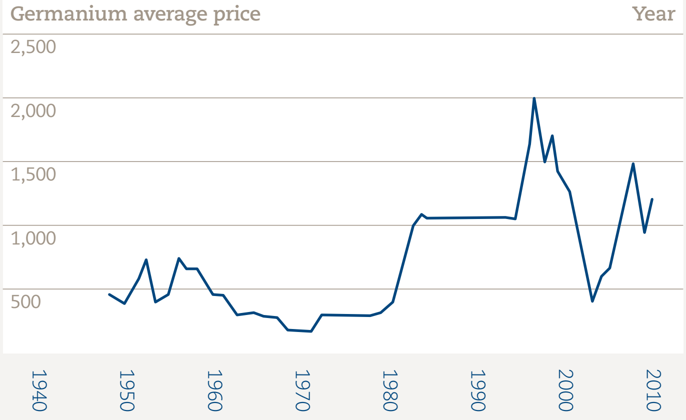
Market factors

Global consumption of germanium is expected to increase in the future due to growth in glass, fibre optics and solar panel manufacturing for both terrestrial and space applications. The solar panel market is expected to be a significant driver of future germanium demand.

The price of germanium has been volatile for over a decade, with average year-on-year variation of around 20% in every year since 2000 and total price range of between ~$500 and ~$1,500 per kg over the same period.

Supply of germanium is largely driven by demand for zinc. This makes it difficult for germanium supply to respond to price signals, which feeds back, creating more volatile prices. By 2009 a decreasing germanium price resulted in many germanium projects being halted or delayed. As a result of the global economic downturn, zinc production decreased, decreasing germanium production. However, as demand returned, germanium prices increased again as supply tightened.

Germanium average yearly price



Source: USGS (2011)

UKERC
UK Energy Research Centre

Indium
Fact sheet

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High future demand for indium is anticipated due to expected increases in thin film PV manufacturing

Indium is most commonly recovered during the production and refining of zinc.

Indium was discovered in 1863 by German chemists Ferdinand Reich and Heironymous Richter.

They identified the existence of a new metal from the presence of indigo blue lines in the spectrum of a zinc ore. Indium metal was isolated a year later and was named after the colour of the spectral lines. Indium is silver in colour and very soft.

Indium does not occur naturally in its native state but is found as a trace element in a number of sulphide minerals. Zinc bearing minerals typically contain the highest concentration of indium, followed by lead and copper minerals. As such indium is most commonly recovered during the production and refining of zinc.

Concerns over future indium availability arise as a consequence of forecast demand in the thin film PV manufacturing sector.

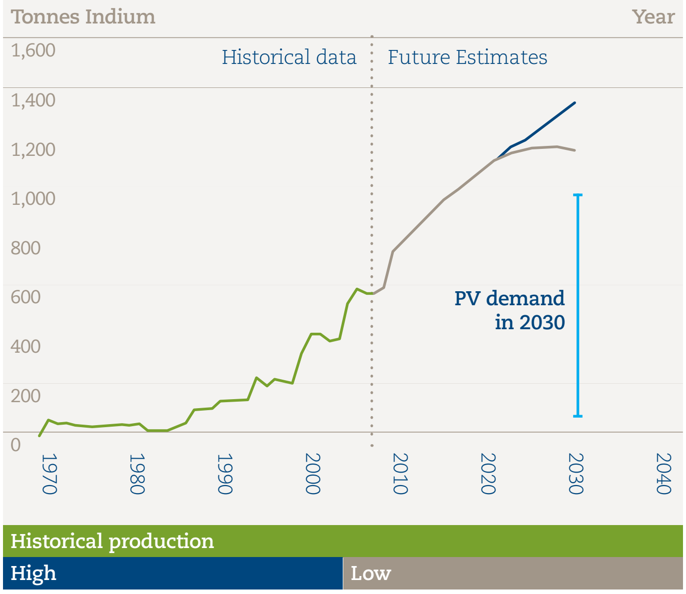
Key Facts

Symbol	In
Atomic number	49
Density (g/cm³)	7.31
Crustal abundance (ppm)	0.16 - 0.25
Energy-related uses	Thin-film PV

Key points

- High future demand for indium is anticipated due to expected increases in thin film PV manufacturing
- Most indium supply is as a by-product of zinc production
- Efficiency of indium recovery techniques is relatively high, but these techniques are not always applied and indium is discarded in mine waste
- Some believe that these wastes can be exploited in the future, and that they represent a significant resource that should be accounted for
- Indium is recycled within the manufacturing process, though end-of-life modules are often not recycled

Historical production, forecast supply, and estimated future PV demand



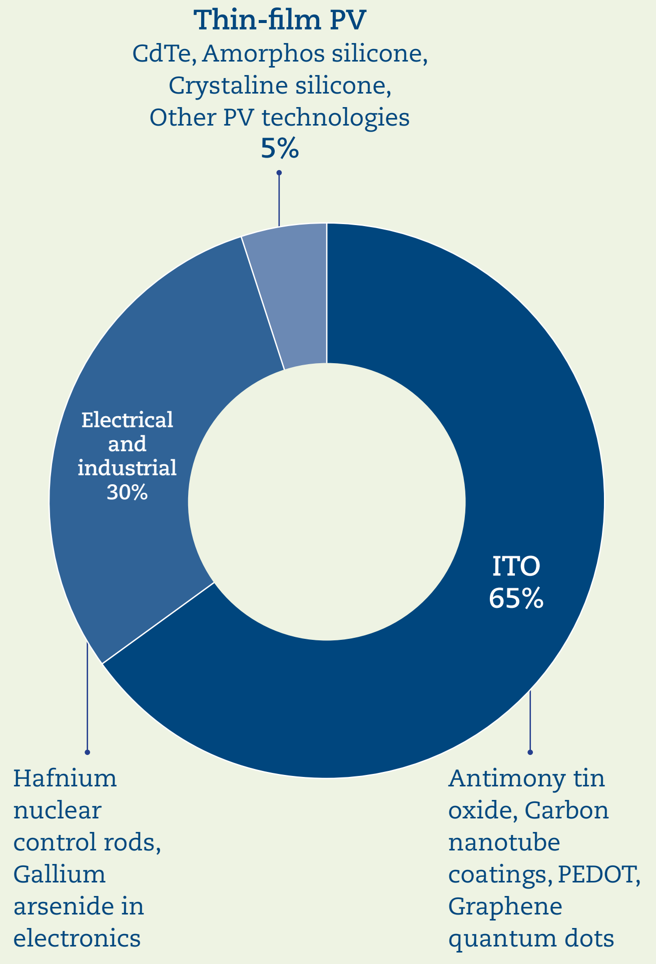
Source: USGS (2012); Speirs et al (2011); Fthenakis (2009)

2007 Data (Tonnes)

Country	Production	Reserves
United States	–	280
Belgium	30	–
Canada	50	150
China	250	8,000
France	10	–
Japan	50	–
Korea	85	–
Peru	6	360
Russia	17	80
Other	15	1,800
World Total	**513**	**10,670**

Source: USGS (2008)

End uses and substitutes

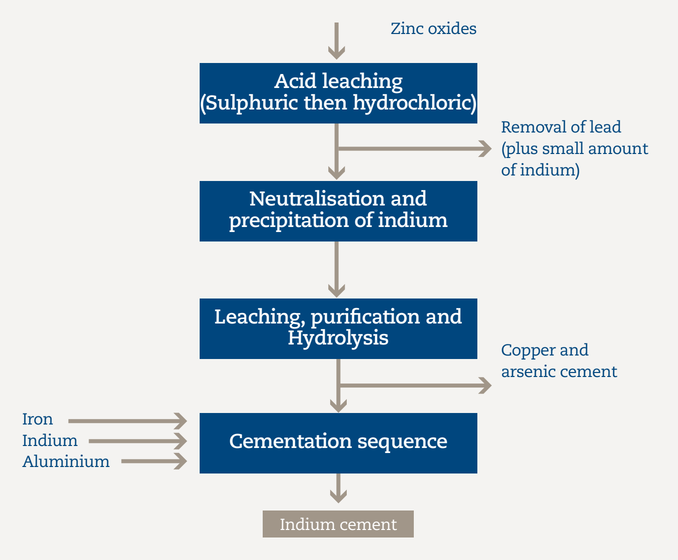


Source: USGS (2012)

Production, extraction and refining

The most important zinc ore is sphalerite, which can typically contain 10-20ppm indium. The mined ore is crushed and milled to a fine powder which is then concentrated by froth flotation to separate ore minerals.

Indium production from Zinc



Source: Ullman & Bohnet (2012)

The concentrated sulphide is roasted in air to convert the sulphide to oxide. The oxide is converted to zinc metal either by high temperature smelting or by acid leaching and electrolysis. When the lead content of the concentrate is high, it is fed in lump form with metallurgical coke to a blast furnace which is heated to about 950˚C by injection of hot air into the base of the furnace. The air converts coke to CO which reduces zinc and lead oxides to metal. The zinc metal exits the top of the furnace as vapour. Approximately half the indium contained accompanies the zinc from which it can be separated. The remainder stays with lead and other impurities in the furnace and is lost.

In the leaching process the calcined ore is dissolved in sulphuric acid. Before electrolysis, iron is removed as jarosite or oxide then zinc powder is added to remove other impurities including the indium. These impurities are selectively re-dissolved in hydrochloric acid then selectively re-precipitated with copper dust. In this way impure indium metal is produced.

Impure indium is refined electrolytically using an acid electrolyte, usually hydrochloric acid. The impure metal is cast into bars or slabs which form the anodes. Pure indium is rolled into sheets to form the cathodes. Repeated refining produces indium of 99.9999% (6N) purity; this level of purity being required for some applications.

Resources and geography

Based on indium content of zinc ores the world reserves are estimated to be approximately 11,000 tons. Major indium producers claim that with improved recovery rates from zinc ores and extracting indium from tin and copper minerals future indium production can be increased.

The largest producer of indium is China, which produced about half the world's indium in 2009. Other producers include Canada, Japan, Republic of Korea and Peru.

Indium reserves have not been published by USGS since 2008 with unreliable data given as reason. In 2007 USGS reported that China produced more than it had in reserves, suggesting inaccuracy in the data available at the time.

Some suggest that resource estimates could be increased significantly through improving recovery factors, exploiting indium associated with other base metals, and by exploiting zinc mine wastes.

Indium reserves

Source: USGS (2012); Mikolajzak & Jackson (2012)

Market factors

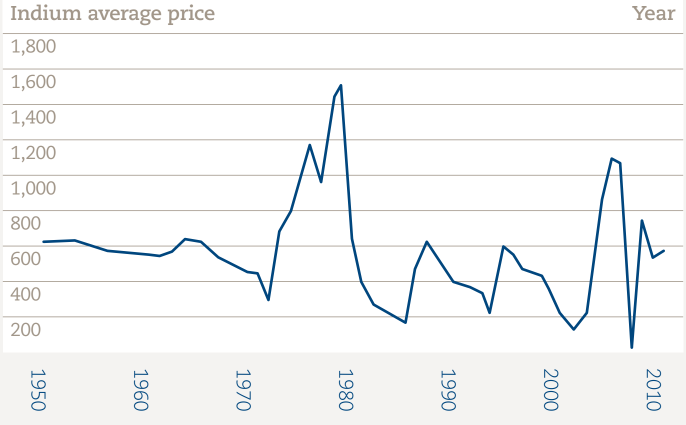
Indium has many applications including the compound indium tin oxide (ITO) used in coatings for sodium street lightings to improve efficiency or as a transparent conductive layer in flat panel displays and thin-film PV.

Flat panel displays account for approximately 65% of annual indium production. However, given concerns over future cost and supply many display manufacturers hope to develop low cost alternatives. If indium was substituted in this way then its availability would become less concerning and thin film PV manufacturing may not be affected.

Indium recycling from end-of-life scrap is unknown and likely small. Recycling of indium within the manufacturing process however, is extensive, particularly recycling of ITO from flat panel display manufacture. Total tonnage of recycled indium is unknown.

The indium price has generally increased in recent years, though volatility can be seen in the figure below. This is the result of increasing demand for flat panel displays, and the Chinese indium export quota, which was unchanged in 2011 at 233 tonnes per year.

Indium average yearly price



Source: USGS (2011)

Lithium

Fact sheet

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Demand for Li-ion electric vehicles and Li-ion consumer electronics raises concerns for future supply of lithium

The new metal was named lithium after the Greek word lithos meaning stone.

In 1817 Johan August Arfwedson discovered the new element lithium in the previously discovered ore petalite. The element formed compounds similar to those of the alkali metals sodium and potassium.

Lithium is also found in the minerals spodumene and lepidolite, and recovered from brine deposits typically found beneath salt flats and dried lake beds. Lithium is abundant but often found in diffuse concentrations. Sea water contains large quantities of lithium, but at such low concentrations it is unclear whether its recovery will become economic.

Lithium has been increasingly used in Li-ion battery technologies due to the desirable properties of these cells. Li-ion batteries are commonly found in consumer electronics though it is their use in electric vehicles that has triggered concern regarding future lithium availability.

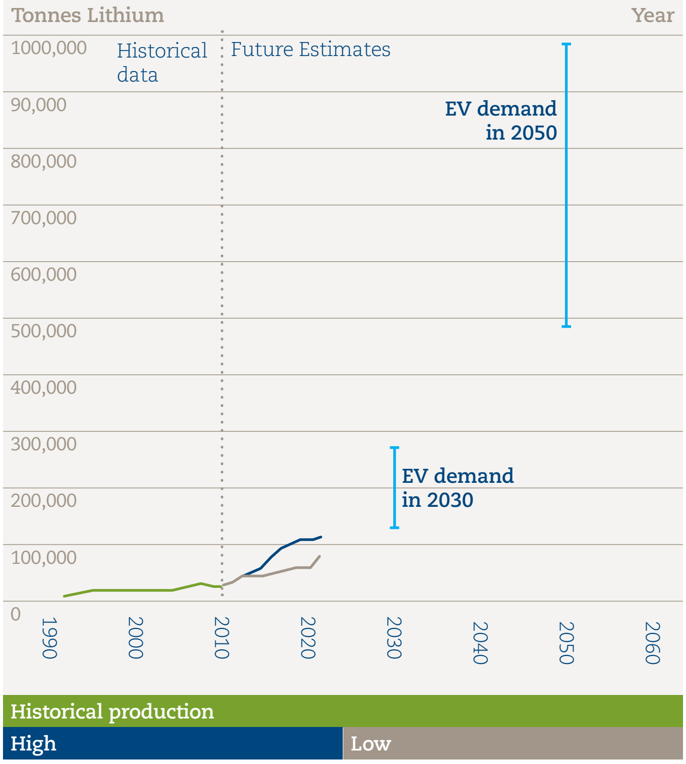
Key Facts

Symbol	Li
Atomic number	3
Density (g/cm³)	0.534
Crustal abundance (ppm)	17-20
Energy-related uses	EV batteries

Key points

- Demand for Li-ion electric vehicles and Li-ion consumer electronics raises concerns for future supply of lithium
- Lithium is currently recovered from ore or from brines present in salt flats
- Lithium in electric vehicles could be a significant source of recycled material in the future once batteries reach the end of their useful lives
- Reserves and identified resources of lithium are extremely large
- However, growth of lithium demand from electric vehicles could be orders of magnitude greater than current production

Historical production, forecast supply, and future estimated EV demand



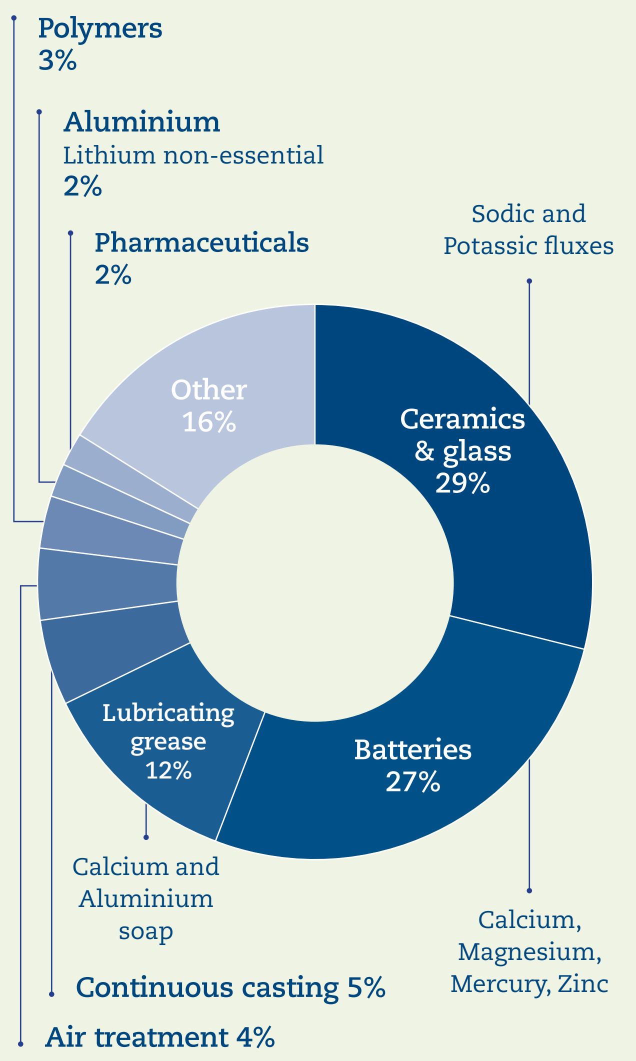
Source: USGS (2012); Speirs et al (2013)

2011 Data (Tonnes)

Country	Production	Reserves
United States	–	38,000
Argentina	3,200	850,000
Australia	11,300	970,000
Brazil	160	64,000
Chile	12,600	7,500,000
China	5,200	3,500,000
Portugal	820	10,000
Zimbabwe	470	23,000
World Total	**34,000**	**13,000,000**

Source: USGS (2012)

End uses and substitutes

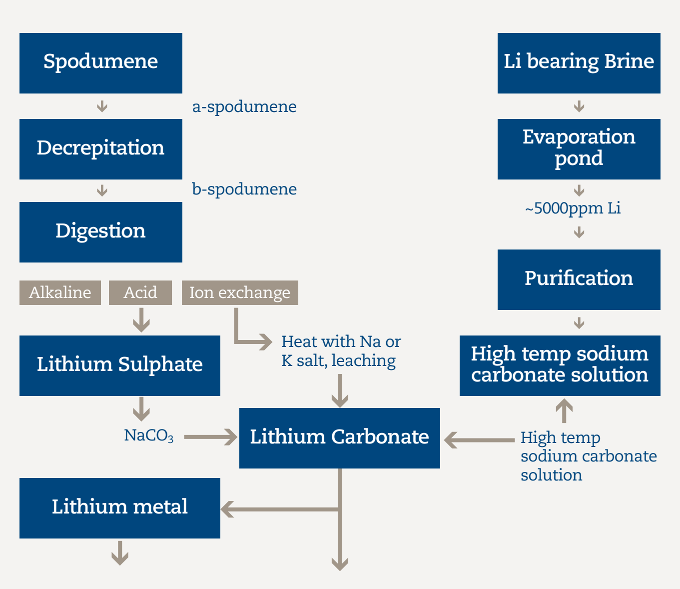


Source: USGS (2012)

Production, extraction and refining

Lithium is most commonly produced from the ore spodumene, or through the concentration of brines.

Lithium production from Spodumene and Brine



Source: Ullman & Bohnet (2012)

Spodumene ore is roasted at 1100˚C to convert it to a form more amenable to crushing and milling to powder, which is required for concentration by froth floatation. The concentrate is then leached with sulphuric acid at high temperature to give lithium sulphate solution. This is leached away from the remaining solids using hot water. The sulphate liquor is then treated with soda lime to remove impurities of calcium, magnesium and iron. It is then re-neutralised with more sulphuric acid and concentrated to 200 – 250 grams per litre Li_2SO_4. The carbonate is formed by addition of sodium carbonate.

Lithium contained in brines is concentrated by evaporation in ponds. The concentration process is particularly effective because lithium chloride has a very high solubility. However yields are reduced in the presence of other metals especially magnesium. The concentration of lithium in the liquor rises to about 6% at which point it is treated with sodium carbonate to precipitate lithium carbonate. Lithium carbonate can be converted to lithium metal through treatment with hydrochloric acid and electrolysis.

World production of lithium in 2011 was ~34,000 tonnes. Large producers in 2011 include Australia (ore), producing ~11,000 tonnes and Chile (brine), producing ~12,000 tonnes. There are also a host of smaller producers including Argentina, Brazil, China, Portugal and Zimbabwe.

Resources and geography

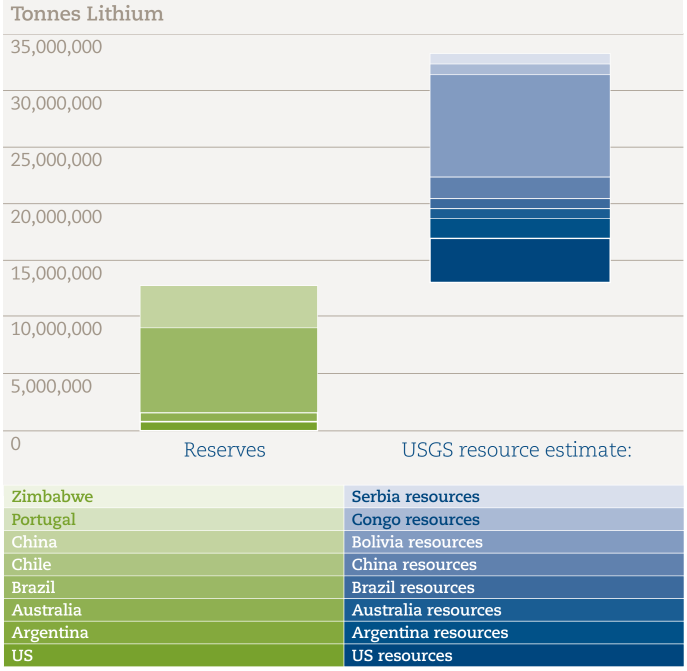
Lithium metal is too reactive to be found in its natural state, but is widely distributed in seawater and in ores at low concentrations.

The minerals spodumene and petalite are the two most commercially developed ores for the extraction of lithium. Crustal abundance is quoted as between 17 and 20 ppm.

Lithium is also present in certain brines (salt deposits) from which the metal can be extracted, and brines now represent approximately half of the world's estimated reserves. A much larger resource is potentially available from brines in the salt flats of Bolivia, where resource estimates are 9 million tonnes. However, these deposits are not currently commercial and it is unclear how much of this resource will ever be classified as reserves. It has been reported that large Li bearing salt deposits also exist in Western Afghanistan.

Finally, a significant lithium resource exists in seawater. Some estimates suggest the resource contains ~45 billion tonnes of lithium, but it is unlikely that this resource will be economically producible in the near to medium term future.

Lithium reserves and resources

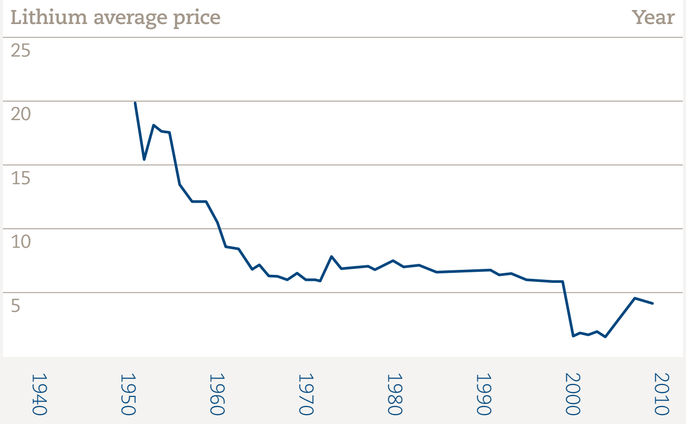


Source: USGS (2012)

Market factors

The future lithium market is expected to increase significantly driven by demand for automotive Li-ion batteries.

Lithium average yearly price



Source: USGS (2011)

The weight of lithium required in vehicle batteries is ~100-500g per kW. Electric vehicles can contain anything from 30-185kW of battery power. If electric vehicle markets grow at even the most conservative forecast rate vehicle lithum demand alone could become orders of magnitude greater than current production.

Lithium recycling from end-of-life batteries is a significant potential source if lithium supply in the future. However the availability of this resource will be delayed by the average lifetime of electric vehicle batteries. In addition, there is very little evidence of the commercial cost and efficiency of automotive Li-ion battery recycling.

The future price of lithium will dictate both how much of the marginal resource is available and how feasible automotive Li-ion battery recycling will be. However, there may be a tension between the higher prices needed to deliver resource availability, and the need for cost reduction in the technologies using lithium, such as electric vehicles.

UKERC
UK Energy Research Centre

Platinum Group Metals
Fact sheet

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Platinum Group Metal (PGM) demand is expected to increase in the future, driven by uses in automotive catalysts and fuel cells

The platinum group metals (PGMs) comprise six transition metals platinum, ruthenium, palladium, iridium, rhodium and osmium.

They are grouped closely together in the periodic table of the elements, appearing in groups 8, 9 and 10 of periods 5 and 6.

They share similar chemical properties: they are non-reactive and resistant to chemicals. For these reasons they can be found naturally in the metallic form, often alloyed with other metals in the group.

They are found in alluvial and placer deposits in Colombia, Canada and the Ural mountains in Russia. The platinum group metals are also recovered as by-products from the mining and processing of nickel and copper ores. This is now the chief source of the metals, major producers being South Africa, Russia and Canada.

The metals are very rare in the earth's crust: of the ten least abundant elements on earth six are in the platinum group. Concern over their availability has potential impacts on their use as catalysts in hydrogen fuel cell technologies.

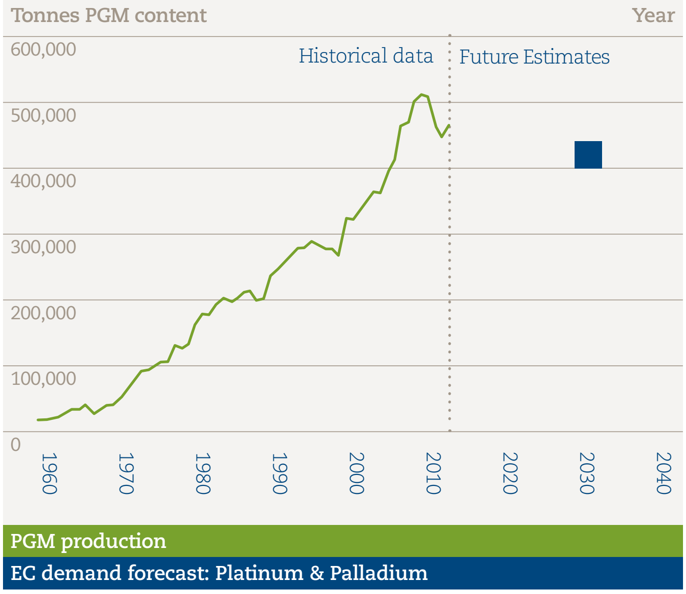
Key Facts

Symbols	Ru,Rh,Pd,Os,Ir,Pt
Atomic numbers	44,45,46,76,77,78
Density (g/cm^3)	12.41-22.59
Crustal abundance (ppm)	0.0007-0.015
Energy-related uses	Fuel cell catalyst

Key points

- Platinum Group Metal (PGM) demand is expected to increase in the future, driven by uses in automotive catalysts and fuel cells
- Most PGMs are produced as by-products of copper and nickel production, or as co-products of PGM ores
- Though only small quantities of PGMs are present in copper and nickel ores, the significant volume of ore processed gives rise to appreciable quantities of PGMs
- PGMs are typically only substituted by other PGMs
- PGMs are precious metals, and their price reflects both their use as a financial hedging tool and supply-demand economics around conventional end uses

Historical production and forecast demand for platinum and palladium



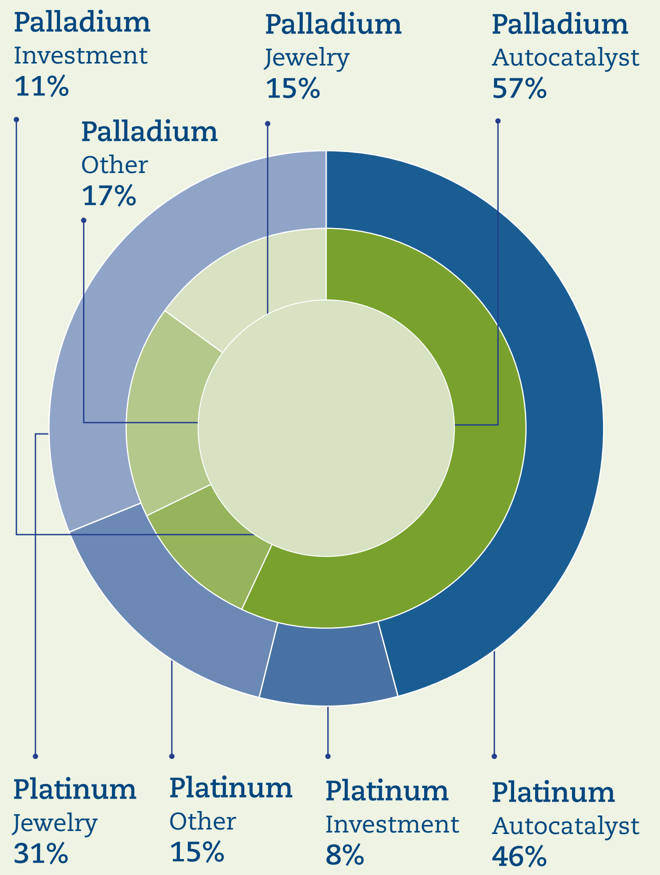
Source: USGS (2012); EC (2010)

2007 Data (Tonnes)

Country	Production		Reserves
	Platinum	Palladium	
United States	3.7	12.5	900
Canada	10	18	310
Colombia	1	–	–
Russia	26	85	1,100
South Africa	139	78	63,000
Zimbabwe	9.4	7.4	–
Other	2.5	6.1	800
World Total	**192**	**207**	**66,000**

Source: USGS (2012)

End uses



Source: USGS (2012)

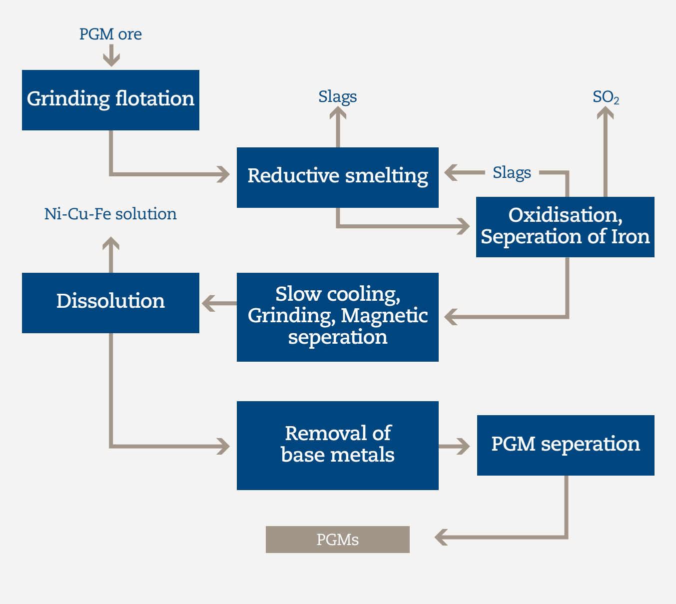
Production, extraction and refining

PGMs can be recovered from PGM ore, but are more commonly produced as by-products of copper and nickel processing.

During the electrolytic refining of these base metals, PGMs are concentrated in the anode slimes. The slimes are first roasted in air with sodium carbonate to remove selenium and tellurium. The remaining residue is leached with aqua regia to dissolve gold, platinum and palladium. The gold is precipitated by addition of ferric chloride solution then platinum can be precipitated by addition of ammonium chloride. Platinum metal is then produced by heating or by cementation using zinc metal. Palladium can be precipitated by addition or mercuric cyanide. Heating the resulting palladium cyanide yields palladium metal. Rhodium is then leached as rhodium sulphate using sodium bisulphate (NaHSO4) and water. The remaining three PGMs residue, containing ruthenium, iridium and osmium is treated with sodium oxide which produces salts, from which the remaining three PGMs can be extracted.

Major producing countries are the Republic of South Africa, Russia, Canada and the USA. Global production of platinum and palladium are 192 tonnes and 207 tonnes respectively.

Extraction of PGM from Ore



Source: Ullman & Bohnet (2012)

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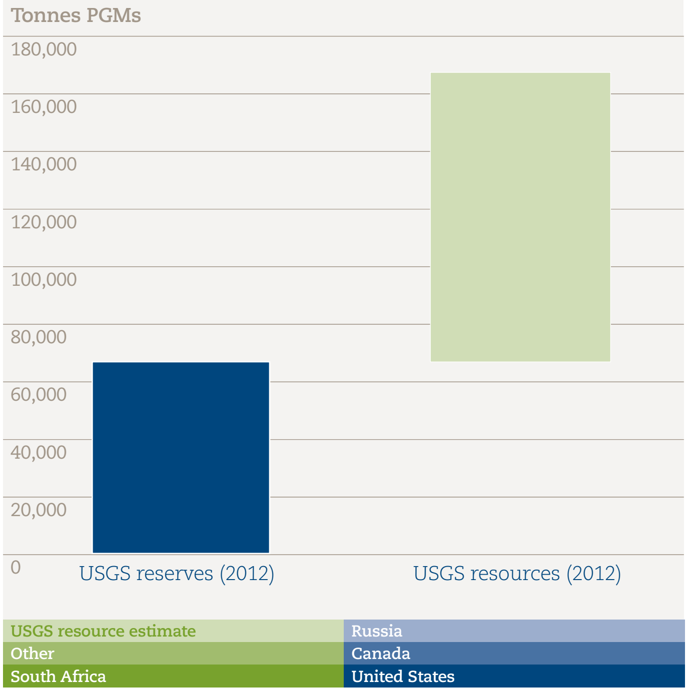
Resources and geography

Although platinum group metals occur naturally as native metal alloys in alluvial and placer deposits, most of the world supply is obtained as by-products of the mining and refining of copper and nickel ores.

The concentration of the platinum group metals in these ores is only a few parts per million. However, the very large quantities of ore processed yield significant quantities of the metals.

In addition to reserves the USGS estimate that over 100,000 tonnes of PGMs could be extracted economically. The largest proportion of this resource exists in the Bushveld Complex in South Africa.

PGM reserves and resources



Source: USGS (2012)

Market factors

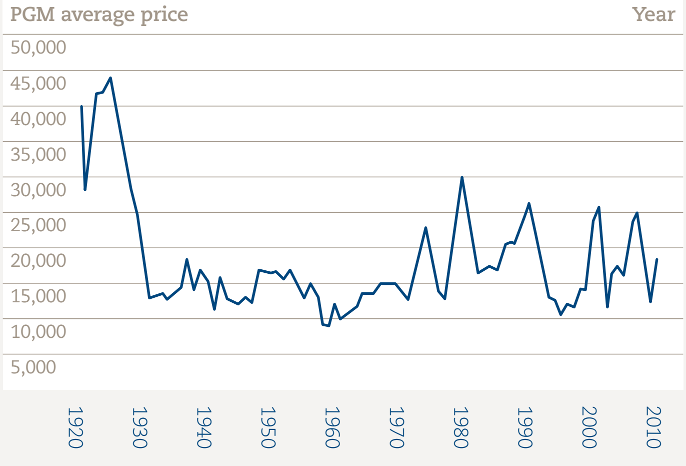
In most technological uses PGMs are usually only substituted for each other, with varying impacts on technological performance. This type of substitution does not mitigate the impacts of supply constraints since PGMs are recovered as co-products of one another.

Being precious metals, the price of PGMs is highly dependent on market sentiment, and the volatility seen in price over the preceding decades reflects both the purchase of PGMs for financial reasons reflecting market conditions and fundamental supply-demand economics around conventional end -uses.

Safety related stoppages, workers strikes and rising production costs contributed to reduced South African PGM production in 2011. This was offset by increases in production from other countries, including Canada, where previous strike action came to an end.

PGMs are recycled from end-of-life scrap, with the USGS estimating that 36 tonnes were recovered from scrap in 2011.

PGM average yearly price



Source: USGS (2011)

Rare Earth Elements

Fact sheet

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Neodymium and dysprosium are of particular concern for energy given their use in magnets used in low carbon technologies

They are grouped together since they occur in the same ore deposits, and exhibit similar chemical characteristics.

The rare earth elements (REEs) consist of the fifteen elements from number 57 to number 71 in the periodic table known as the Lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium holmium, erbium, thulium, ytterbium, and lutetium) plus scandium and yttrium. Due to their similarity and coexistence, it is very difficult to separate them from one another. As a result, the process of identification of the 17 REEs took over a century.

Ytterbite was discovered first (1787), in a quarry in Ytterby, Sweden. Analysis of this mineral indicated an unknown oxide which was named yttria. In Bastnas, Sweden, in 1794 another oxide was discovered, named Ceria. It was 30 years before it was discovered that these oxides each contained other elements. As technology advanced other elements were isolated from known rare earth ores, and by 1901 the final REE, europium, was identified through spectroscopic analysis.

Concern over the availability of REEs is largely driven by their high demand from the growing electronics sector, including use in magnets for low carbon technologies. This is coupled with geopolitical concerns over the concentration of their production in China.

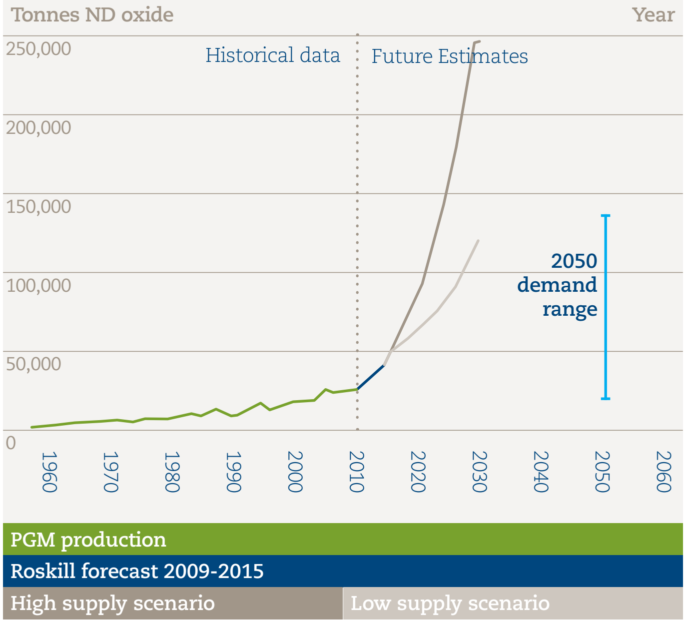
Key Facts

Symbols	Sc,Y,La,Ce,Pr,Nd, Pm,Sm,Eu,Gd,Tb, Dy,Ho,Er,Tm,Yb,Lu
Atomic numbers	21,39,57-71
Density (g/cm³)	2.985-9.841
Crustal abundance (ppm)	0.5-66.5
Energy-related uses	Electric vehicles, Wind turbines, Hydrogen storage, Nuclear batteries

Key points

- Neodymium and dysprosium are of particular concern for energy given their use in magnets used in low carbon technologies
- Reserves are reasonably distributed globally, but China currently produces >90% of global REEs
- Export quotas in China have more recently encouraged investment in non-Chinese production capacity
- Substitutes exist for the key low carbon uses of REEs but these substitutes may affect the characteristics in particular applications affecting performance
- The co-produced nature of REEs and the skewed nature of their relative demand may complicate the economics of their extraction

Neodymium: Historical production, forecast supply and future demand



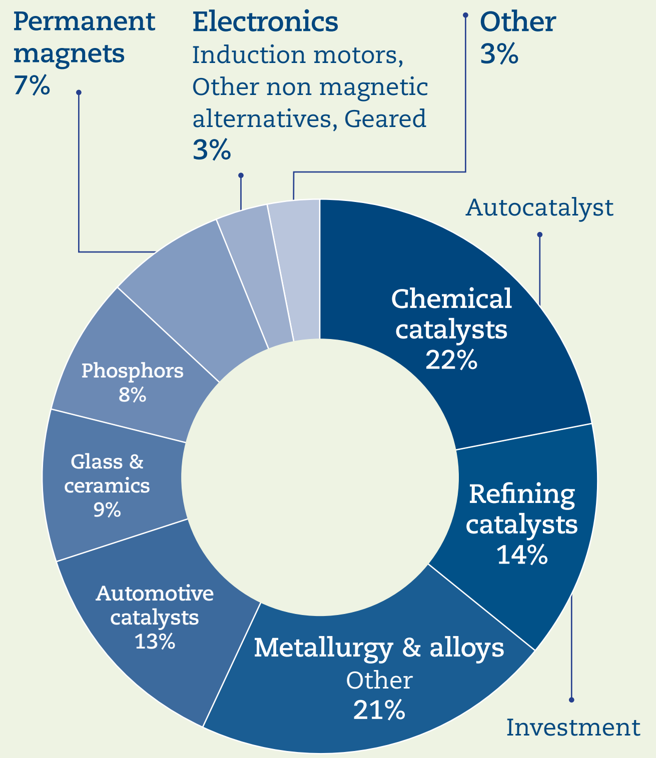
Source: USGS (2012); Speirs et al (2013)

2011 Data (Tonnes REO)

Country	Production	Reserves
United States	–	13,000,000
Australia	–	1,600,000
Brazil	550	48,000
China	130,000	55,000,000
CIS	–	19,000,000
India	3,000	3,100,000
Malaysia	30	30,000
Other	–	22,000,000
World Total	**130,000**	**110,000,000**

Source: USGS (2012)
Note: Data as presented by USGS. Discrepancy between production data and World Total attributed to rounding.

End uses and substitutes

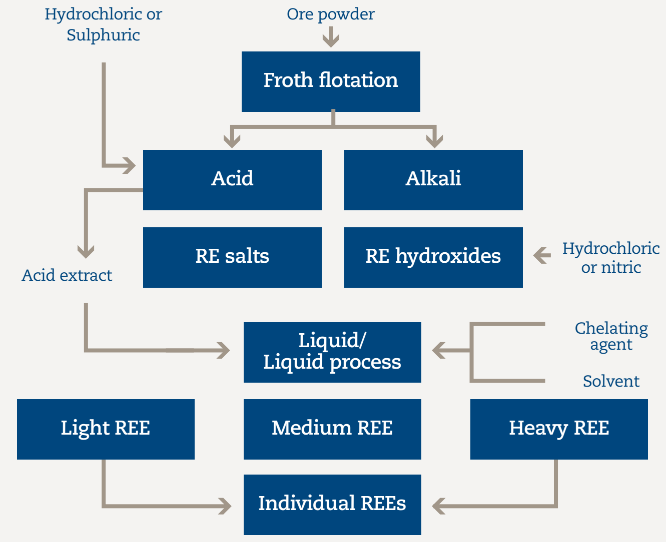


Source: USGS (2012)

Production, extraction and refining

The principal minerals containing rare earth metals are bastnaesite and monazite.

Recovery and seperation of REE from Ore



Source: Ullman & Bohnet (2012)

Ore extraction is mostly by open cast mining. The ore is crushed and milled to a powder (50µm to 1 mm).

Separation of minerals from ore is carried out generally by froth floatation. Treatment of ores with sulphuric or hydrochloric acid converts the metals to soluble salts. Alkaline digestion produces rare earth hydroxides which can then be dissolved in concentrated hydrochloric or nitric acid.

Separation of the rare earth metals is one of the most difficult problems in inorganic chemistry. Liquid/liquid separation is the favoured process. One liquid is the acidic extract from leaching, the other is organic, often containing two components one of which is a chelating agent which is strongly bonding and causes transfer of REEs elements to the organic phase. The two phases are circulated counter current to each other in the extraction plant. The organic phase becomes loaded with REEs that form more stable bonds while those less strongly bonded stay in the aqueous phase. The two phases are separated and the REE content of the organic phase is removed while the separated REE fraction is processed further. Repeated extraction and removal of the metals leads to progressive separation, first into groups of metals and then into individual metals. The processes are complicated and the above account gives only a basic outline.

2011 production was ~130,000 tonnes of rare earth oxide, with the majority produced in China. This trend is likely to change in the future as planned production capacity in other countries is developed.

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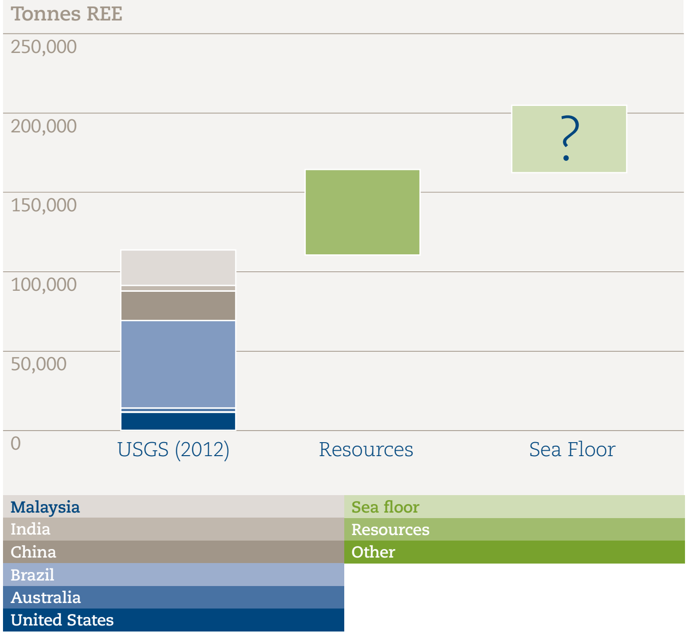
Resources and geography

Before 1950, most REEs came from placer sand deposits in India and Brazil.

During the 1950's large veins of rare earth bearing rock, particularly monazite, were discovered in South Africa, which soon became the primary source of the world's REEs metals. Later (1960-1980) the Mountain Pass Mine in California became the rare earth leading producer.

Today, an estimated 90% of the world's supply of rare earths comes from China, mostly from Inner Mongolia. This concentration of production has precipitated fear over the geopolitical availability of REEs. However, while China produces the vast majority of REEs, its reserves represent <50% of global reserves. As a result of increased world demand and export restrictions countries such as China, Australia, Brazil, Canada, South Africa, Tanzania, Greenland and the USA are all investing in domestic production capacity.

REE reserves and resources



Source: USGS (2012)

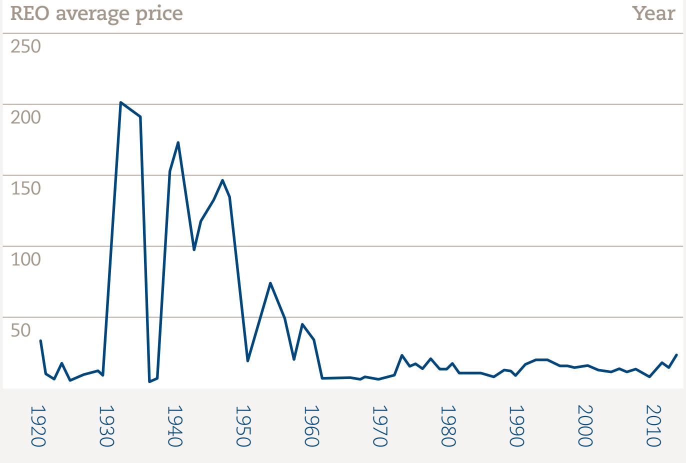
Market factors

REEs are used in many electronic applications, with their demand expected to increase in the future. However, the use of neodymium and dysprosium in magnets for electric vehicles and wind turbines is of most concern for the low carbon transition.

REEs can be split into light, medium, and heavy, with light REEs experiencing highest demand. Neodymium is a light REE and is largely the driver of their demand. This creates a complicated economic picture, with demand creating a positive pressure on neodymium price, incentivizing REE production and potentially encouraging over supply of its co-products. It also places a premium on ores rich in neodymium.

Geopolitical pressures have also created concern, with China limiting exports to 35,000 tons per annum, from 2010 to 2015, to "conserve scarce resources and to protect the environment". However, the price increases associated with these concerns have encouraged investment in non-Chinese production capacity.

REO average price



Source: USGS (2011)

REE prices have generally increased in recent history, driven by decreasing supply associated with export quotas set by the largest REE producer, China. This situation is likely to change as production capacity is developed in several other countries.

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Selenium

Fact sheet

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Future demand for selenium containing PV modules may generate significant increases in demand

Selenium is a red or dark grey element, largely exhibiting non-metalic properties, and with similarities to sulphur and tellurium.

It was discovered by Jons Jacob Berzelius in 1817, who found a red precipitate during the production of sulphuric acid produced at from pyrites (FeS_2).

Initially mistaken for an arsenic compound, and subsequently a tellurium compound, Berzelius finally identified the new element in 1818. It was named selenium after the Greek word selene, meaning moon.

Selenium exists naturally in the elemental form but only rarely. It also occurs as selenides, selenites and selenates. Most importantly it exists in trace quantities in sulphide ores of other metals, in which it replaces a small proportion of the sulphur.

Naturally occurring selenates and selenites are soluble in water so can be leached into rivers, therefore sea water contains significant quantities of selenium. Crustal abundance is reported to be 0.05 ppm, making it the 12th rarest element. Recent concern over supply of selenium is largely driven by the expected demand arising from thin film PV manufacturing.

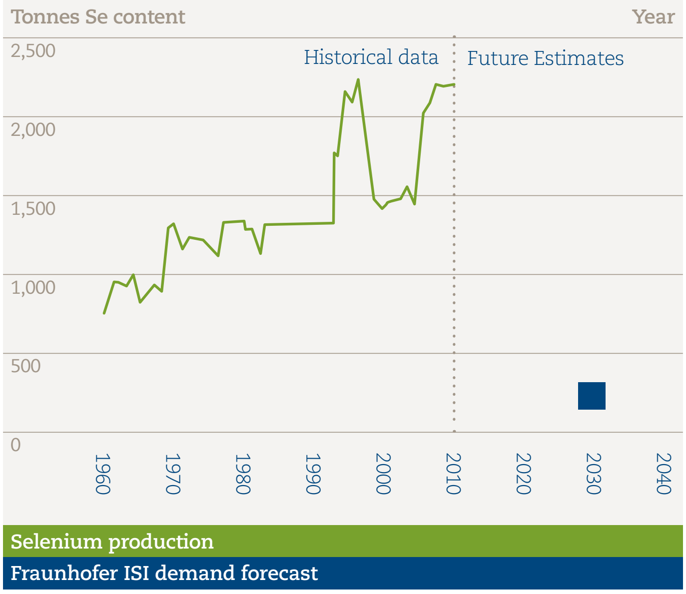
Key Facts

Symbols	Se
Atomic numbers	34
Density (g/cm^3)	4.28-4.81
Crustal abundance (ppm)	0.05
Energy-related uses	Thin-Film PV

Key points

- Future demand for selenium containing PV modules may generate significant increases in demand
- Selenium supply is largely dependent on the production of the base metal copper
- Potential resources contained in coal may be exploited in the future, increasing reserves estimates
- Selenium can be substituted by other PV types
- Recycling of certain end-of-life products to recover selenium is increasing
- Recovery of selenium from end-of-life PV modules will be delayed by the average PV module lifetime

Selenium: Historical production and forecast demand



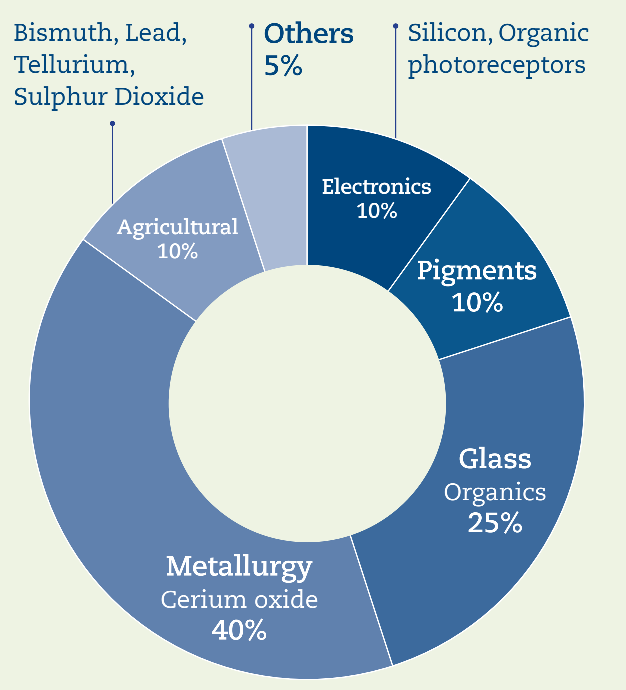
Source: USGS (2012); Angerer et al (2009)

2011 Data (Tonnes)

Country	Production	Reserves
United States	–	10,000
Belgium	200	–
Canada	95	6,000
Chile	90	20,000
Finland	60	–
Germany	650	–
Japan	630	–
Peru	45	13,000
Philippines	70	500
Russia	140	20,000
Other	40	23,000
World Total	**2,000**	**93,000**

Source: USGS (2012)

End uses and substitutes

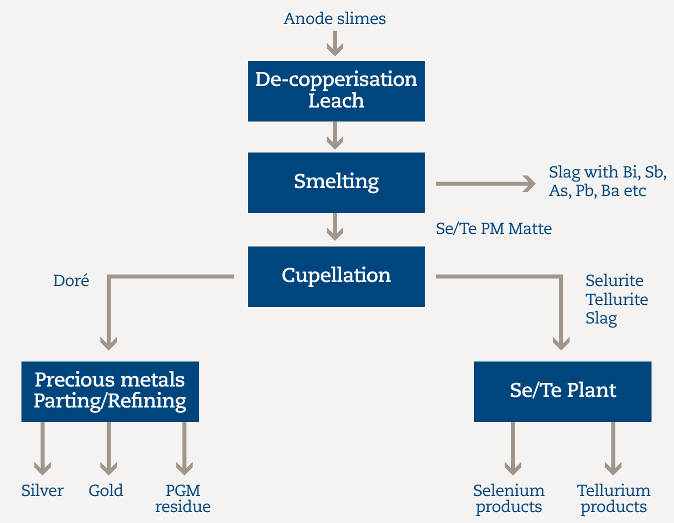


Source: USGS (2012)

Production, extraction and refining

As with tellurium, elemental selenium is recovered as a by-product of the extraction and refining of copper.

Selenium from copper anode slimes



Source: Ullman & Bohnet (2012)

During the electrolytic refining process copper dissolves from the crude copper anode and migrates to the cathode. Impurities in the anode do not dissolve but fall to the tank floor as anode slimes. They contain precious metals, nickel, selenium and tellurium.

Concentration of selenium in these slimes ranges from 0.6% to 19.5%. Selenium is removed by roasting in air with sodium carbonate which forms sodium selenite. This is removed by leaching with water.

World production in 2011 was approximately 2000 tonnes, with Germany and Japan reporting production of over 600 tonnes each. A host of other countries also report production including Russia, Belgium and Canada.

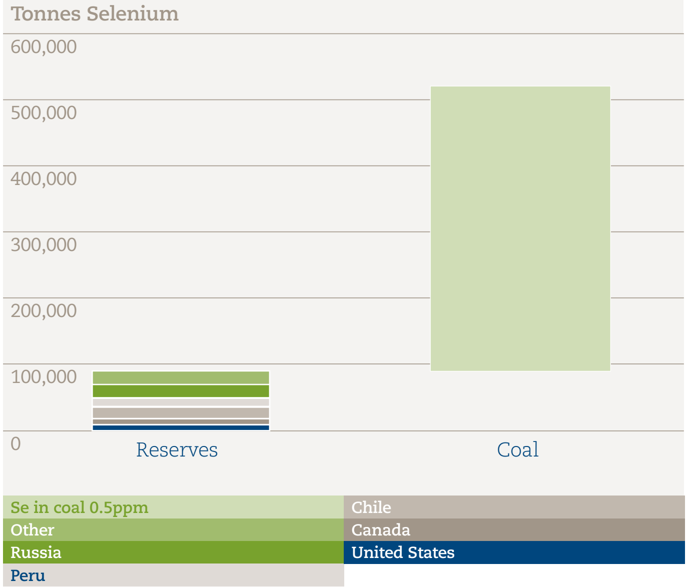
Resources and geography

Currently USGS report global selenium reserves of ~90,000 tonnes, with reserves spread over a number of countries including Canada, Peru and the Philippines.

Chile and Russia report the largest reserve figures at 20,000 tonnes each. The USGS aggregate other reserve endowed countries under the category ‘Other’ to which 23,000 tonnes is attributed. This presents a reasonably balanced picture of reserve endowment, insulating selenium production somewhat from geopolitical factors.

A potentially significant resource of selenium exists in coal, and the USGS estimate this resource to be 80 to 90 times more concentrated than selenium in copper ores. Though it is unlikely that all of this can be recovered it does indicate the potential to grow the reserve in the future, particularly if global selenium prices increase.

Selenium reserves and resources



Source: USGS (2012); BP (2012)

Market factors

In the 1870s, selenium was found to exhibit certain photo electric properties which were developed by Werner Seimens.

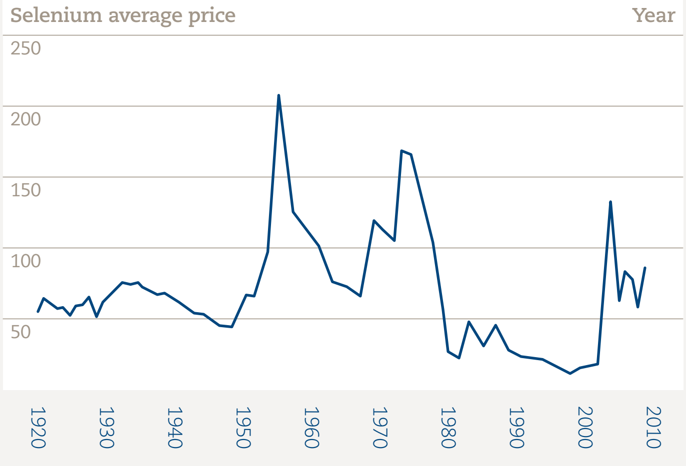
In particular it was found to produce electric current proportional to the amount of light to which it was exposed. Later, its semiconductor properties found applications in electronics leading to its current use in thin-film PV manufacturing.

As with other co-produced materials the production of selenium is dependent not only on its own demand but also on the demand for the base metal with which it is associated.

Selenium is increasingly recovered from end of use products, particularly uses in rectifiers and photocopying drums. Recycling is therefore a growing market. However, recycling from PV applications is likely to increase gradually, and as with other end-use recycling, will be delayed by the average useful life of the PV modules it is used in.

Selenium price has increased in recent years, driven by increasing consumption and a slight decrease in production.

Selenium average yearly price



Source: USGS (2011)

Silver
Fact sheet

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Silver demand in PV is expected to increase in the future, influencing availability and ultimately price

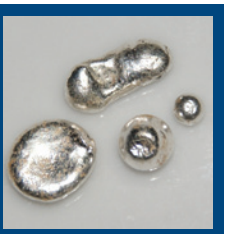
Silver is a group 11 transition metal, with soft, white, lustrous characteristics, and the highest electrical and thermal conductivity of any metal.

It is malleable and has long been used for ornaments, flatware and coinage. Archeological evidence suggests that silver has been in use for over 5000 years.

Silver is commonly found in its native state, and also in the ores argentite (Ag2S) and horn silver (AgCl). It also exists in traces in ores of lead, zinc, copper, nickel and gold, from which the silver can be recovered as a by-product.

Concern over the supply of silver is largely driven by expected future demand in solar applications including crystalline silicon (c-Si) photovoltaics (PV) and Concentrated Solar Power (CSP).

Key Facts

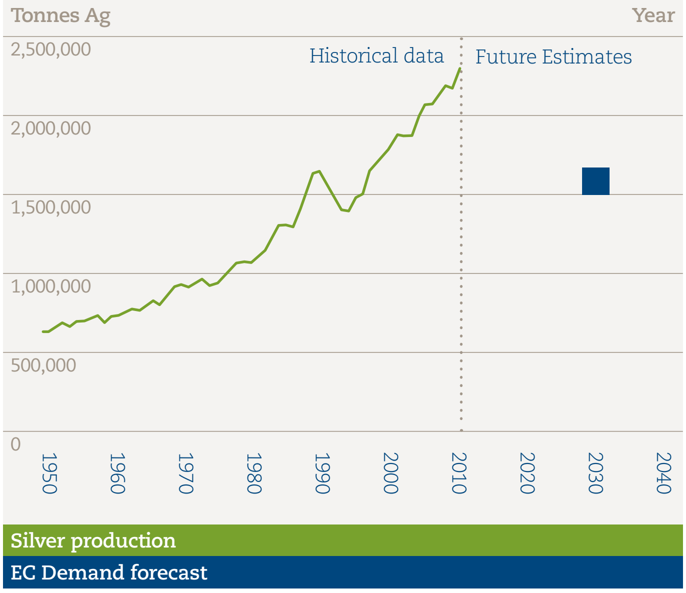


Symbols	Ag
Atomic numbers	47
Density (g/cm^3)	10.5
Crustal abundance (ppm)	0.05-0.1
Energy-related uses	TPV (c-Si), Concentrating Solar Power, Nuclear

Key points

- Silver demand in PV is expected to increase in the future, influencing availability and ultimately price
- Silver is recovered from a diverse range of base metal ores and precious metal ores including true silver ores
- Diversity of silver producers globally will insulate silver markets from geopolitical issues
- Substituting for silver in PV may result in reduced conductivity, though it is likely that silver alternatives will be developed
- Currently recycling is ~7 % of global production, though this could increase with increasing silver price

Silver: Historical production and forecast demand



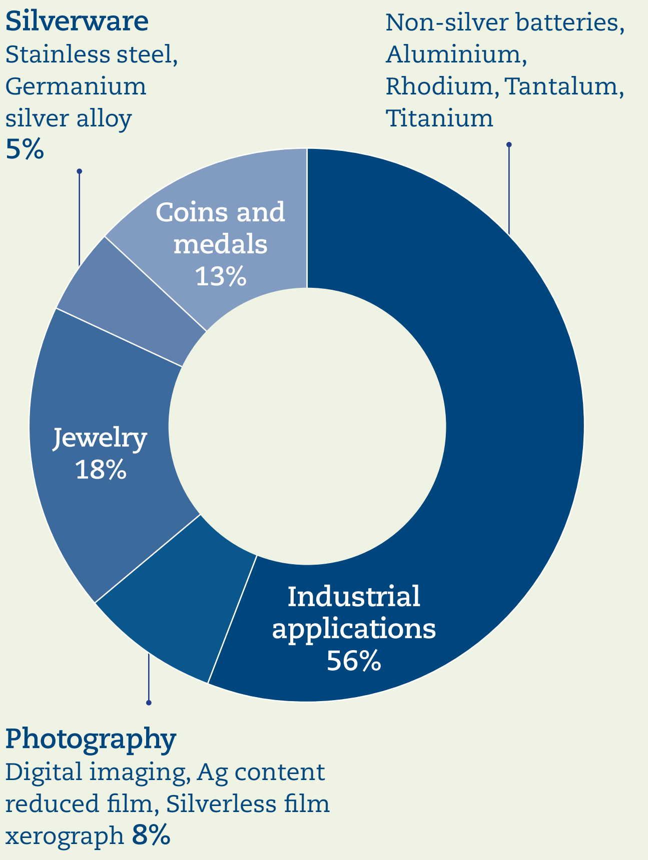
Source: USGS (2012); EC (2010)

2011 Data (Tonnes)

Country	Production	Reserves
United States	1,160	25,000
Australia	1,900	69,000
Bolivia	1,350	22,000
Canada	700	7,000
Chile	1,400	70,000
China	4,000	43,000
Mexico	4,500	37,000
Peru	4,000	120,000
Poland	1,200	85,000
Russia	1,400	–
Other	2,200	50,000
World Total	**23,800**	**530,000**

Source: USGS (2012)

End uses and substitutes

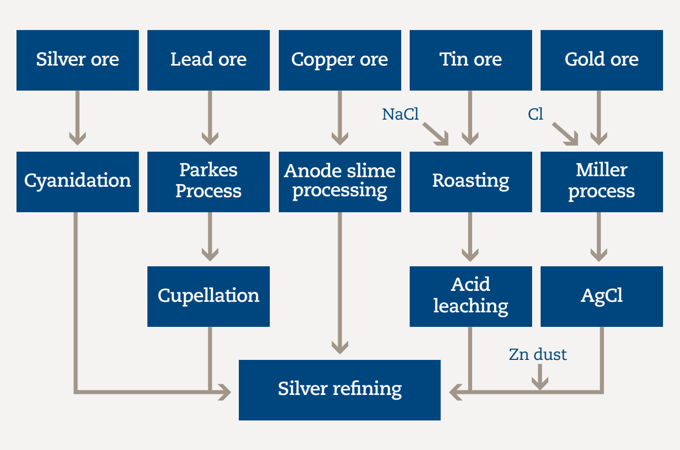


Source: USGS (2012)

Production, extraction and refining

Silver is recovered from a range of different ores including true silver ores, copper ores, lead ores, tin ores and gold ores.

Selenium from copper anode slimes



Source: Ullman & Bohnet (2012)

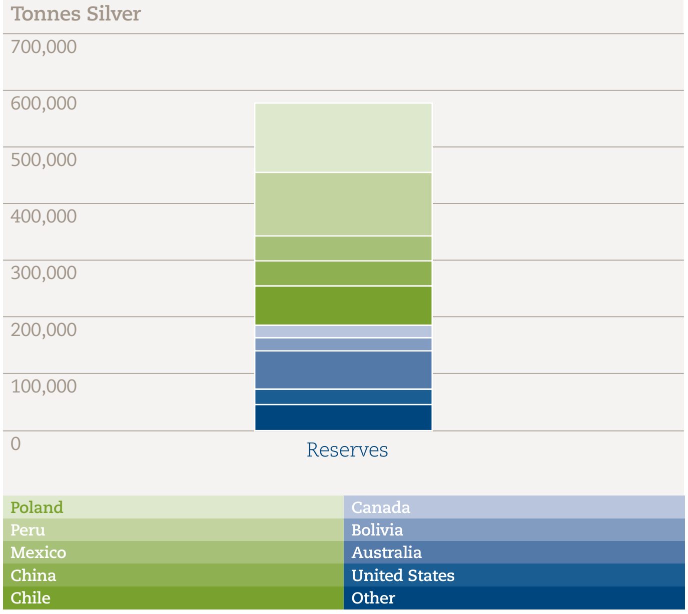
During copper extraction silver follows copper through various processes to precipitate out in anode slimes. Two successful processes for recovery of these metals from the slimes are roasting in the presence of oxidising agents and pressure leaching. Both methods have advantages and disadvantages and the choice often depends on the site condition and location. Precious metals can be extracted using cyanide or thiouria. Silver is produced as doré bullion (98% Ag) which can be refined electrolytically.

Silver can also be recovered during the processing of lead ore, where silver is separated from lead by the Parkes process. This process uses zinc metal to extract the silver. Lead and zinc do not mix. Silver is more soluble in zinc than lead by a factor of 3000. The silver-containing lead is melted and molten zinc is added and stirred. On standing, zinc and lead separate with the zinc floated above the much denser lead. Because of the much higher solubility of silver in zinc, nearly all the silver is contained in the zinc. The two liquids are separated and the zinc is heated to a higher temperature causing zinc to volatilise leaving purified silver.

Resources and geography

Silver resources exist in a number of countries.

Silver reserves



Source: USGS(2012);

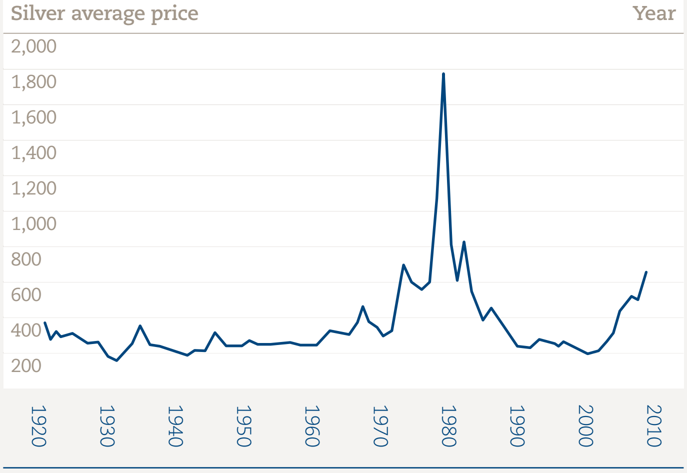
Amongst the top producing mines globally in 2011 Cannington mine, Australia produced ~900 tonnes of silver in association with lead and zinc extraction, Fresnillo mine, Mexico produced ~850 tonnes of silver from silver-lead-zinc ore and the Dukat mine, Russia produced ~380 tonnes silver from silver-gold ore and silver-base metal ore. A relatively large number of other mines spread over a wide geographical area also contribute to silver production, insulating it somewhat from geopolitical influence.

While estimates of silver reserves are available, there are few estimates of the wider silver resource, complicating any estimate of future reserve potential.

Market factors

Silver has a diversity of end-uses, including energy uses such as nuclear reactor control rods. However it is silver’s use in PV that is likely to increase future demand significantly.

Silver average yearly price



Source: Ullman & Bohnet (2012)

Silver is useful in electrical applications due to its high conductivity.

Silver price has been increasing steadily in recent years, incentivising substitution of its uses. However, substitution of silver may come with a loss of conductive performance given silver is the most conductive element known. Silver oxide is also conductive, limiting performance losses through oxidative wear. However, substitution for other materials and other PV technologies is likely to take place.

In the past the silver price has been significantly influenced by investors, who were responsible for the significant price spike in 1980 known as silver Thursday.

In 2011 ~1,700 tonnes of silver was recycled, representing ~7% of global production in that year. This has decreased from recycling estimates of 2,000 tonnes throughout the late 1990’s and early 2000’s. This is likely to increase with increasing silver price.

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UK Energy Research Centre

Tellurium

Fact sheet

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There is a large anticipated demand for tellurium from PV, but CdTe may lose market share to other PV technologies

Tellurium is a crystalline, white-silver substance, which is brittle and easily crushed.

Tellurium is a group 16 metalloid with an atomic weight of 127.6. It was discovered in 1782 by Müller von Reichenstein and named in 1798, from the Greek tellus meaning earth.

Tellurium is occasionally found in low concentrations in its native state, though it is more usually found as precious metal telluride or in association with base metals. The recovery of tellurium is typically reliant on its concentration in slimes arising from the extraction and refining of base metals. Copper ore is the most significant source of tellurium, which is concentrated during the electrolytic refining process, along with precious metals and selenium. Tellurium is also concentrated during the refining of zinc, gold and lead.

Recent concern over supply of tellurium is largely driven by the expected demand arising from thin film PV manufacturing.

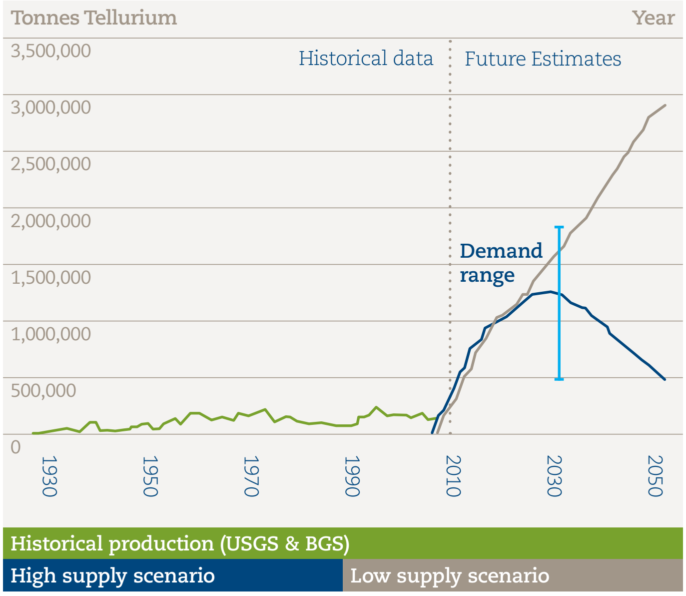
Key Facts

Symbols	Te
Atomic numbers	52
Density (g/cm^3)	6.25
Crustal abundance (ppm)	0.001
Energy-related uses	Thin-film PV

Key points

- There is a large anticipated demand for tellurium from PV, but CdTe may lose market share to other PV technologies
- Most tellurium supply is as a by-product of copper production
- Extraction efficiency of tellurium from copper anode slimes is low but maybe increased
- Substitutability outside PV uses comes with a loss of performance
- Negligible recycling at present since most uses of tellurium are dissipative
- End-of-life recycling from PV modules is possible but delayed by the average PV module lifetime

Tellurium: Historical production forecast supply and future demand



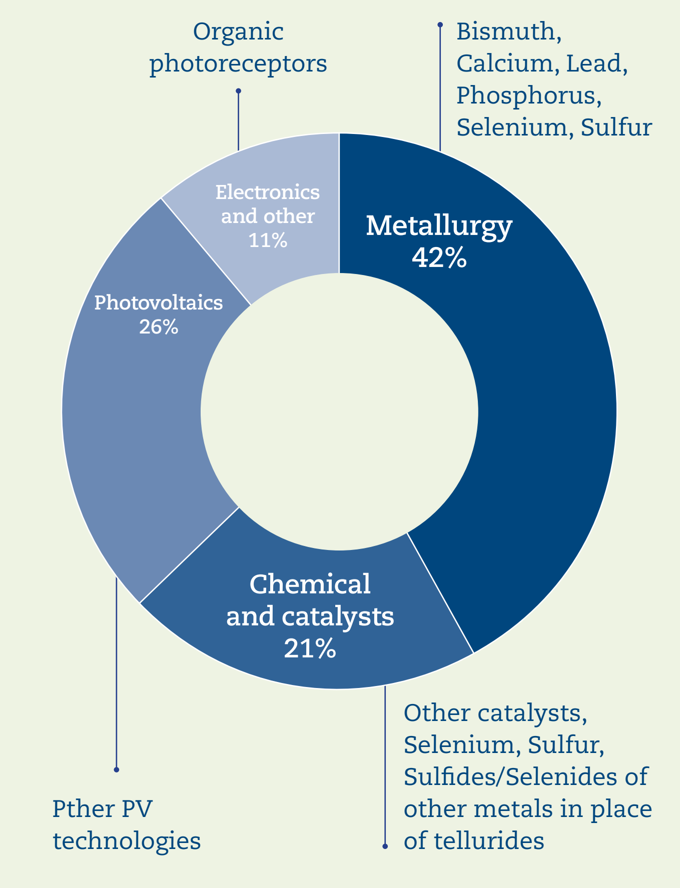
Source: USGS (2012); Speirs et al (2011)

2011 Data (Tonnes)

Country	Production	Reserves
Canada	10	800
Japan	40	–
Peru	30	3,600
Russia	35	–
United States	–	3,500
Other	–	–
World Total	**–**	**24,000**

Source: USGS (2012)

End uses and substitutes

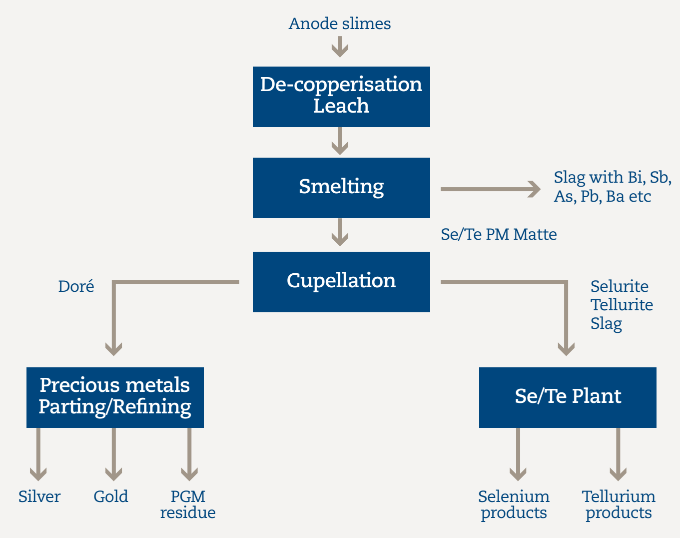


Source: USGS (2012)

Production, extraction and refining

Over 90% of tellurium supply is as a by-product of copper production. The remainder is from skimmings at lead refineries and from flue dusts and gases generated during the smelting of bismuth, copper and lead ores.

Tellerium from copper anode slimes



Source: Ullman & Bohnet (2012)

Tellurium is also found in zinc, silver, and gold ores. As a by-product, tellurium is only extracted from the anode slimes produced during the electrolytic refining of smelted copper. Other copper production techniques such as solvent-extraction and electrowinning are increasingly used and do not produce tellurium. The extraction process for tellurium selenium and precious metals from anode slimes is shown in the flowchart.

The average extraction efficiency of tellurium from anode slimes is 33%. Some authors have suggested achievable future rates of 80%, significantly improving future supply potential. Others note that this is difficult to achieve, in part due to frequently occurring phenomena that limit extraction efficiency, notably re-precipitation of tellurium as other compounds in the post-filter press. While it is clear that increased demand for tellurium will improve the extraction efficiency, the extent to which this factor can increase is unclear.

Resources and geography

Tellurium reserves data typically refer only to those reserves associated with copper, based on an assumed ratio of tellurium per tonne of copper produced.

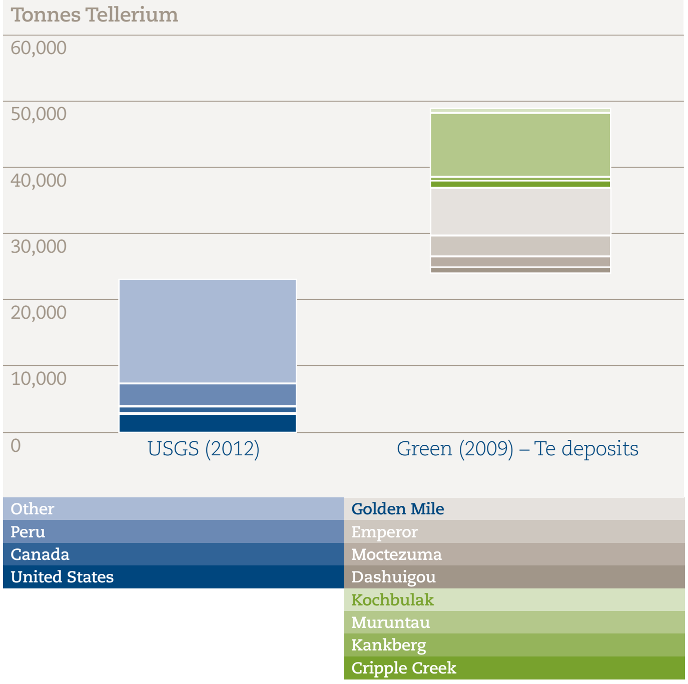
Tellurium reserve estimates could be increased by: a) improving the recovery ratio; or b) including other potential deposits for direct mining of tellurium, e.g. tin, zinc gold or lead deposits with relatively high tellurium content.

Direct mining of tellurium is highly price dependant. Two tellurium deposits have been identified as potentially viable with a tellurium price of $500/kg: Dashuigou (China) and Moctezuma (Mexico). The former has commenced mining operations at about 12 tonnes/annum.

Tellurium reserves are distributed around a number of countries, including Peru, USA, Canada, and a host of other countries with smaller reserves including Australia, Belgium, China, Germany, Kazakhstan, the Philippines, and Russia.

The wide spread of reserves and production across many countries, and the perceived political stability in those countries suggests that geopolitical issues are unlikely to have any significant impact on the availability of tellurium in the foreseeable future.

Tellurium reserves and potential deposits for direct mining



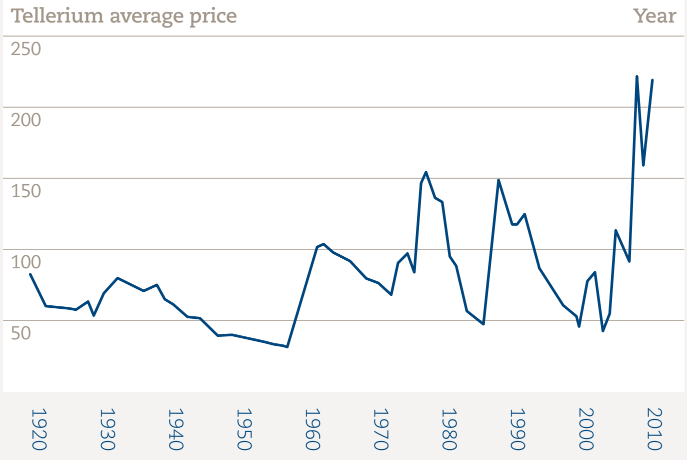
Source: USGS (2012); Green (2009)

Market factors

Future tellurium demand may be driven by the decarbonisation agenda and resultant large scale thin film PV deployment. Significant increase in demand will place positive pressure on the tellurium price, influencing future availability.

Tellurium is not listed on any major commodity exchange, and is traded exclusively by negotiated purchase and bilateral contracts. As a result, price information can only be obtained from trade journals and producer information. The USGS estimated average yearly price of tellurium from 1920-2010 (in 2011 dollars per kilogram) is shown below.

Tellerium average yearly price



Source: USGS (2011)

High tellurium prices may also increase the cost of CdTe PV, reducing demand. Recent studies estimate the maximum allowable tellurium price to keep CdTe PV competitive as $800 in one study or up to $3000 in another.

There is almost no recorded recycling of tellurium from scrap since most traditional uses of tellurium are dissipative.

A very small amount is recovered from used or obsolete photo copiers. Recycling of Cd-Te thin-film PV modules may be a significant source of tellurium in the future, but will only be accessible once current modules have reached the end of their life cycle.

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