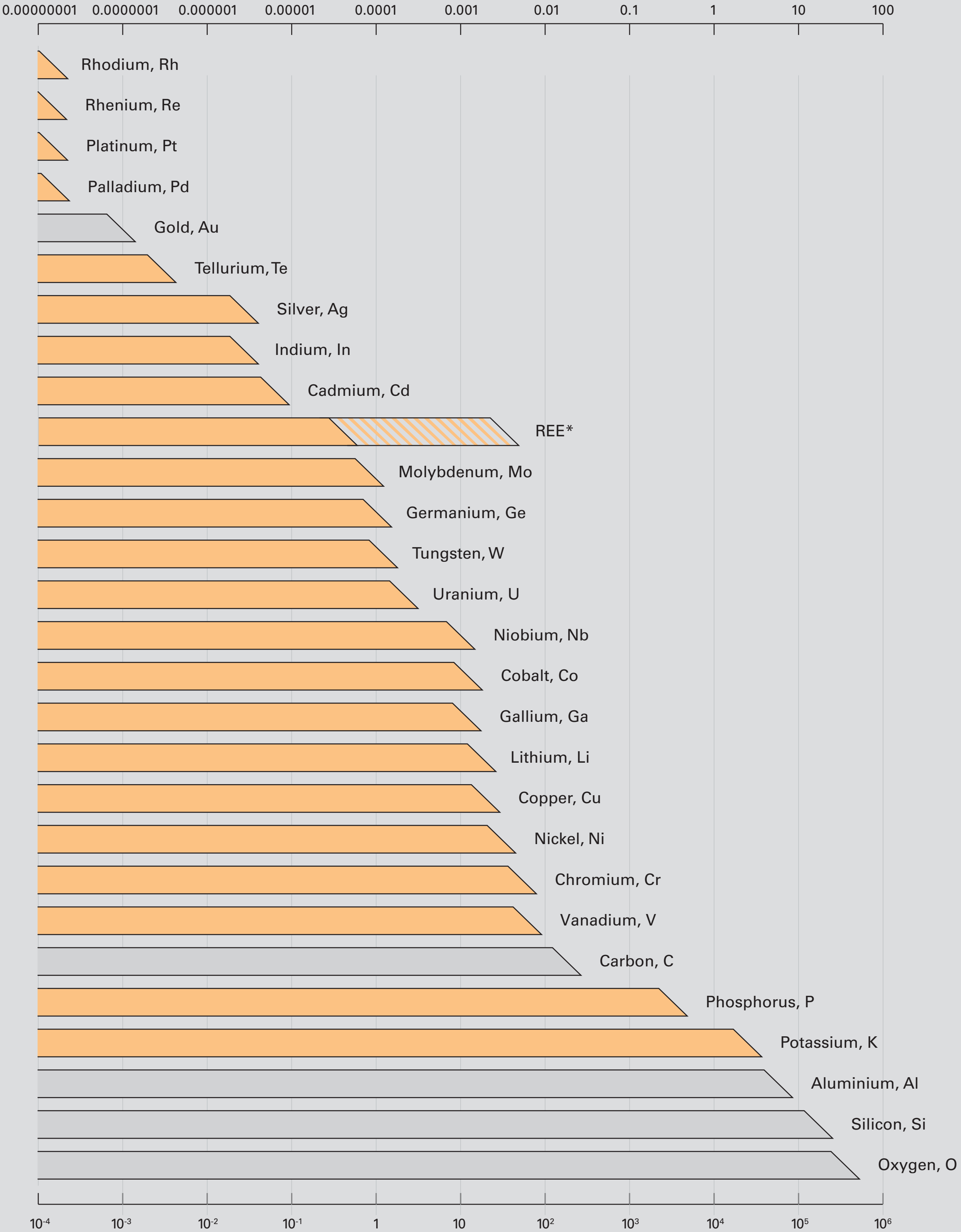
Materials critical to the energy industry
An introduction

SECOND EDITION

Estimates of abundance of elements in the earth's continental crust in percentages (%)



Estimates of abundance of elements in the earth's continental crust in parts per million (ppm)

- The crust is regarded as the rocks above the mantle and separated from it by the Mohorovičić discontinuity. Continental crust averages 20 – 50km thick. The vast majority of mining is contained within the top 2km.
- In addition to the elements described in this handbook, five others have been included for reference: oxygen, silicon and aluminium because, between them, they make up 81% of the crust; carbon because it is found in coal, oil and natural gas plus all living organisms; and gold because it is a useful benchmark, which most people regard as rare. The elements described in this handbook constitute less than 1% of the crust.
- One ppm is equivalent to 1 gramme per tonne (or 1 ounce in 27.9 long tons).

* Concentrations of the 17 rare earth elements (REEs) range from 0.3ppm (Tm) to 63ppm (Ce).

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John Simmons
Armin Reller
Morag Ashfield
Cameron Rennie

In this second edition we have updated the production and reserves figures using 2012 data. Four new elements have been included and the Rare Earth Elements section has been expanded to include descriptions of those that are used in energy pathways. There is a new section describing the rationale behind the choice of elements for inclusion and several of the introductory sections have been revised to incorporate substantial new content and diagrams.

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The Materials handbook is part of a series that reflects the work of the BP sponsored Energy Sustainability Challenge.

The other titles are:

Water in the energy industry – An introduction
Biomass in the energy industry – An introduction

These books can be downloaded at:
www.bp.com/energysustainabilitychallenge

Contents

About this book

The aim of this handbook is to provide an introduction to the complex supply chains that lead from geological processes to the refined materials needed to maintain existing energy pathways and build new ones. These supply chains are vulnerable to interruption by a range of factors, which this handbook outlines. The book also indicates the likelihood of supply interruption for the materials described. This will enable any reader, who has an interest in existing or developing energy pathways, to improve their understanding of the risk to the sustainability of each pathway brought about by restricted supply of materials. That understanding can help build a broader view of the analysis required to underpin business decisions in the energy sector.

This handbook concentrates on 23 materials. Please note that the rare earth elements are treated as just one material, with brief descriptions being offered for those used in energy pathways. The choice of what to include was based on a review of what materials are essential to current and foreseen energy pathways and appear to have potential constraints on economically sustainable supply or use.

Foreword by Ellen Williams
BP Chief Scientist

Energy is essential to human civilization, and the production of energy is dependent on a range of technologies, which, in turn, depend on a multitude of materials. Serious scarcities of any of these materials could limit our choices in the production and use of energy. The impact of materials availability on energy production is one of many questions addressed in BP's Energy Sustainability Challenge programme (www.bp.com/energysustainabilitychallenge). Researchers from leading universities have collaborated in this programme to establish trusted data on the land, water and ecosystems footprints of different energy pathways, and assess the sensitivity of these to changing patterns of demography, climate and natural resource governance.

BP is pleased to support this second edition of *Materials critical to the energy industry*, which has been spearheaded by the University of Augsburg. They have identified materials on which the energy supply chain is critically dependent, and developed a resource book that will help anyone interested in understanding the facts behind recent reports of materials shortages. Inevitably, there are some materials not included, but this is a concise and useable compilation showing how materials, such as lithium and the rare earth elements, are used and the geographic locations, size and nature of their sources.

This book illustrates how issues of market effectiveness in enabling trade and economically competitive supplies often weigh more heavily than actual limits of geological availability or ecological impact. It also documents a substantial history of innovation through the ages. We may remain hopeful of continuing technical development to enable substitutes for materials that are expensive, constrained in supply or environmentally harmful.

We thank the University of Augsburg and all who have provided their expertise and understanding of what underpins criticality of materials in the energy sector. We expect that this work will provide a foundation for sound policy and technical decisions that reflect the facts about which materials are available, affordable, accessible and admissible.

Foreword by Andrew Mackenzie
Group Chief Executive, BHP Billiton

Sometimes, we can be forgiven for believing oil is the only commodity that matters and drives politics and wars. This book broadens our perspective. It highlights the criticality of the supply of much of the periodic table to even oil's survival. The good news is that the authors show that many of their selections are substitutable with other materials if their supply runs out or gets too expensive. Oil is a 200-year-old industry that depends on the products of 5,000-year-old industries that are harder to substitute – such as steel and copper. And we are not about to run out of iron ore, or copper, or coal, or gas, or uranium if we give up on oil. And like silver before, when copper is too expensive as a conductor, there is always aluminium, the third most abundant element in the crust, with bauxite as the easiest to find and develop orebody.

The sudden growth in China and elsewhere in Asia has reminded us of the role of materials in all our happiness. We cannot grow on dotcoms and spiritualism alone. The price signals are already unlocking more supply and, if we had more free trade and open societies and less resource nationalism, the cost of the new supply, growth in well-being and pace of poverty alleviation would be even cheaper. But the ingenuity of our species makes me even more optimistic – if some areas are off-limits for new supply, new technologies will win the supply from other areas where grades are lower but resources are plentiful. Think deepwater oil and shale gas in response to OPEC's cartel. Think solvent extraction-electrowinning in response to falling copper grades. Think nickel laterites and nickel pig iron in response to rising nickel sulphide costs.

We live in a material world – everything we can touch started off being dug up or grown (with rocks added for fertility). And a growing population that, through increased democracy and urbanization, is pulling itself out of poverty needs more materials, not just oil. The good news is there is plenty to go round for millennia to come, to support many more people on this planet with rising average living standards, and less climate risk. Then there is the solar system…

I see this book as a celebration of the abundance of the earth and magnificence of our ingenuity to tap its supply to provide for a population that can keep on growing and removing more from poverty – as long as no one gets too greedy.

Introduction by Professor Armin Reller
Chair of Resource Strategy, University of Augsburg

During the past two centuries of industrialization, the man-made technosphere has changed in an unprecedented manner. Nutrition, individual mobility, health care, information and communication systems have all been revolutionized. Those revolutions have all been supported by the exploitation of globally distributed natural (mineral) resources on an enormous scale. Myriads of chemical compounds have been transformed into technically reliable functional materials and all these activities are powered by appropriate energy inputs, with fossil fuels as the main source. Moreover, fossil fuel industries have required many elements to enable extraction, processing and production of the fuels, power and carbon-based commodities and polymers we use today.

Our energy system is on the verge of major change. Energy consumption is set to increase steadily and concerns about the global carbon cycle, coupled with the desire for greater energy security, drive substitution of conventional energy systems by renewable technologies, leading to new energy pathways. This poses an enormous challenge. The dominance of electricity will grow. Many metals – formerly unused or rarely used – will become indispensable in energy production, energy transformation, storage systems and also in innumerable electricity-consuming products and devices such as computers and mobile phones. More than 60 metallic elements are involved in energy pathways to a greater or lesser extent. The quantities required and available vary dramatically and some bring new challenges with their use.

Securing future energy supply requires a critical awareness of the functionality, availability, substitutability and recyclability of the metallic resources. Uncontrolled ecological and adverse socio-economical impacts, as well as creeping dissipative losses, have to be minimized. It is therefore necessary to help decision makers understand the nature of the valuable materials and metals extracted from the earth's crust and what defines the continuation of sustainable supplies.

Fortunately, metals can be both used and reused – they do not 'die'. Therefore, we seek to define and validate criteria to identify the most critical metals for feasible and efficient energy systems. By thinking about the concepts of substitutability, recycling and trade; about geological and market availability; and about the socio-cultural and ecological impacts, we can keep metals circulating in the economy, powering our generation and the ones that follow.

The ages of energy

Breugel, Vermeer and their fellow painters of the 16th and 17th centuries depicted societies where few people ever travelled more than 10 kilometres from their birthplace, many went hungry, most were never warm in winter and the majority retired to bed at dusk as lighting, even by candle, was too expensive for all but emergencies. Although the artists' paints contained minerals from far-flung places, most of the entire material needs of the figures they portrayed came from less than a day's cart ride away. Today, while for more than a billion people on earth there has been little or no change in material conditions, every home and office in the developed world is well lit, temperature controlled and crammed with goods that are assembled using elements from across the globe. Not only has the population and energy demand exploded, but so has the demand for materials.

Wood, wind and water

The old masters' landscapes often featured all the energy forms then known to man: sun, wind, gravity, muscle, coal and wood. Machines produced to capture these relied on materials that were locally available. The mills, wind and water used just stone, wood and iron and the tools needed to build them also used wood and iron, the latter smelted with charcoal or, in some regions, coal. Light came from candles and, for the rich, whale-oil lamps. The entire energy demand for most of the population consumed just three elements: carbon, iron and calcium, used in the flux to smelt it.

The Industrial Revolution

The invention of the steam engine triggered a revolution that enabled goods to be carried in quantity across the globe, and the range of materials required to sustain the revolution grew accordingly. Copper improved boiler efficiency and, when alloyed with tin to produce bronze, bearings could be manufactured that allowed many mechanical devices to be developed, including a catalyst of the revolution, machine tools. Coal fuelled the revolution and also later lit it, via gas. Lead pipes carried gas, and thorium and cerium dosed the mantles in the lamps.

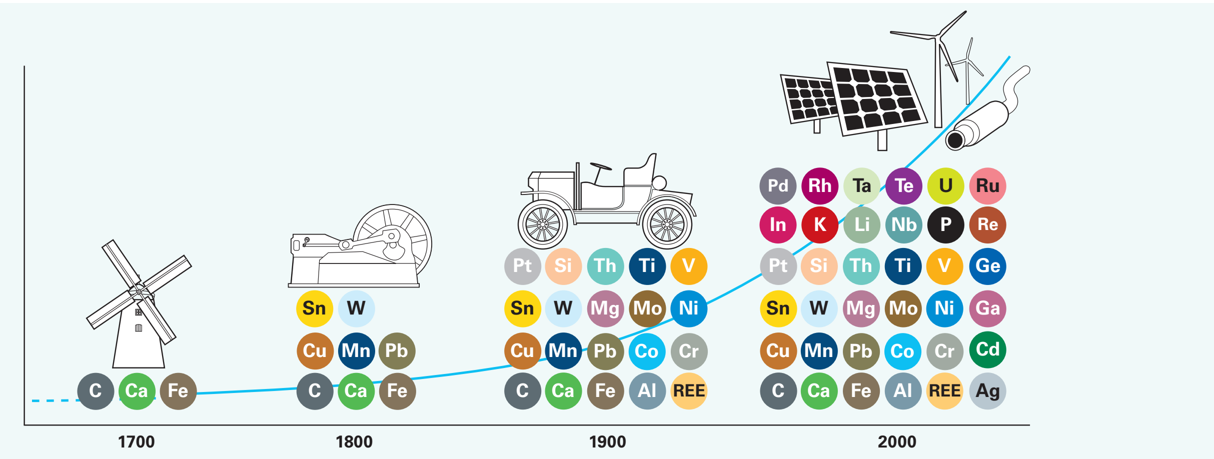
Steelmaking joined in the revolution and the steel-masters soon discovered the benefits of adding minerals such as chromium and manganese. Steam engines also empowered the first commercial generation of electricity and the light bulbs, devised to use it, required tungsten.

The age of oil

Nikolaus Otto and Karl Benz changed the world by inventing the internal combustion engine. Life is but timing, and the ready availability of oil from wells saved the whales, and cleared the path for the petrol engine to start on the journey to today. Early engines could run on oil products not far removed from crude oil, but advances in engine technology and refining led to the highly-efficient engines we now take for granted. Maximizing the end products from crude oil required catalysts such as platinum and molybdenum. Getting the most from cars required sophisticated alloys and steels. Mass production of hydrocarbon-fuelled vehicles raised concerns about pollution, mirroring those surrounding coal use, leading to the aspiration to reduce our reliance on carbon.

Electrifying times

The road to lower-carbon energy demands new forms of generation and utilization. Both require new materials. Nuclear energy demands, in addition to uranium for fuel, a range of materials as moderators. Photovoltaics (PV), which have been primarily silicon based, are now moving to compounds using, among other elements, cadmium, gallium, germanium and tellurium. Some wind turbines need super-strength magnets to be efficient and, for those, you need rare earth elements (REEs). Lithium and lanthanum are the elements of choice for high-performance batteries – an essential for electric vehicles. Lying between the distribution grid and consumers, and at the heart of nearly all electrical devices, is copper, possibly the element of the electric age.



Elements widely used in energy pathways

N.B. Position on the time axis is indicative only

Energy pathways

As life has become more sophisticated and complex for inhabitants of the developed world, we have become distanced from the fundamentals. Few of us have a thorough understanding of what energy pathways are involved in ensuring that the light bulb illuminates when the wall switch is turned on, or how many processes are needed to guarantee our car delivers the family safely home. To maintain the routes from energy source to end use, and to contemplate innovations leading to new ones, we need to understand not just the sources, but also what materials are needed to construct and maintain these complex pathways. Sufficient supply of critical minerals at a price that makes economic sense will enable existing pathways and ensure the uptake of new sustainable energy supplies.

Supply

Oil

The exploration and production of oil and gas is totally dependent on specialized steels. From seismic acquisition on land or sea, through to drilling and pipelines and tankers, steels are needed that rely for strength and durability on a range of alloying elements, including chromium, nickel, molybdenum, manganese, cobalt, vanadium and tungsten. Production in ultra deepwater had to wait until suitable steels could be developed to make pipework that could withstand the high pressures and temperature differentials involved in producing oil from thousands of metres below the surface and under severe corrosive conditions. Without copper, the motors that drive so much of the industry would be far less efficient.

Once oil reaches a refinery, catalysts, including platinum, rhodium, REEs and also rhenium, palladium, molybdenum and vanadium pentoxide, work their magic in upgrading crude oil and allowing the multitude of fuels and lubricants to be produced.

Gas

Like oil, the exploration and production phases are dominated by steel structures. Natural gas undergoes relatively limited treatment before flowing through steel pipes or being shipped in steel tanks to generating stations or homes, factories and offices. Electricity generation requires another group of specialist steels with which to fashion turbine blades. Most other uses of gas are in heating appliances and central heating systems, both of which rely on copper.

Biomass

Plant material that has grown by using photosynthesis to capture solar energy can be transformed into energy forms useful to humans in two ways, in addition to simply burning it for heat. First, anaerobic digestion of biomass can produce gas for space heating or generating electricity. Second, biomass can be turned into liquid fuels in processing plants that in some ways resemble refineries. Both methods of extracting energy from plants require the elements to provide steel for structures and catalysts when thermochemically processed. For all bioenergy generation it is essential to grow the right crops efficiently, using the least amount of land, and, for that, in addition to nitrogen-rich fertilizers, phosphorus and potassium-rich fertilizers are crucial.

Coal

Over time, this centuries-old industry has relied less on muscle and more on steel. A massive amount of low-grade steel is used to support underground roadways. More specialized steel provides rails and coal-cutting machinery. Copper also plays a vital role in the complex web of wires and motors in a modern mine. The vast majority of coal fuels electricity generation, where specialist steels are vital for turbine manufacture.

Nuclear

Although this is an industry based almost exclusively on uranium, it also requires a host of specialized steels to contain the reactors and materials, including lithium and REEs, to both moderate the reactions and seal the reactors, plus indium for control rods. Depending on the particular reactor design, there may be zirconium plus tin, niobium, iron, chromium nickel (zircaloy) for fuel cladding. As with other electricity generators, turbines in nuclear power plants also need steel alloys designed to ensure sustained performance in high-temperature, high-stress environments.

Geothermal

This has been a steel-based industry until recently, with steam used to drive turbines in large-scale plants. As long as geothermal energy production is limited to this form of technology, no excessive material demand is expected. The rise in popularity, however, of domestic-scale heat pumps that rely on the heat energy extracted from the top few metres of the subsurface through shallow boreholes, will increase the use of copper.

Wind

This industry requires steel to build towers on top of which sit generators that convert the mechanical energy of the rotating blades into electricity by rotating conductors through strong magnetic fields. These magnets can either be built as permanent magnets rich in the REEs neodymium, praseodymium and maybe dysprosium, or as huge copper-coil magnets. The vast majority of rare-earth-based systems are presently manufactured and installed in China. Western manufacturers are just starting to use this technology. Increased prices of REEs are stimulating further developments in generators with reduced material demand.

Two types of wind turbines are used for commercial power generation: those that drive the generators through gearboxes, and those that drive generators directly. Increasingly, direct-drive wind turbines are built – they are gearless systems that offer higher reliability and require lower maintenance, both major factors in the economics of wind, in particular offshore. They do, however, require larger permanent magnets and hence more REEs.

Hydro

This industry is reliant on steels for generator-driving turbine blades capable of dealing with abrasion and cavitation. For conventional freshwater hydro installations on rivers and hydroelectric dams, no critical material issues are expected. For future seawater installations, including tidal wave plants or submerged-rotor systems, special steels are required capable of withstanding saltwater corrosion.

Solar

There are currently three technologies used to capture solar energy: PV, solar thermal and concentrated solar power (CSP).

- Photovoltaics convert solar energy directly into electricity. Two main categories exist: crystalline silicon cells that account for approximately 90% of the global market and thin-film materials based on combinations of elements, including gallium, arsenic, cadmium, tellurium, copper, indium and selenium. The potential cost advantage of thin-film systems compensates for the lower conversion efficiency. What could hinder the evolution of thin-film technology is the price drop in silicon-based cells, which has occurred since about 2008. Both silicon and thin film predominantly use silver as the contact material. New semiconductors are being developed, including organic compounds, but are not yet commercially viable.
- Solar thermal generation, which is used for water heating mainly in domestic systems, is dominated by copper and zinc.
- CSP systems use solar energy to heat a fluid with a boiling point higher than water, which is stored in a tank. Heat exchangers use that stored energy to raise steam that drives turbines and generators to produce electricity. The reflectors used to concentrate solar energy rely on highly polished surfaces, typically with an aluminium or silver coating. The scale of CSP installations is illustrated, for example, by three plants at Andasol in Spain, each using 200,000 parabolic mirrors to generate 50MW of electricity.

The electricity grid

Building the networks that feed electricity throughout nations, and even across national borders, has required vast amounts of aluminium and copper for cables and generators, as well as steel for pylons. Today the grid is changing as large thermal stations are being supplemented and in some cases replaced by numerous forms of distributed generation, including solar and wind systems. To connect these new generators to the consumer requires not only more of the traditional aluminium or copper cables but also sophisticated switching and control systems. The intermittent nature of wind and solar generation will also require the building of energy storage systems. Technologies being developed include pumped storage and compressed air schemes that use conventional building materials including steel, and giant battery banks using vanadium-redox or lithium-ion cells.

Another development being discussed in grid systems is the possibility of a long-distance transmission network connecting national grid systems. One such scheme envisages large offshore wind farms in the North Sea, connected to northern European electricity grids and markets. To carry electricity that distance would require either a new breed of ambient-temperature super conductors, with the most promising developments based around iron-REE alloys, or high voltage direct current systems (HVDC). HVDC requires conductors made of tin- or silver-plated copper or aluminum similar to standard AC cables. In addition to the materials for conductors, the control systems, as for distributed generation grids, will require a variety of metals.

Demand

Transport

Henry Ford, when referring to the benefits of light-steel alloys, was quoted as saying, "You can't have cars without molybdenum." The modern vehicle has evolved greatly since Ford's Model T, but they rely evermore on sophisticated steels that are lighter, and easier to press and to finish. They also now need a host of other materials, including platinum, palladium and rhodium, as emission-cleaning catalysts, and REEs in the numerous electric motors expected in modern vehicles. For electric cars, next to the development of more efficient electric traction motors, a key challenge is to increase battery performance (at present, typically less than 0.2kWh per kilogramme) where lithium and cobalt may play a vital role. In the aerospace sector, there is a need for materials that retain strength at high temperatures in turbines and light alloys for structural components.

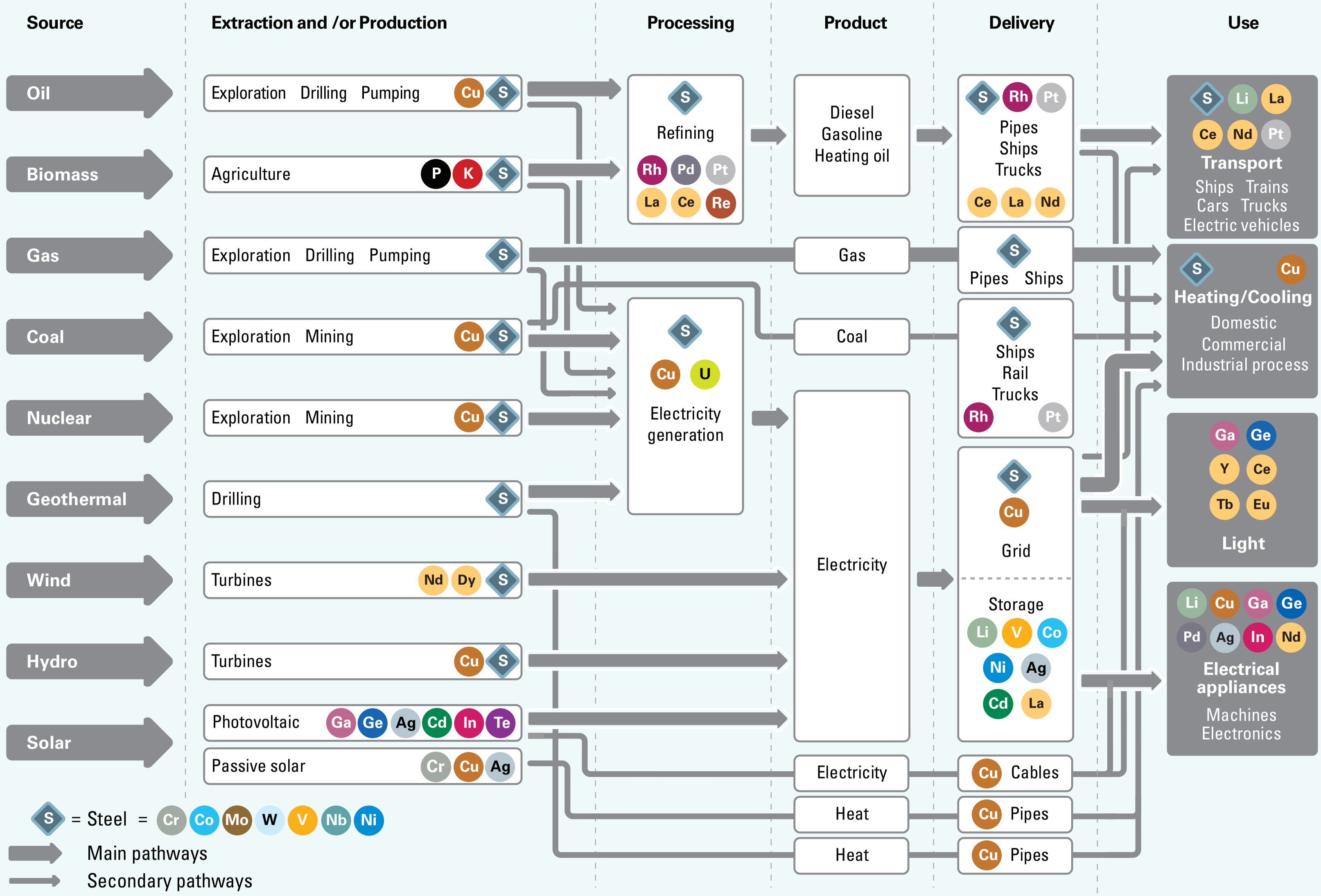
Heating and cooling

Heating appliances are predominantly steel and copper based. For cooling and air conditioning, a number of systems are commonly used, some of which use REEs. As economies grow, so does the uptake of air conditioning, with subsequent demand for further raw materials, and this may accelerate if climate change causes temperature rise.

Light

As tungsten bulbs are phased out, gallium, indium and REEs are being increasingly used in innovative replacements, including light-emitting diodes (LEDs) and compact fluorescent bulbs. In LEDs the semiconductor host materials, often phosphides containing aluminium and indium, are doped to improve conductivity. Host and dopant combinations have been developed to improve the conversion of electricity into light and different colours of emission. The REEs, cerium, europium, terbium and yttrium, are all being used in modern LEDs. Like all fluorescent lamps, the compact versions rely on the fluorescence of mercury vapour. A variety of materials are used as phosphors inside the tubes to change the colour of the emitted light. These include the same REEs as used in LEDs as well as lanthanum.

Materials in energy pathways



N.B. Only the 23 materials discussed in this handbook are included in this diagram.

Al not included because, although used in energy pathways as a conductor, it does not meet the criticality criteria for this book. Likewise, Si, the dominant material used in solar PV, and Fe are not listed above because they are not scarce.

Electrical and electronic appliances

The vast increase in the number of appliances and the desire for energy efficiency provide a contradictory story. REEs facilitate more efficient electrical motors and indium-based flat screens are far more energy efficient than the cathode ray tube (CRT) screens they replace. High-speed chips, however, together with flat screens, have enabled many technologies, such as handheld computers and smart phones. The individual gadgets might use less energy than before, but the total number in use leads to an increasing demand for raw materials and electrical power. This increase in demand as products and services become cheaper is commonly called the rebound effect.

Innovation drives new demand

Industrial history, from the copper, bronze and iron ages onwards, has been punctuated by episodes of innovation sparking demand for materials that were previously little or completely unused. These sharp changes in the fortunes of materials still occur and three examples are briefly described in this section.

Fuel cells

In the middle of the19th century two scientists, one Swiss and one British, independently discovered that the process of electrolysing water could be inverted and that hydrogen and oxygen could be combined to produce electricity. The great news was that this process is much more efficient than any heat engine and that the products of the reaction are heat and water. Great promise was heaped on this discovery but it was only in the second half of the 20th century that technically useable fuel cells were developed for space flights and military use, where the advantages of high energy density, near silent operation and reliability outweighed the cost.

A step change in research effort was spurred by the 1973 oil crisis and resulted in the first fuel cell driven cars. Forty years later the automotive industry seems poised to bring practical fuel-cell-powered cars to market with announcements from several major manufacturers including Toyota, Mercedes-Benz and General Motors promising production models for 2014 – 15. Fuel cell use in stationary applications, such as domestic and commercial power and heat generation, are also growing with reported delivery of more than 81MW in 2011. It is also reported that the largest growth of fuel cells is in the portable electronic sector where there is potential to replace batteries. The potential for growth is large across all sectors where fuel cells are known to have benefits; however, the twin barriers of material cost and performance need to be overcome.

The leading technology for vehicle and some stationary systems, proton exchange membrane fuel cell (PEMFC), relies on platinum-layered electrodes. PEMFCs require pure hydrogen as fuel but the long-awaited hydrogen infrastructure is still nascent. Hydrogen, however, can be delivered to fuel cells as methanol that needs reforming over a catalyst to release the gas. The favoured materials for catalysts are platinum and palladium, both expensive metals with high supply interruption indicators. Palladium in the form of palladium hydride also has potential as a storage medium for hydrogen. Finding substitutes for platinum group metals (PGMs) is one of the main challenges for the fuel-cell industry.

Thermoelectric generators

With the exception of wind, solar and hydro, most of the electricity used in the world is generated by turbines driven by steam that has been heated by burning coal, gas, oil and biomass, or from nuclear fusion. Devices that turn heat directly into electricity without any moving machinery, thermoelectric generators (TEGs), have been known about since the early part of the 19th century and some leading companies are promising the commercial-scale launch of such devices in the near future. The real benefit will be that they are designed to capture waste heat.

The world is full of man-made devices that radiate waste heat, as anyone who has inadvertently touched a car or motorbike exhaust will know to their cost. Power stations have vast cooling towers, buildings are festooned with air conditioning units, and cars and trucks carry radiators and fans to keep engines cool. All of these devices are dissipating energy that was concentrated mainly in the form of fossil fuels. Capturing any of this in an efficient manner would be a major advance in reducing our demand for fuels.

The right material

In 1821, the German physicist Thomas Seebeck discovered that some metals when joined together display an exciting phenomenon: when one is heated, they produce electricity. The efficiency of this phenomenon is low, around 3% in the materials he investigated, less than that of contemporary steam engines, so no development took place. In recent years, however, materials have been identified with efficiencies much higher, some up to 7%, and this has led to the possibility of commercial applications.

The most efficient known thermoelectric materials today are chalcogenides with bismuth telluride (BiTe), lead telluride (PbTe), LAST ($AgPb_{18}SbTe_{20}$) and silicon germanium alloys (SiGe). These devices are produced in small numbers and are limited in use because of certain performance characteristics: for example, BiTe thermoelectric devices display efficiencies up to 5 – 7% for most applications, but performance falls off rapidly when hot-side temperatures exceed 230°C.

New materials, however, are being investigated that have the potential to solve this temperature and efficiency challenge, so they could be used to capture heat across a broad range of industrial applications.

Commercial applications

At present, the closest to commercialization are TEGs, designed to capture automobile exhaust heat. Development has been publicized by BMW and Ford, with trials being quoted as improving the efficiency of cars by up to 5%.

Future applications being investigated include fitting hybrid vehicles with TEGs to recover heat from batteries and applying thermoelectric films to the back of PV panels to convert heat as well as light into electricity. Thermoelectric materials may also be used in concentrated solar power systems, in place of the present phase-change processes. Capturing waste heat in many material-processing plants would yield significant efficiency gains and the vast quantities of low-grade heat wasted at power stations are an attractive target for research.

Naturally, all of this potential to build an entirely new energy pathway relies on the adequate supply of the relevant materials and the most appropriate, tellurium and germanium, are subject to a number of supply constraints.

Magnetic refrigeration

Certain materials change temperature when exposed to a variable magnetic field. This phenomenon, known as the magnetocaloric effect, can be used to lower temperatures and offers a route to refrigeration that is more efficient than conventional systems based on compressing volatile fluids. Although the effect was first described in 1881, it has been used primarily in laboratory settings to produce very low temperatures for research purposes.

Magnetocaloric systems require both a strong permanent magnet and a magnetocaloric element that rotates through the magnetic field, getting magnetized and demagnetized to absorb and emit heat. Neodymium-iron-boron (NdFeB) alloy is a good choice for the permanent magnet but it is not a good magnetocaloric. There are a few candidates for the magnetocaloric rotor material but there is no clear winner at this stage. Identifying a magnetocaloric material is a much bigger challenge than identifying a permanent magnet. Candidates for magnetocaloric materials include germanium, silicon, iron, lanthanum, manganese, phosphorus, arsenic and gadolinium.

What drives materials choice

Every energy pathway considered in this handbook is made up of machines and systems that each require the design and manufacture of numerous components. Needs are identified by engineers and specifications including specific material properties crafted to define the solution that will meet those needs. Where the properties are not critical, and substitution to provide an adequate combination of physical and chemical properties is possible, other factors can be considered, such as price and availability or, increasingly, the environmental impact of using a particular material.

Raising performance requires new materials

Of course, as new technologies emerge and existing ones evolve, specifications for machines and systems and, ultimately, materials do radically change. The initial delight that surrounds each new invention is quickly swept away by a tide of demand to improve it. The transport sector provides a host of good examples, from trains to cars and planes. Each of these has evolved hugely since their first appearance and progress has mostly been born of the improved functionality of materials.

The turbine blades in aero engines provide a cautionary tale. The route to increased performance demands that engines run at higher temperatures and, for that to be possible, the blades need to be capable of enduring the extraordinary conditions that are at the physical limits of metals. Exotic alloys have been developed to provide the necessary combination of strength, flexibility, corrosion resistance and low weight. Developing new blades for the fan stage of the RB211 engine bankrupted Rolls-Royce, when the original material chosen for its exceptional stiffness at high temperatures, carbon fibre, failed a vital bird impact test. The cost of developing replacement blades in metal was only possible with government support.

The RB211 story may appear to be an extreme case of material development, but the drive to improve efficiency across most energy pathways is leading to evermore demanding functionality from materials. As Rolls-Royce discovered, materials that are optimized for one property may have shortcomings in others. Just as for every problem there is usually one elegant solution, for every function there is often one ideal material.

The agricultural, physical resource and manufacturing industries that ensure our continued existence, naturally rely on a range of materials, the choice of which has been refined through time. Most industries in recent years have become increasingly aware of the energy needed per unit of production, but it would be instructive to consider the volume of each of the materials used in a similar manner. Such an exercise may well lead to a better understanding of where processes are vulnerable to supply-chain interruptions or where there are opportunities for improvements or the provision of substitutes.

From rock to use

Elements in the crust

Every day, we receive from the sun thousands of times more energy than we use. However, the only store humans have for physical resources is fixed: the upper layers of the earth's crust, the oceans and the atmosphere. The elements that we consider in this handbook exist today in the same proportions as they did at the formation of the planet. Nothing much, apart from a few million meteorites, has swelled the ranks of the earth's materials and only a fraction of the earth's hydrogen and helium escape the planet's gravity, along with a few tonnes of spacecraft. Over time, however, a range of processes has been active in and on the surface of the crust to concentrate elements into deposits useful to humans.

Concentration processes

The idea that heat from radioactive elements in the crust could cause rocks to melt and move, plus the quite recent revolution in understanding plate tectonics, allow rational explanations for mineral concentrations.

When rocks melt and recrystallize in magmatic processes, elements are redistributed and concentrated in certain minerals. At the edges of magma bodies, the heat and fluids from the intrusion can change the rock, which has been intruded, concentrating minerals into a metasomatic deposit. The intrusion of hot magma into other rocks often produces hydrothermal cells, where fluids driven by convection absorb minerals in the hot part and deposit them as they cool. As these fluids will penetrate all available space, hydrothermal mineralization takes on many forms, ranging from discrete veins to vast stockworks of interlaced veinlets. Magmatic fluids entering the sea form mineral-rich black smokers, a potential source of metal. Another process that leads, over time, to concentrations of metal, particularly manganese, is precipitation at the seafloor around sand or shell fragments, to form nodules.

When rocks meet the atmosphere, a whole range of weathering processes cause concentration of minerals: gravity-sorting in flowing water and wind-blown sediments result in placer deposits; solution and evaporation lead to evaporites forming.

Any concentration of minerals that can be mined economically can be regarded as an ore. The grade of ores deemed economic varies dramatically, depending on the value of the minerals it contains and the costs of extraction and processing. Relatively rare elements, such as platinum, are now economic at a few parts per million, whereas the fertilizer minerals, potassium and phosphate, need to be concentrated to many per cent before being considered worth mining. Lower grades become economically viable to extract, as technological advances drive both mining and processing, and also as the price of some minerals has risen in real terms. Using new extraction processes has enabled the economic re-working of old tips, built of waste from earlier extraction processes that were less effective at extracting materials from ores.

The abundance of an element in the crust is not necessarily a guide to its availability, as abundance should not be confused with concentration. The REEs appear in published crustal abundance lists as more abundant than gold and platinum and some of their abundances compare with copper. However, processes in the crust concentrate gold and platinum to such an extent that they are found in native form, i.e. as pure metals, whereas REEs never occur in such a state.

Exploration

Many mineral deposits have been found by using straightforward geological mapping – observing associations between rock types and the minerals they contain. Today geological understanding can facilitate the deployment of appropriate exploration techniques – mainly geochemistry and geophysics. The former uses large-scale rock, soil and stream sediment sampling and automated chemical analysis to highlight areas of interest. The latter relies on instrument systems that can detect variations in the physical properties of rocks, such as magnetism, density and electrical conductivity to discover anomalies from normal crustal values. Geology, geochemistry and geophysics can all now be carried out from airborne platforms and most mineral surveys combine all three.

All techniques that indicate an anomalous concentration of minerals have to be followed up by physical sampling, usually by drilling and analysing cores. Sophisticated computer programmes can then be deployed to model the size, shape and mineral content of an orebody so allowing investment decisions to be made.

Mining

Mining can be defined as moving the least amount of rock possible to gain access to the most valuable ore. In the context of this handbook, the main mining methods, which depend largely on the nature of the deposit, are:

- High-grade veins, such as many silver deposits, first seen at surface, led to the first underground working. Depth will preclude surface mining. Orebodies are reached by vertical shafts or by means of horizontal or sub-vertical adits from the surface. Veins tend to be followed in small-scale workings, often with limited need for roof support. Extraction usually involves breaking of ore either by blasting or machine, and loading on to conveyor belts or shuttle trucks for transport to the bottom of the shaft or adit.
- Flat-lying deposits, such as some platinum and phosphate ores, are worked by long-wall methods with machines cutting through them in long, temporarily supported faces that resemble long-wall coal workings.
- Larger vein complexes and deep stockworks are usually taken by stoping, a process of progressively blasting down the roof of an orebody and removing the shattered ore at the lowest level.

- Large near-surface orebodies, especially stockworks, in which copper is often found, are now exploited by open pits. Hard rock is usually drilled and blasted to loosen it before loading using hydraulic shovels. Dump trucks or conveyors carry ore to the mill. For flat-lying and softer ores, open-cast techniques can be employed – basically a trench that works its way across the deposit and is filled in behind.
- Ores that are soluble in aqueous solutions or dilute acids such as potash and uranium oxide can be extracted by solution mining also known as in-situ leaching (ISL). The leachate is pumped down boreholes, dissolves ore that it contacts and is then extracted through a further series of holes. The material in solution is recovered at surface by either evaporation or ion-transfer. ISL accounts today for 39% of the global uranium production.
- 'Urban mining' is a term that has recently been introduced to the mining world. It is used to describe the re-use of the vast amounts of materials entrained in our present day infrastructure and the re-working of landfill sites. The waste in city landfills contains concentrations of some materials far above crustal averages and this, combined with the relative ease of access, increasingly renders this process economically viable.

The often-discussed possibility of mining seafloor nodules, although fraught with legal and environmental challenges, is being actively developed in some countries.

Mineral processing

The run-of-mine material consisting of valuable minerals and gangue, or waste, is processed in two principal operations, both designed to reduce transport costs and energy costs in smelting:

- Liberation basically breaks mineral structures and releases the valuable ore from the gangue and usually involves energy-intensive processes, comminution by crushing and, possibly, grinding. Comminution can take up to 50% of the entire processing energy.
- Concentration, in which the ore is physically separated from the gangue, requires careful study of the physical and chemical properties of both ore and gangue. Gravity, magnetism, electrical conductivity and surface properties can all be exploited to produce an ore concentrate.

Another process, heap leaching, is being more widely deployed to deal with disseminated ores. Here, piles of finely ground materials are sprinkled with acids and sometimes bacteria for months or possibly years. Metals can then be extracted by electrolysis from the resulting liquor.

Smelting and refining

Most ores are compounds and metallurgy/chemistry is needed to release the metal or metals they contain. Ore is concentrated by the processes described previously, to minimize the energy in smelting. To free metals from ores, several methods are available, depending on the physical and chemical properties of the element and the ore that contains it. One of the most common techniques, and certainly the oldest, is heating of oxide ores in the presence of a reducing agent, such as carbon, and a flux, often limestone, which combine to form slag that can be easily removed. Solution and electrolysis (electrowinning) methods, which require huge amounts of energy, can be deployed for certain ores.

Metals that emerge from a smelter are then often subjected to a variety of refining stages to remove impurities before reaching market specifications.

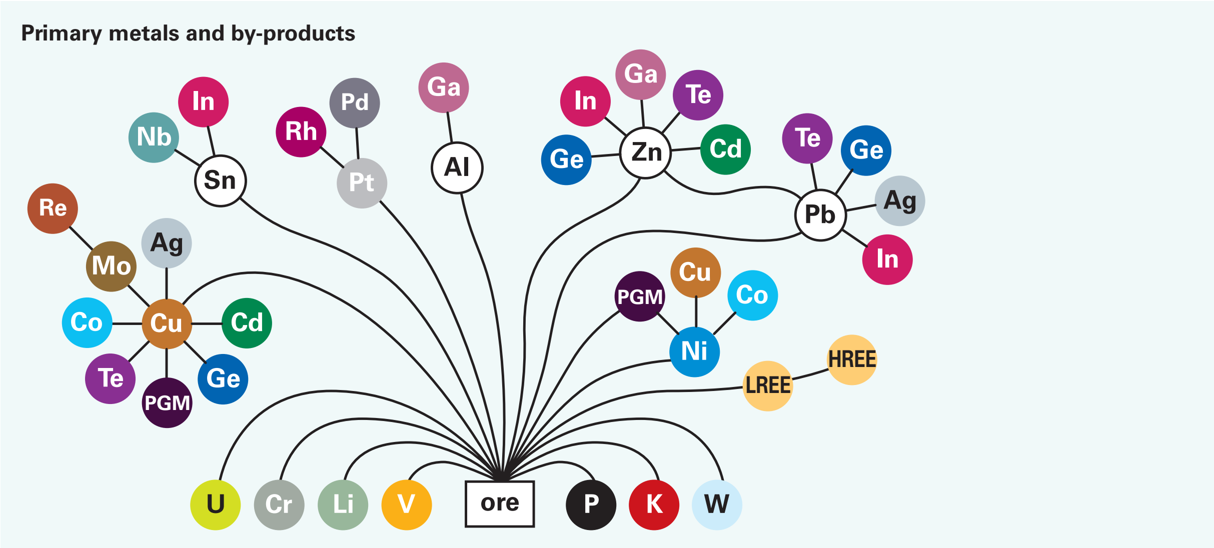
Smelting can release large quantities of pollutants unless processes are well monitored and effective off-gas treatment is installed. Environmental considerations have driven technological changes in recent years, as well as driving up cost. Waste materials from mineral processing are usually stored in tailings dumps, while chemical fluid residues are often stored in ponds. Leaks from these ponds have caused several devastating environmental incidents in the past. Radioactive elements encountered in mineral processing present particular challenges, and handling any radioactive material can raise costs significantly.

Cost and time

Meeting new or increased demand for minerals takes time. The success rate for exploration is extremely low. Natural Resources Canada quotes that for grassroots exploration fewer than one in 10,000 mineral showings discovered actually become a mine. Even when discovered, to turn a mineral deposit into sellable metal or material, timescales range from 10 to 15 years, with investments of more than a billion dollars required for most projects. Enormous capital investment is required, which may only provide a return after several years, if at all.

By-products

Several of the minerals described in this handbook are mainly or partly mined as a by-product or co-product of the primary desired metal. These by-products constitute only minor concentrations in the mineral or are waste products from processing. Therefore, they can only be economically extracted during the processing of the main metal. This means that a growth of demand for the 'by-products' does not necessarily lead to a higher production volume, even under high-price scenarios.



Schematic representation of the routes from ore to elements described in this handbook, indicating primary versus those produced as co- or by-products (adapted from Hagelüken & Meskers, 2010).

Recycling

The collection, sorting and recycling of manufactured products emerged in the late 20th century from an occupation on the edges of polite society to a fashionable profession. Yesterday's scrap men have become the environmentally sensitive recyclers of today and business is booming. Although every case must be examined on merits, especially energy balance, there may be compelling reasons to re-use refined materials in preference to extracting new ores and proceeding along the lengthy and often energy-demanding route of beneficiation, concentration, smelting and refining. The percentage of demand that can be met by recycling varies greatly from material to material and through time. Supply constraint has often increased efforts to recycle, as has been well demonstrated in times of war. Conversely part of the peace dividend at the end of the Cold War resulted in the dismantling of thousands of nuclear weapons and the recycling of sufficient uranium to supply about 13% of the nuclear power industry's needs between 2000 and 2012. As the cost of materials, especially the energy required to produce them, the cost of waste disposal, environmental awareness and associated legislation all increase, the future for recycling appears positive.

Dissipation

Dissipation is a term used to describe the loss of materials from recycling routes. Dissipation occurs when metals are used in such small quantities in devices, that the cost of reclaiming them is prohibitive, or when they are used as catalysts, particularly autocatalysts (device to clean up internal combustion engine exhaust gases), where their use causes a proportion to be lost in the exhaust stream. Another route to dissipation occurs when metals are added to fuels, such as the use of cerium as an additive in diesel.

Energy in materials production

As anyone who has ever dug a garden in hard soil or shifted a few tonnes of rocks to make a patio can imagine, digging ores from solid rock and transporting them to processing plants requires energy – lots of energy. Skillful miners work to minimize the amount of energy expended by moving as little overburden as possible in open mines and taking as little gangue as possible in underground mines. They also have to ventilate and possibly cool underground mines and dewater mines of all types, both processes requiring significant energy inputs. Once the ore has been extracted, processing and refining also require energy.

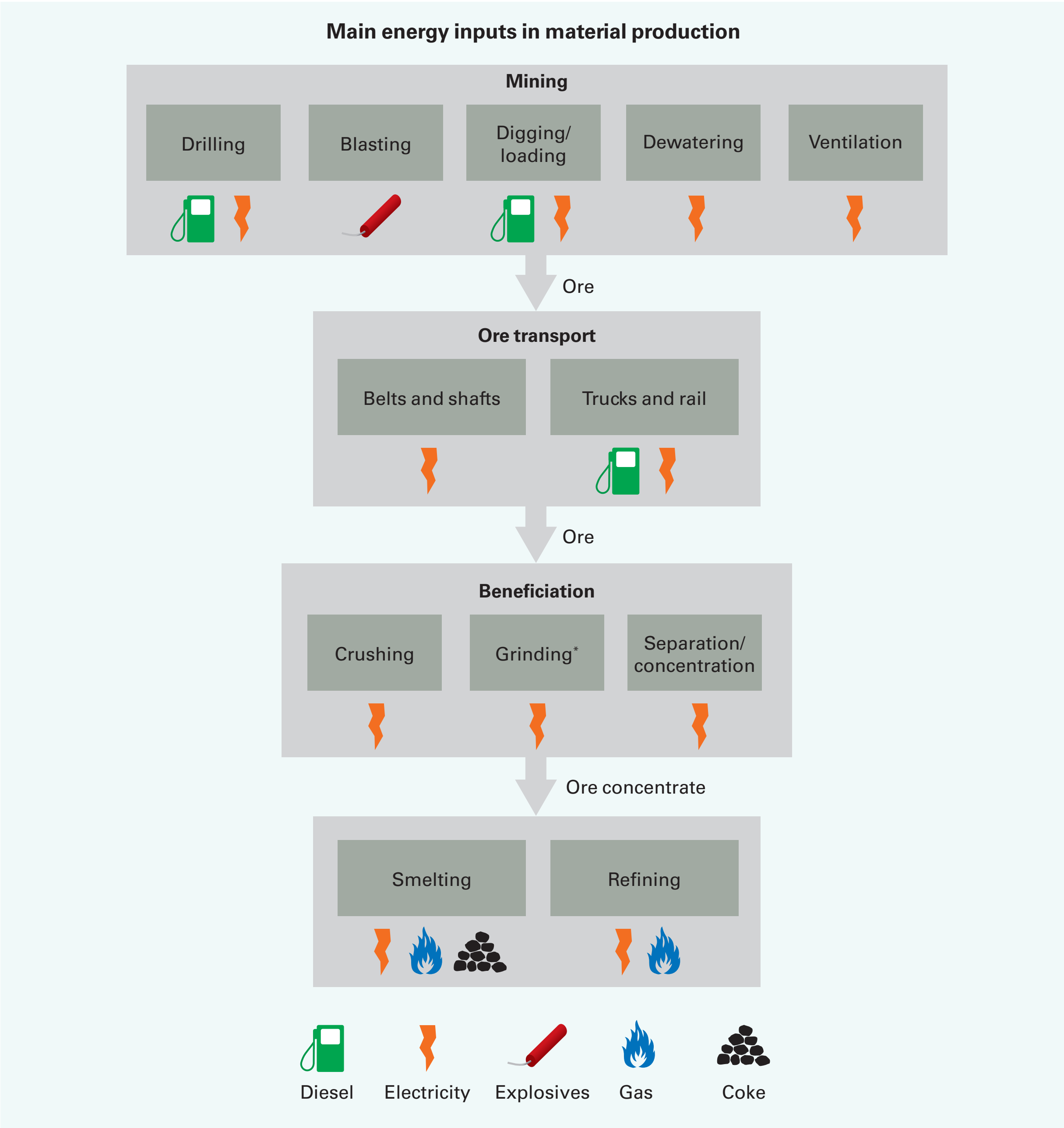
Estimates for worldwide energy consumption in the mining sector vary, but certainly represent several per cent of total global energy use. Several studies in recent years tried to determine or estimate the actual amount of energy required to extract and process ores. However, all studies face the common problem that every orebody is unique and consequently every mining venture is unique. The grade and chemistry of the ore, the size, depth and structure of the orebody, its hardness and abrasivity, the nature of the overburden, the water table and a host of surface conditions, such as remoteness from services and environmental considerations, are some of the factors that influence energy requirements.

A study by the US Department of Energy (DOE) offers the example of just one factor, the energy required to grind rock, known as work indices. These vary from approx. 1.4kWh/tonne for calcined clay to 1345kWh/tonne for mica. This results in large variations in grinding equipment energy requirements. Therefore, different mines will have drastically different energy requirements for a given process.

The industry has, over the past decade, been working with equipment manufacturers to develop energy efficient systems ranging from water-powered drills to replace air-driven drills in underground platinum mines, to A/C motors on huge haul trucks and excavators. The DOE study reports total energy consumption of the US mining industry to about 1.3EJ/year. If all mining projects used best practice techniques and equipment, the energy consumption would be reduced by approximately 20%. By implementing research-and-development-based energy savings, this could be further reduced to a practical minimum of approximately half of present consumption.

Most studies identify diesel use and grinding operations as both the largest consumers of energy and where the greatest efficiencies can be made.

In some countries, including South Africa and Chile, the output of mines has been restricted by the inability of electricity generators to meet demand and the rising costs of energy have rendered many mines uneconomic. Mining companies are increasingly investing in energy production to ensure continuity of supply. Examples include Rio Tinto, which operates more than 3,500MW of hydroelectric generating plant, and Vale, which has a fund in Brazil to develop new power generating technologies.



*Typically, grinding and transport consume about one-third of the energy in the entire rock-to-use process.

Resources and reserves

The definitions of resources and reserves have troubled geologists, miners and financiers throughout history. In this handbook, we have chosen to follow the thinking of the agency that is most quoted when this subject is raised: the US Geological Survey (USGS). This, the world's largest geoscience organization, is recognized as the most informed source and its definitions are used as a basis for mining laws in many countries. Their definitions and an accompanying diagram adapted from USGS publications, that shows the relationship between resources and reserves, can be found on page 80.

Exploration versus production

Geologists and mining engineers are engaged in an unending struggle. Geologists find valuable minerals that add to the known inventory and miners reduce that stock by extracting and distributing the minerals to consumers. So, reserves are dynamic. For example, in 1970, the global reserves of copper were 280 million tonnes. By 2010, more than 400 million tonnes had been extracted; however, the reserve figure had risen to 630 million tonnes. This is a good example of how reserves can be affected by continuing exploration using existing techniques, by new techniques that encourage exploration in areas previously thought barren, and through innovations that allow for extraction in previously impossible conditions. The best examples of this come from the oil industry, where 3D seismic imaging and the ability to operate in deepwater continue to expand the reserves of oil and gas. In the mining world, the introduction of airborne geophysics revolutionized exploration, and the development of heap leaching opened up huge reserves of gold ores that were previously of too low a grade.

Technological advances affect reserves

Technological developments can also affect what we consider to be of value. Before the 1980s, REEs were mostly regarded as not having significant economic uses, until strong neodymium-iron-boron permanent magnets were developed. This changed the demand, nearly instantaneously, from 'of no use' to a 'potential shortage for several years to come' for neodymium. Subsequently, the same change occurred with another REE, dysprosium. A similar story can be observed with lithium where demand and publicity soared after Li-ion batteries advanced in safety aspects and are now first priority concerning energy storage in automotive applications.

Prices versus costs

These developments take place under prevailing national and global economic conditions and many factors affect what is economically extractable at any point in time. It is, therefore, vital to assess resources by two sets of parameters: first, geological and chemical characteristics of the material in place – volume, grade, quality and accessibility – and, second, the costs of extraction against potential sales revenue. The former is, in general terms, measurable; the latter is subject to the vagaries of the market.

As the price of a commodity increases, the grade at which ore can be economically extracted and processed naturally drops, so orebodies that yesterday were uneconomic, could today be exploitable. It is impossible to know what the situation will be in the future, as prices may drop again, for example, as a result of speculation. This problem was aggravated in recent times and should not be underestimated. Generally speaking, rising commodity prices bring new mines to production and breathe life into old mines with borderline balance sheets. As long as market instruments work properly, the price mechanism will continue to function; if, however, too much doubt and uncertainty exist in the market, proven mechanisms may not work properly any more.

On the other hand, rising energy costs have stopped many mining ventures. Rising labour costs were blamed for the closure of the REE mine at Mountain Pass, California, US, as Chinese operations undercut them in the 1980s.

Here, additional environmental problems contributed to the decision to stop. Also around 2000, REEs did not yet have particular attention and economic importance; that, however, changed rapidly when climate-relevant topics became popular. The minerals in the mine, of course, did not change in volume or grade during the time the mines were shut, but when China announced continued and further reduced export quotas, the resulting rise in price persuaded some US operations to begin reopening their mines.

Where the truth lies

It is important to note that the accuracy and veracity of reporting by companies and countries varies dramatically and there are many influences to consider, in addition to reasonable science. This indicates the difficulties of obtaining reliable data.

Developments in exploration and mining will continue to add minerals to the reserves, but one fact cannot be ignored: all mineral reserves are finite. What Mark Twain said about land can generally be said about minerals: "God ain't making any more."

The materials market

The routes that materials take from smelter to end user are varied, often complex and can significantly affect whether supply is sustainable. Beyond the arrangements struck between individual suppliers and users, distinct routes have evolved for each material.

Traded with terminal markets

These routes centre on well-established exchanges, including the London Metal Exchange (LME), which averages daily trading of $46 billion; COMEX, the division of the New York Mercantile Exchange (NYMEX) that deals mainly in metals; the Australian Securities Exchange (ASX); the Tokyo

Commodity Exchange (TOCOM) in Japan; and markets in Shanghai and Hong Kong. The major metals tend to be traded in this way.

The exchanges, which are regulated by government agencies, work to bring order to the trading of materials, help to manage risk and dampen volatility. They offer futures options that allow both sides of trades to hedge or manage risk by establishing positions, in some cases up to 10 years. Traders, both sellers and buyers, have to be members of the exchange, which demands significant funds and ensures, by threat of reputational and financial loss, transparent trading. The main mining houses and banks actively use exchange liquidity to hedge production via members of the exchanges.

The exchanges fix prices on a daily basis, based on trading performance. This barometer allows all concerned to make decisions on sales, purchases and investments. The fixes provide transparency to markets and support contractual agreements. The fixes for platinum, palladium, gold and silver are not based on the futures market, but on a form of trading between two trading partners known as over-the-counter. The closing prices for these trades are published daily for benchmarking purposes.

The exchanges also approve and oversee a physical delivery mechanism involving warehousing and quality controls. The entire system is based on the notion that trading through an exchange can, if required, bring about a 'good delivery' – an agreed amount of materials that reach recognized specifications, traded by parties known and accepted by the market overseers.

The LME is the main futures market for base metals, including cobalt, copper and molybdenum, while platinum and palladium futures trade on NYMEX, and gold and silver feature at COMEX.

Traded without terminal markets

This is a term used to describe the numerous trades, mainly of small volumes of specialist materials in a usually opaque market that does not involve regulated exchanges, for example, REEs, germanium and rhodium. Purchases are normally made through agents who enjoy a pivotal position when materials are scarce. The passing on of the often-substantial price increases, between that agreed at the time of ordering and the price demanded at delivery, is accepted practice. The companies that control the market tend to be those at the end of the production process – not necessarily the miners – and good intelligence around the supply/demand situation ensures their control of the markets.

Bilateral ventures

Another form of trading has recently emerged. The need to ensure adequate supplies of reasonably priced materials is causing major manufacturers, such as Toyota and Siemens, to cut out the intermediaries and invest directly in mining ventures for REEs.

The following materials are not traded on any of the main exchanges: germanium, cadmium, chromium, rhodium, vanadium, wolframite/tungsten, lithium, indium, REEs, gallium and tellurium. Bulk materials, including phosphorus and potash, are traded directly. Uranium is a special case because of its regulation by the International Atomic Energy Agency, but effectively is traded directly, with end users buying it from companies along the production chain from mine to useable nuclear fuel.

Cautionary tales from the market

Anyone wishing to profit from trading in materials needs to have a full understanding of the factors that affect price over the period in which they wish to trade. One story in particular illustrates this truth. A major motor manufacturer, along with all other automobile manufacturers, responded to the legislation demanding lower emissions by designing and fitting catalytic converters to its vehicles. These initially used platinum as the catalyst, but their engineers promoted the use of palladium as a cheaper alternative. At the time they were moving to palladium-based catalysts, the supply suffered a series of disturbances centred around uncertainties from Russian mines and the price rose from around $200 an ounce to more than $1,000. To avoid disruptions to their supply chain, the company instructed its purchasing department to buy palladium, either physically or on long-term contracts, which they did with vigour. The employees in this department were skilled in sourcing materials with far more stable prices such as steel.

The price rises, spotted early by some car manufacturers, resulted in efforts to reduce the amount required per vehicle and also persuaded mining companies outside Russia to increase supplies. These two factors contributed to a dramatic drop in price in 2000-01 to around $400 an ounce. Good news for some, but a disaster for this motor company as it was caught with huge quantities of palladium bought at the peak of the market and a reduced demand. In February 2002 the company reported a billion-dollar write down in the value of its palladium stockpile.

Cornering the market

In 1979 two Texan brothers, Nelson Bunker Hunt and William Herbert Hunt attempted to corner the silver market by buying substantial percentages of the world's silver output. The price rose by more than 700% and caused huge concern among silver consumers, particularly the jewellery trade. That concern caused the authorities running COMEX to change the rules around the amount of each metal that could be bought in certain types of trades. This caused the price to drop rapidly, 50% in four days, and the Hunts had to borrow heavily to meet their obligations to purchase. At one stage they owed more than a billion dollars to banks, who had to step in with a rescue package. Huge losses, and a court case brought by a Peruvian silver mining company, ruined by the price fluctuations, eventually bankrupted the Hunts and the price of silver returned to 'pre-Hunt' levels.

Criticality and constraints

This handbook defines criticality as the degree to which a material is necessary as a contributor to an energy pathway. Other definitions have been produced and some of these are referenced on page 86. Factors that adversely affect the required demand and supply balance, we define as constraints. Many factors need to be considered when attempting to describe the supply and demand balance through time, with economics by far the most important, not least because of it being subject to rapid change. For example, current ore grades for some metals and some recycling processes would have been deemed wholly uneconomic in the recent past. Technological advances can allow processes that were previously not economically viable to be considered.

Reserves

Given the volumes physically available in the crust and oceans, and the potential to recycle, there is no obvious overall constraint for any of the materials considered.

It should be remembered that the continental crust averages 40,000 metres thick, but most exploration drilling is less than 200 metres deep, open pits are all less than 1,000 metres, and underground mines have yet to penetrate deeper than 4,000 metres. Underground mines have to contend with the rise in temperature the deeper they get and at 4,000 metres, even with a benign geothermal gradient, rock temperatures reach 65°C. Workings have to be cooled and miners wear ice-filled vests, all adding to the costs of mining.

Reserves are dynamic. Economics, new geological understanding and new technologies drive exploration and reserves figures. There are plenty of examples of reserve growth in the oil industry through discoveries in basins previously thought uneconomic or in formerly uninterpretable geology, such as sub-salt.

When materials are produced as by-products, the economics can be complicated, as is the case with gallium in bauxite and tellurium in copper and lead. The additional revenue they produce has to be balanced, in some cases, by the extra costs involved in extracting the prime target metal from these 'impurities'.

Trade

Mineral deposits do not respect borders. They were all in place long before political boundaries or even man. Some countries possess extraordinary percentages of reserves and production: for example, South Africa with more than 75% of platinum reserves and China with 97% of rare earth elements production from at least 2009 until 2012. The unequal geological distribution of materials is compounded by the ability or inclination for a country to explore for, produce and export them.

The availability of minerals through trade can be linked to factors such as political stability and financial issues such as speculation and currency exchange rates. As 2011 has highlighted, especially in northern Africa, revolution is not far away in some parts of the world and the ability of most countries to develop and export materials can change rapidly, both positively and negatively, when influenced by trading agreements, embargos or restrictions. An example of the latter was the signing, in 2010 by President Obama, of the Dodd Frank Act, aimed at improving regulation of the US financial industry. The act requires companies to declare use of so-called 'conflict minerals'. This has affected the trade in tantalum, tin, tungsten and gold from the Democratic Republic of Congo (DR Congo) and surrounding countries.

Trade is also influenced by the huge power of the major transnational companies whose technical, financial and political impact can influence entire economies of weak countries and sway the supply of materials on a global basis. Where production of natural resources is effected by a very limited number of companies or locations, constraints in supply can arise. Attempts have been made in the past to corner the market in particular materials, most famously, and as noted previously, the Hunt brothers' attempt in 1979 – 80, with silver.

Changes in technology may bring a rapid rise or fall in the demand, but we must be aware of the paradox pointed out by the 19th century economist, William Stanley Jevons.

His observations of the industrial revolution were that improvements in the efficiency of coal use actually led to a growth in demand. Today improved car efficiency has led to more car use. New technologies can bring completely new demand: lithium, once a laboratory curiosity, is now in huge demand for batteries. While predictions about the future are subject to large uncertainties, it is reasonable to presume that the demand for materials needed for further electrification and lower-carbon energy will grow.

Technological development can optimize the entire supply chain, reduce the volume of material in products and improve extraction efficiency from orebody to end use.

At the same time technological advance can add new competitors to the supply chain. This competitive use can prove to be one of the most critical issues in raw materials trading and handling. This is compounded when valid and reliable numbers are not known because markets are not transparent.

One factor that should not be underestimated is incentives that may promote the development of new products and consequently increase demand for the materials they contain. An example of this is the government subsidies that have been paid in Germany to promote the uptake of PV solar generation.

Finally, transport and logistics play a vital role in supply risk. As long as transport remains cheap, moving materials across the globe will not add significantly to overall product price.

Ecological impact

Materials and their extraction processes are under scrutiny for environmental performance that can significantly affect both demand and supply. Discovery of a large orebody in an environmentally sensitive area raises serious questions on its status as a reserve. As the population grows, pressure on land increases and mining on agricultural or urban land will be constrained. The discovery that a material is harmful to man and/or the environment can seriously reduce demand, as demonstrated by cadmium, a material banned from most uses in the European Union (EU). Dissipation of elements is a phenomenon that is not well researched yet, but early findings suggest that it could pose a potential hazard to humans and the environment.

Processing

The processes required to produce useful products from run-of-mine material vary from virtually nothing, in the case of phosphorous and potassium, to highly complex, energy-intensive and commercially confidential work in metals including germanium, platinum, tellurium and the REEs. In these latter examples, the know-how and the necessary investments are often in the control of a small number of companies, whose influence can constrain supply and certainly affect price. In some cases, mineral concentrates are shipped internationally to smelters and refiners, which potentially adds another layer of constraint.

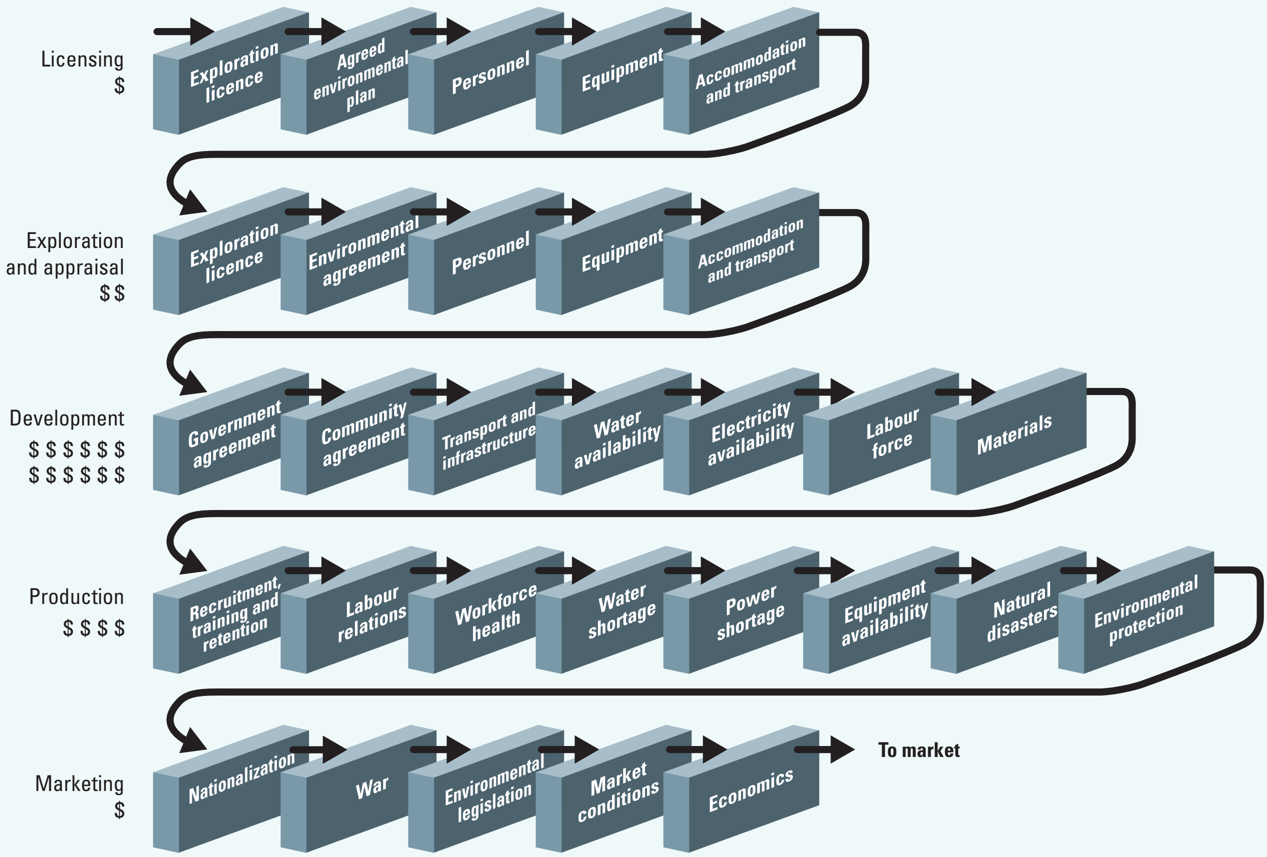
Substitutability

Most materials can be substituted, although usually at a reduction in performance: for example, aluminium is already used in place of copper in electricity transmission and rhodium-silver alloy instead of palladium in automotive exhaust systems. In many cases, the most appropriate substitutes themselves are subject to supply and/or demand constraints, so posing new potential risks. The adoption of a substitute may lead to competitive situations for the material's original use. For example, substituting terbium in place of dysprosium in permanent magnets has a knock-on effect in the availability and price of terbium in its prime use in energy efficient lighting.

Recyclability

Sustainable manufacturing practices can determine the potential for recycling the materials in products and some landfill sites are already becoming reworked for their metal content. Not all materials built into gadgets, however, can effectively or physically be recycled as the grades are too low or the alloys cannot be separated. Design-to-recycle is one option to improve recyclability. In this context the re-processing of tailings is becoming more attractive, especially as new separation technologies are developed.

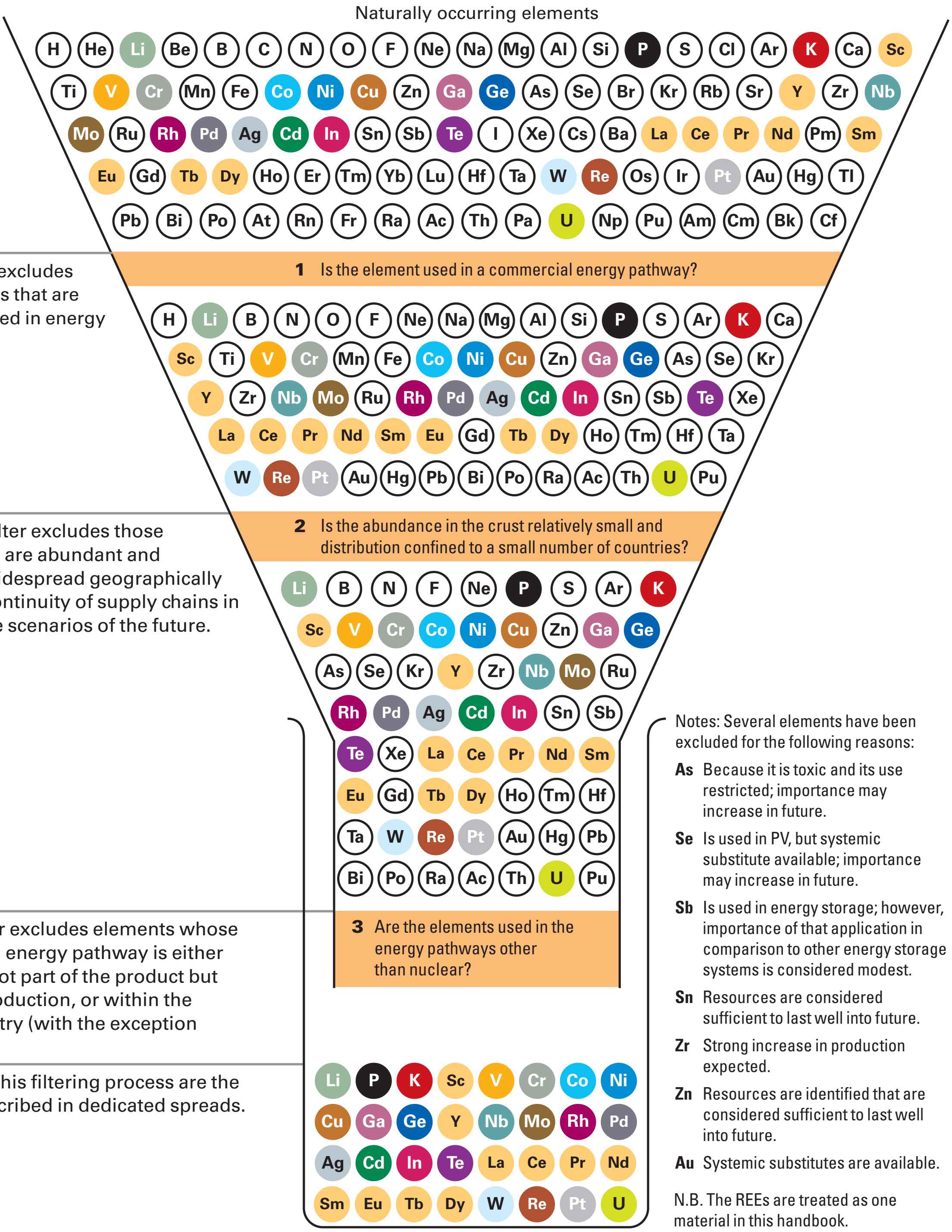
Barriers to negotiate in mining projects



Schematic illustration of the possible barriers to be overcome in order for a project to move from an exploration idea to a mine that is delivering material to the market place. Failure to negotiate any of the barriers could lead to project failure. Dollar signs are an indication of the level of expenditure associated with the related stage of a project.

Filtering process to determine the elements selected

An introductory handbook cannot be both introductory and encyclopaedic; the rationale supporting the choice of which elements to include in this handbook is illustrated in this figure. Simply put, a set of filters has been applied to all the naturally occurring elements.



The first filter excludes those elements that are not directly used in energy pathways.

The second filter excludes those elements that are abundant and sufficiently widespread geographically to facilitate continuity of supply chains in all reasonable scenarios of the future.

The third filter excludes elements whose only use in an energy pathway is either indirect, i.e. not part of the product but used in its production, or within the nuclear industry (with the exception of uranium).

The result of this filtering process are the elements described in dedicated spreads.

Notes: Several elements have been excluded for the following reasons:

As Because it is toxic and its use restricted; importance may increase in future.

Se Is used in PV, but systemic substitute available; importance may increase in future.

Sb Is used in energy storage; however, importance of that application in comparison to other energy storage systems is considered modest.

Sn Resources are considered sufficient to last well into future.

Zr Strong increase in production expected.

Zn Resources are identified that are considered sufficient to last well into future.

Au Systemic substitutes are available.

N.B. The REEs are treated as one material in this handbook.

Guide to the materials data pages

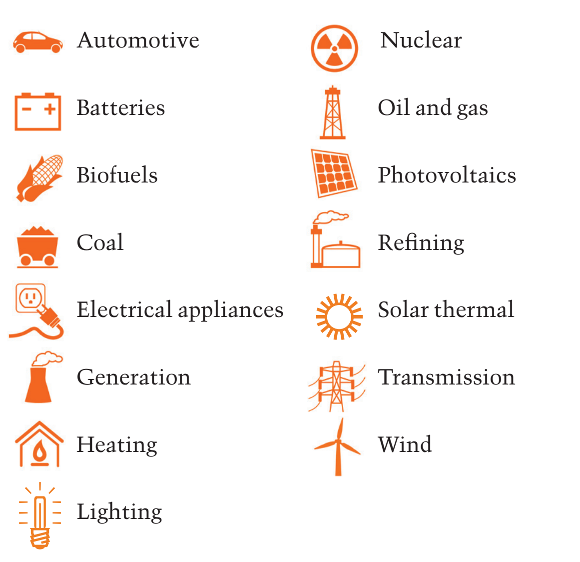
The aim of the following outlines is to give the reader key data, at a glance, to help develop a perspective on energy-critical materials.

Each two-page outline contains the following sections:

Uses in the energy sector

Icons

These are pictorial guides to the main uses of the material in energy pathways.



Pie chart

The chart indicates the scale of use in different sectors, both energy and non-energy, shown by shades of red/orange and greys respectively. Where materials are used in steel production, it is impossible to define what percentage of the steel would be required in the energy sector and we have indicated this with a dotted red line around the chart. The same applies to phosphorus and potash, some of which are used in the biofuels industry. A segment of the pie charts where the colour fades towards the centre, such as the chemicals and catalysts in molybdenum, shows a use that impacts on some energy pathways, but is difficult to define numerically.

Properties and origins

This section gives an overview of the essential properties and an indication of the geological settings in which the material can be found. There is a comparative chart on pages 78 – 79 that offers more physical and chemical properties. A selection of technical terms are explained in the glossary on pages 82 – 83.

Production and price

The cube diagram indicates the volume of annual production relative to the size of an average human, a double-decker bus or the Eiffel Tower. The annual production is shown in tonnes and, where applicable, in traded units, for example troy ounces for platinum and rhodium. The data for the annual production cube and for the key producers is taken from the USGS. The company data is taken from annual reports of the respective companies. Historical price and production data also comes from the USGS. The use of two different databases leads to minor anomalies in the data displayed. For example, in some cases the reported production of the top three companies exceeds the reported total global production. Another example of this is price and production values. Production values from 2012 are mostly available unlike prices, for which the most recent consistent data is 2011 and that is why the price and production graphs only go to 2011. This typifies the difficulty in accessing data – and helps explain why rumour can take the place of fact-based analysis.

Please note that the USGS has reserved the right to amend historical estimated price and production data, as more information becomes available. Prices have not been corrected for inflation and rounding errors in production data may occur.

Supply interruption indicators

Many factors can potentially interrupt supply of materials.
The table below outlines the criteria used in this handbook to classify the major factors into high, medium or low impact. The indicators are noted for each element.

Criteria for	H	M	L
Reserves	■ Reserves-to-production ratio (R/P) <20 years ■ **or** R/P <100 years but semi-monopolistic production	■ R/P = 20-80 years ■ **or** uncertain data	■ R/P >80 years **and no** monopolistic situation
Trade	■ Element **not** traded on metal exchanges **and** semi-monopolistic production (see below)	■ Element **not** traded on metal exchanges ■ **or** semi-monopolistic production ■ **or** uncertain data	■ Traded on metal exchanges **and no** monopolistic production
Ecological impact	■ Element is toxic ■ **or** ores contain low-grade toxic or radioactive substances that might get enriched during processing ■ **or** risk of bioactivity is not refuted	■ Low toxicity known ■ **or** uncertain data ■ **or** toxicity has been put/is in the process of getting into jurisdictional context	■ No toxicity **and** no handling problems known
Processing	■ Element is produced as by-product	■ Element is main product **and** complex refining technologies are required ■ **or** uncertain data ■ **or** element produced as co-product	■ Element is main product **and** technology proven
Substitutability	■ **No** substitute on materials level available ■ **or** substitute available but itself considered critical	■ Substitute available with degradation in performance ■ **or** **no** substitute available on materials level but on systemic level (e.g. wind turbine without REEs)	■ Substitute available
Recyclability	■ **No** recycling technology in mass operation **and** material concentration in end-of-life product low	■ Recycling technology in place **and** logistics as limiting factor ■ **or** uncertain data	■ Recycling technology in place **and** global recycling rate >50%

Semi-monopolistic =
- single country or company >50% of production
- **or** two companies or countries >70% of annual global production

Notes

Data used for determination of the classifications are primarily based on:
Reserves, Processing, Substitutability – USGS MCS, USGS MYB, Johnson Matthey Platinum Report and annual reports of producing companies.

Trade – stock exchange information.

Ecological impact – toxicity, extracted from EU classifications and chemical literature.
Further ecological impact assessments have not been included.

Nuclear – data has been extracted from World Nuclear Association reports.

The table below applies the supply interruption indicators to particular energy pathways, allowing the relative risks to individual pathways to be assessed. For each material the highest interruption indicator across all criteria (reserves, trade, ecological impact, processing, substitutability, and recyclability) is shown, but lower indicators may also apply for certain criteria. The grey circles show where a material is not typically used in a pathway.

		R/P	Oil and gas	Bioenergy	Coal	Nuclear	Wind	Photovoltaics	Solar *Thermal and CSP*	Refining	Thermal power generation	Transmission	Batteries	Automotive *Electric*	Automotive *Petrol & diesel*	Heating	Light	Electrical appliances
Cd	Cadmium	22						H					H					
Cr	Chromium	19	H		H	H	H		H	H	H	H						
Co	Cobalt	68	H		H	H	H			H	H	H	H	H				
Cu	Copper	40	M		M	M	M		M		M	M				M		M
Ga	Gallium	n/a						H									H	H
Ge	Germanium	n/a						H									H	
In	Indium	n/a						H									H	H
Li	Lithium	351											H	H				H
Mo	Molybdenum	44	H		H	H	H	H		H	H	H						
Ni	Nickel	36	H		H	H	H			H	H	H	H	H				H
Nb	Niobium	62	H		H	H	H			H	H	H						H
Pd	Palladium	n/a								M				M	M			M
P	Phosphorus	319		H														
Pt	Platinum	n/a								H				H	H			
K	Potassium	279		H														
REE	Rare Earths	1,000				H	H			H			H	H	H		H	
Re	Rhenium	48								H					H			
Rh	Rhodium	n/a								H					H			
Ag	Silver	23						M	M			M						M
Te	Tellurium	n/a						H										H
W	Tungsten	44	H		H	H	H			H	H	H						
U	Uranium	91				H												
V	Vanadium	222	H		H	H	H			H	H	H	H					

It is important that the time factor is carefully considered in these applications in two ways. First is the period over which a constraint can take effect. A major fire or earthquake at a mine or processing plant that supplies a significant percentage of a material can affect supply literally overnight, and large-scale industrial unrest can stop mining across entire nations for months.

The coal miners' strike in the UK that started in March 1984 cut coal supplies for nearly a year, and the 2012 strikes across the South African mining industry caused a reduction of output and prices of platinum-group metals to rise by some 60%.

The second consideration is how long it takes to find a way around the problem. Mines, especially underground mines, take years to construct and often longer to gain finance and necessary permissions.

Please note that all the data included is sourced from reputable organizations. Where we have doubts about the reliability or relevance of data, we have regarded it as not available and marked it as 'n/a'.

Cadmium Cd 48

Cadmium is essential for one photovoltaic technology, but is known to be toxic.

Note: Uses pie chart could not be produced because no reliable data is available.

Uses in the energy sector

Cadmium has two main uses in the energy sector, one well established but meeting competition, and the other relatively new and growing rapidly.

- **Rechargeable batteries**: Nickel-cadmium (NiCd) batteries are long-lasting and have the ability to accept a high number of charge-discharge cycles. Individual cells produce 1.2 volts but combinations of up to 12 volts are common for uses such as cordless power tools. An AA-size battery contains around 2.9 grammes of cadmium. Environmental concerns have caused the banning of such batteries for most domestic uses so other technologies, such as lithium-ion and nickel-metal hydride (NiMH) storage, are replacing them. NiCd batteries are still used for a variety of stationary applications, such as fire alarms and hospital emergency lighting. There is a potential for growth if large batteries are widely adopted to store electricity produced during daylight by solar generation.
- **Photovoltaic cells**: Thin-film cells, which use a compound of cadmium and tellurium (CdTe) as a p-type semiconductor layer, and cadmium sulphide (CdS) as an n-type layer on the light-facing side, are proving cost effective against silicon-based cells. Thin-film cells account for about 10% of the total PV market and CdTe cells have captured about half the world's thin-film market, some 5.8% of total PV production in 2012. The CdTe material is encapsulated in the manufacturing process and many researchers believe this renders it harmless. The EU, however, through the Restriction of Hazardous Substances Directive, and Japan still impose strict regulation on its use in PVs.

Because of its ability to adsorb neutrons, cadmium has a minor use in nuclear reactor control rods.

Uses outside the energy sector

Cadmium compounds are used as a pigment in paints and as stabilizers in plastics, particularly where resistance to high temperatures is required.

The metal is used for corrosion-resistant coatings and platings. Its ability to cope with alkali attack and seawater is better than all alternatives, and the same applies when it is used for corrosion protection in the form of sacrificial anodes. Although undoubtedly effective, environmental concerns have caused it to be phased out of the car industry.

These uses have been restricted by several pieces of EU legislation, mainly in the Restriction of Hazardous Substances (RoHS) and Waste Electrical and Electronic Equipment (WEEE) directives.

Properties and origins

Melting point 321°C
Density 8.64g/cm³

Cadmium is a soft, malleable and ductile bluish-white metal with a low melting point.

Cadmium is a common impurity in zinc ores, and it is most often isolated during the production of zinc. Zinc is a common metal found in a variety of geological settings.

Production and price

Annual production 23,000 tonnes

Key producers 2012	Annual production 2012		Reserves	R/P
Country	Tonnes	%	Tonnes	
China	7,000	30	92,000	13
Korea	4,100	18	n/a	n/a
Japan	2,130	9	n/a	n/a
Others	9,770	42	408,000	42
World	**23,000**		**500,000**	**22**
Company*				
n/a	n/a	n/a	n/a	n/a

* Reliable company data not available.

Supply interruption indicators

Reserves	M
Trade	M
Ecological impact	H
Processing	H
Substitutability	M
Recyclability	M
Reserves-to-production ratio	**22**

Sustainability

Reserves — M

World reserves of cadmium are more than adequate for the foreseeable future, especially since the amount of cadmium produced depends on zinc smelter output. Zinc reserves are thought to be adequate for at least the next 25 years.

Trade — M

The production of cadmium is almost entirely dependent on the zinc industry. This is dominated by China, Peru and Australia with more than half the world's production between them, but for cadmium many other countries have substantial reserves and production. The supply and demand balance is heavily influenced by environmental legislation and the outright banning of cadmium use is the biggest threat.

Ecological impact — H

The health effects of inhaling cadmium-bearing dust or ingesting cadmium compounds are well understood and, as a result, general use of the metal is banned, with some exemptions, in many countries, including the EU. EU directives exempt the use of cadmium in PVs, some electrical contact applications and nuclear systems. Exposure in humans can lead to acute lung disease and, in the famous case of a population exposed to mining waste in Japan, kidney failure and bone disease known as 'itai-itai' or, literally, 'ouch-ouch'. Across the world, the most common exposure is among cigarette smokers who absorb the element from tobacco smoke, as a result of the plant concentrating cadmium in its leaves. The European Food Safety Authority, in a report of 2011, suggests that current dietary habits for the non-smoking population in Europe make exposure to cadmium above its recommended safety limit unlikely. There is still concern about appropriate methods for the disposal of cadmium-bearing batteries and flue dust. Legislation is being tightened in many countries to improve recycling facilities and minimize the disposal of cadmium-bearing batteries to landfill.

Processing — H

Cadmium found mainly in zinc sulfide ores can only be extracted after the zinc has been liberated. This is done by converting the sulphides to oxides through roasting the ores in the presence of oxygen, and then producing zinc metal by smelting the oxide with carbon or by electrolysis in sulfuric acid. Cadmium is isolated from the zinc metal by vacuum distillation if the zinc is smelted, or recovered from zinc smelter ash by electrolysis.

Substitutability — M

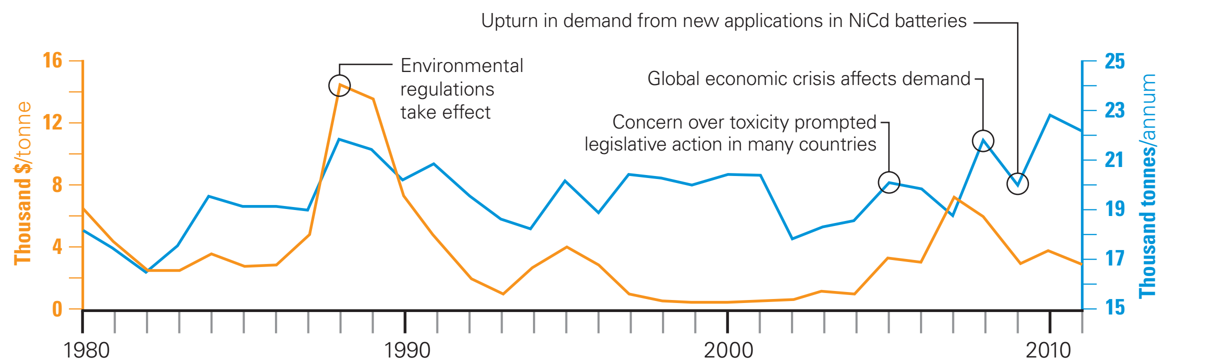
Despite legislation restricting the use of the metal in many countries, cadmium is still favoured in high-performance applications. NiCd batteries are being replaced by other non-cadmium-containing storage systems, such as lithium-ion and lead-acid batteries, but they are still specified for stationary battery systems because of their cost benefit.

Cadmium cannot be substituted in CdTe solar cells, but there are systemic alternatives, such as copper-indium-selenide (CIS), copper-indium-gallium-selenide (CIGS) and amorphous silicon thin-film solar cells and crystalline silicon technologies.

Corrosion-resistant applications using cadmium still remain in the aerospace and military sectors because of operational safety, but in the paint industry, cerium sulphide can be used in place of cadmium sulphide as a paint pigment.

Recyclability — M

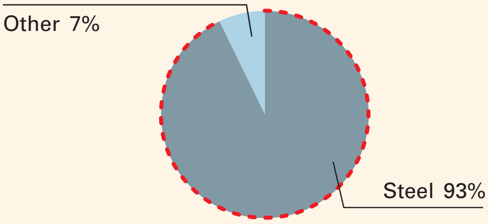
Global secondary cadmium production is approximately 20% of the total cadmium production. Most of this secondary metal is provided by NiCd batteries, which are mainly sold in Asia. Cadmium in CdTe solar cells is recyclable and the old modules are expected to be recycled at the end of their lives. The challenge in recycling, however, is to separate the metallic elements from the glass substrate. First Solar, the world's largest manufacturer of CdTe cells, accepts end-of-life returned product.



PRICE & PRODUCTION

Chromium Cr 24

Essential alloying element that revolutionized the steel industry.



Uses in the energy sector

Simply put, chromium is at the heart of most of the world's energy pathways. As an essential component of stainless steels and super alloys, it is found wherever corrosion-resistant, hard metals are needed – from the piston rods on generators driving drilling rigs, through to the stators on down-hole mud motors, and the containment vessels surrounding nuclear reactors.

Chromium also is used in the solar thermal industry, where black chromium plating is used to absorb solar energy, and has a minor use in the oil and gas sector, where chromium salts are added to drilling muds as an anti-corrosion agent.

Uses outside the energy sector

As with uses in the energy sector, chromium is essential where hardwearing corrosion-resistant metals are required, so all steel made today contains it. In addition to use in alloys, chromium is used extensively as a plating metal, not just in the decorative form beloved by 1950s US car manufacturers, but in a variety of more utilitarian forms.

Chromium compounds are used as pigments in glass, although the previous use as a pigment in paints has ceased due to environmental concerns. The toxicity of chromium salts does, however, prove useful in the preparation of solutions to treat wood against fungal and insect attack. Chromium salts are widely used in the tanning of leather, but concerns over the environmental impact of these salts are growing.

Properties and origins

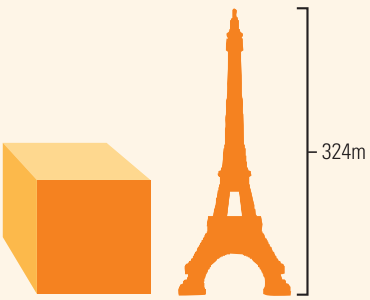
Melting point 1,857°C
Density 7.14g/cm³

Chromium is a hard, lustrous, steel-grey metal, which has a high resistance to corrosion. This latter property occurs because, when chromium is exposed to air, a stable protective oxide layer, a few atoms thick, forms.

The element is fairly abundant in the crust, averaging 122ppm and, although there are rare occurrences of chromium as a native metal, the vast majority occurs as the oxide formed with iron known as chromite. This mineral forms in ultrabasic rocks, and ore grades develop when magmas are subject to separation based on the density of their constituents. The best-known examples are in the vast Bushveld Igneous Complex in South Africa, where some layers contain up to 90% chromite.

Production and price

Annual production*
24,000,000 tonnes



Key producers 2012	**Annual production 2012***		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
South Africa	11,000,000	46	200,000,000	18
India	3,800,000	16	54,000,000	14
Kazakhstan	3,800,000	16	210,000,000	55
Others	5,400,000	23	n/a	n/a
World	**24,000,000**		**>464,000,000**	**>19**
Company**				
Eurasian Natural Resources Corp	3,730,000	16	n/a	n/a
Samancor	>1,000,000	>4	n/a	n/a
GlencoreXstrata	938,000	4	n/a	n/a

* Marketable chromite ore.
** South African mining industry reported total national output at 10,721,000 tonnes; individual company production not reported.

Sustainability

Reserves H

Although the reserves-to-production ratio (R/P) quoted is relatively small, the estimates for chromium resources as chromite are huge: some 12 billion tonnes. The potential for constraints lies in the fact that the vast majority of these resources lie in South Africa and Kazakhstan. South African production is hampered by the same problems affecting platinum production in the country, namely inadequate electrical power and the loss of skilled workforce due to strikes and HIV/AIDS.

Trade M

Trade in chromium is driven by the steel industry and this, in turn, is a barometer of global economic health. The biggest importer of chromium is China. Chromium is not traded on the major commodity exchanges.

Ecological impact H

While the metal has a low toxicity, some chromium oxides are toxic, especially those used in the leather tanning industry, which are known to lead to animal and human health problems. The UK's Health and Safety Executive issues warnings for those working with chromium compounds, suggesting that long-term health effects include damage to the nose (including ulcers and holes in the septum), irritation of the lungs, kidney damage and the risk of cancer of the lung and nose.

Processing L

Chromite ore is comminuted before the gangue is removed, by gravity separation.

The most common method of producing metal is to smelt chromite in electric arc furnaces, with carbonaceous reductants and fluxes. Adding carbon steel and other components into the melt produces different grades of steel. To produce chromium metal, chromite is leached and the resulting sodium chromate fed into electrolysis cells.

Cr 24

Supply interruption indicators

Reserves	H
Trade	M
Ecological impact	H
Processing	L
Substitutability	H
Recyclability	M

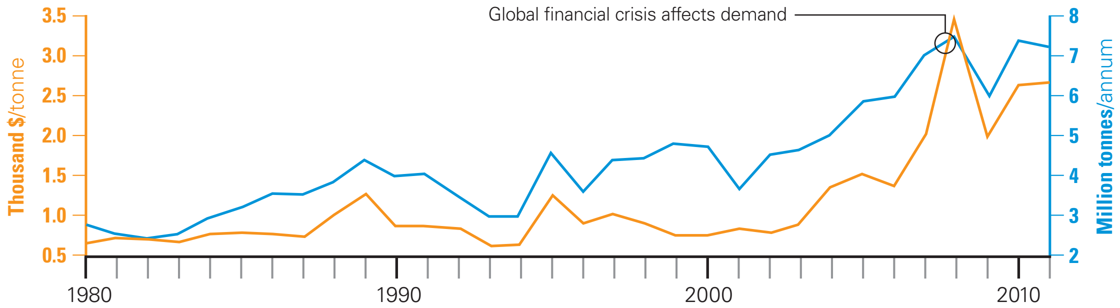
Reserves-to-production ratio **>19**

Substitutability H

Chromium cannot be substituted in stainless steel or super alloys. Substitutes for its other uses exist but result in lowered performance. Chromium-containing scrap can be used as substitutes in ferrochromium uses.

Recyclability M

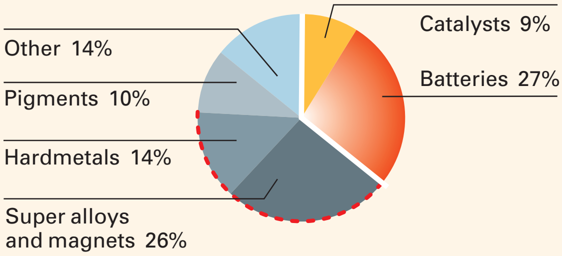
Chromium is readily recycled and considerable quantities are recovered from scrap metal. Even though exact numbers are not known, it is assumed that the majority of this recycling is from scrap metal. Concerning the demand itself, some estimates are as high as 60% being met by recycled material.



PRICE & PRODUCTION

Cobalt Co 27

Critical constituent of specialized steels, rechargeable batteries and permanent magnets. Nearly half of known reserves in one war-torn country.



Uses in the energy sector

- **Alloys**: When mixed with nickel-based alloys, cobalt enhances their high-temperature strength, leading to uses in jet engines and gas turbines in the electricity-generating sector.
- **Batteries**: Cobalt is essential to the production of the cathodes used in three main types of rechargeable batteries: lithium-ion, where it forms up to 60% of the cathode; nickel-cadmium, with up to 5%; and nickel-metal hydride batteries, where the cathodes are 15% cobalt.
- **Magnets**: Cobalt alloys, with the expensive metal samarium in different mixtures, can be formed into powerful magnets capable of retaining their strength at up to 350°C. These magnets are a little less powerful than NdFeB magnets, but persist at higher temperatures. They are used in a wide range of electrical appliances.
- **Catalysts**: Cobalt oxide catalysts are used in refineries to remove sulphur from crude oil. This use is expected to grow as crude quality deteriorates. Cobalt catalysts are also used in gas-to-liquids technology, which is a growing sector.
- **Electrical conductors**: High-quality electrical contacts on integrated circuits can contain up to 15% cobalt.

Uses outside the energy sector

Cobalt-based alloys enjoy a wide range of uses, including steel-cutting tools, prosthetic joints and corrosion-resistant coatings. One of the original uses of cobalt, as a pigment (hence 'cobalt blue'), still accounts for around 10% of production. The metal is also used in radio-medicine and as a feed supplement for animals.

Properties and origins

Melting point 1,495°C
Density 8.89g/cm^3

Cobalt is a very hard, brittle, greyish-silver metal. Its high melting point and the ease with which it makes alloys enable it to impart strength when combined with other metals. It has fairly low electrical and thermal conductivities, but is strongly ferromagnetic and capable of retaining magnetism at high temperatures.

The element, which forms about 29ppm of the crust, is never found native and its compounds are widely distributed. Cobalt is found in soil, plants and animals with many organisms needing the element for good health. Vitamin B12, also known as cobalamin, is structured around cobalt.

Cobalt mineralization starts with concentration in basic magmas and, where magmatic fluids meet sulphur-rich sediments, such as evaporites, sulphides are formed. Deposits of this origin include sites known primarily for other metals, such as the platinum-rich Merensky Reef of South Africa and Russia's nickel/platinum Norilsk deposit. Concentrations average around 0.1%. Erosion of rocks containing minerals rich in cobalt, followed by deposition in arid climates, produces sedimentary deposits, ranging up to 0.4% concentration, including the largest-known reserves in the Central African copper belt.

Production and price

Annual production 110,000 tonnes

Key producers 2012	Annual production 2012		Reserves	R/P
Country	Tonnes	%	Tonnes	
DR Congo	60,000	55	3,400,000	57
China	7,000	6	80,000	11
Canada	6,700	6	140,000	21
Others	36,300	33	3,880,000	107
World	**110,000**		**7,500,000**	**68**
Company				
GlencoreXstrata	16,100	15	n/a	n/a
Freeport-McMoRan Copper & Gold	11,325	10	n/a	n/a
Eurasian Natural Resources Corp	9,623	9	n/a	n/a

Sustainability

Reserves H

Morocco hosts the only deposit where cobalt is mined as prime ore, as the metal is produced almost exclusively as a by-product of copper and nickel mining. By far the largest reserves, some 50% of the world's total, are found in the sedimentary rocks of the Central African copper belt in Zambia and the Democratic Republic of the Congo (DR Congo), where grades generally run between 0.17% and 0.25% cobalt. A geological setting with similar origin, the Kupferschiefer, spans from north-east England, across Germany and into Poland. This deposit has been extensively mined in the past and gave rise to much of the metallurgical history of Europe. In addition to the Russian and South African magmatic deposits mentioned above, this type of mineralization led to major deposits at Sudbury in Canada and Kambalda in Australia, both mined primarily for nickel.

Trade M

With more than half the world's production coming from DR Congo, a country devastated by war in recent years, continuity of supply is always in doubt. China is also in a semi-monopolistic position, it being the world's leading producer of refined cobalt. This results from domestic mine production and the import of substantial quantities of ore through life-of-mine contracts with Australia and DR Congo. World production is growing as many new projects come on stream, surprisingly a fair number in DR Congo. Cobalt is traded on the LME.

Ecological impact H

As an element vital for health, it is to be expected that plants and animals can tolerate reasonable concentrations. Cobalt is not known to biomagnify up the food chain. Soils near mining and smelting facilities, however, may contain very high amounts of cobalt, so that the uptake by animals through eating plants can cause detrimental health effects.

Supply interruption indicators

Reserves	H
Trade	M
Ecological impact	H
Processing	M
Substitutability	M
Recyclability	M

Reserves-to-production ratio **68**

Processing M

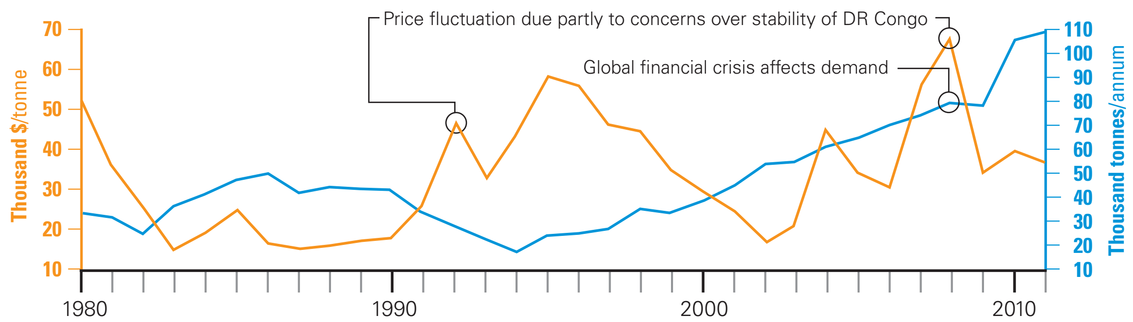
As most cobalt is a by-product, the primary processing techniques will be engineered for the prime metal. Cobalt is normally extracted from the processing stream by hydro- and pyrometallurgical processes. Unlike many materials, a large percentage of cobalt concentrates are shipped internationally for smelting, with China leading this trend.

Substitutability M

Scarcity and price drive the search for substitutes. In batteries, cobalt use has decreased with the introduction of newer alloy, but in steel alloys, cobalt's unique properties are not matched by alternatives and performance suffers. Ceramics have replaced some of the high-temperature, high-hardness materials that rely on cobalt, and cerium, iron, lead, manganese and vanadium all can, to some degree, replace cobalt in pigments.

Recyclability M

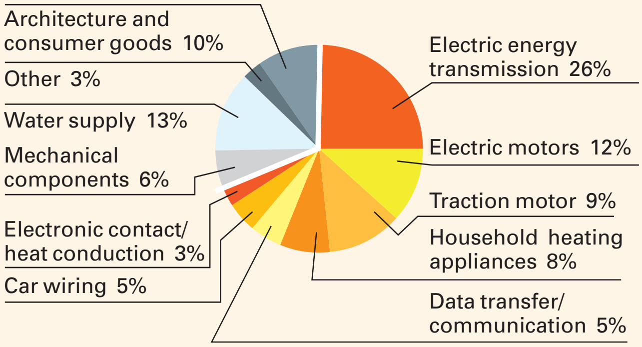
Because of the high price of cobalt and its unpredictable supply, recycling has reached high levels, meeting approximately 25% of world demand. Also, the desire to reduce environmental impact of cobalt-laden batteries in landfills has accelerated moves to recycle, especially in countries where legislation has helped. Alloys containing cobalt in obsolete components, such as turbine blades, are re-melted and re-used without separating the individual metals.



PRICE & PRODUCTION

Copper Cu 29

Without copper, there would be virtually no electrical appliances and certainly no electricity to power them.



Uses in the energy sector

Copper is at the heart of all electricity generating equipment, is present in nearly all transmission circuits, in every home and office as wiring, in the wiring loom of every road vehicle, and is an essential constituent of the power circuits of virtually all electrical appliances.

In addition to the use of copper for propulsion in electric vehicles, many automotive components are made of copper, especially as cars contain an ever-growing array of electrically driven seats, windows, fans and more. Copper is also widely used as a conductor in the PV industry and directly as a component of copper-indium-gallium-selenide (CIGS) cells.

The move to more renewable energy production, with multiple decentralized generation sources, requires substantial investment in new transmission networks and this will create additional demand.

Uses outside the energy sector

As a native metal and displaying a strong colour, copper was obvious to early civilizations and was one of the first metals to be used by man, as early as 8700 BC, mainly for ornaments and some tools. Smelting of copper ores is thought to date back to 5500 BC and alloying with tin to produce the harder metal, bronze, can be traced to 3000 BC.

Copper sheeting was fixed to the hulls of ships to prevent attack by marine invertebrates, hence the expression 'copper-bottom'.

Present-day uses make copper one of the most widely used metals. In construction, it provides numerous components of plumbing systems, including piping and water heaters. Copper has been used for roofing since ancient times, as weathering leads to a patina of green corrosion-resistant copper carbonate. There are many alloys of copper, such as brass and nickel silver, with numerous uses, for example in bearings, ammunition, cutlery and silverware.

Properties and origins

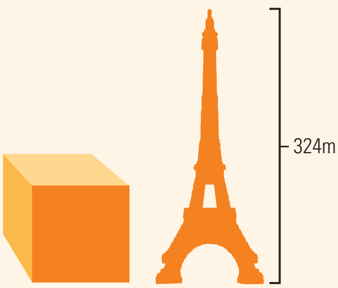
Melting point 1,084°C
Density 8.92g/cm3

Copper, with a warm pinkish colour, is one of only three elemental metals not to be grey or silvery. It is soft, highly malleable and ductile, allowing it to be easily worked. It has the second-highest electrical and thermal conductivity of all pure metals, after silver, and the metal is reactive and forms a wide range of compounds.

Copper, a fairly common constituent of the crust at 68ppm, does occur as a native metal but is much more commonly found as a range of sulphide and carbonate minerals. The biggest deposits are in porphyries – large volumes of rocks on top of major intrusions – where episodes of hydrothermal fluid circulation have produced a stockwork of fine mineralized veins. Most of the Andean deposits, such as La Escondida and Chuquicamata in Chile and Bingham Canyon in Utah, US, are porphyries. Hot fluids associated with volcanism have produced a range of copper deposits, which vary depending on the rock type that the fluids pass through.

Production and price

Annual production 17,000,000 tonnes



Key producers 2012	**Annual production 2012**		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
Chile	5,370,000	32	190,000,000	35
China	1,500,000	9	30,000,000	20
Peru	1,240,000	7	76,000,000	61
Others	8,890,000	52	384,000,000	43
World	**17,000,000**		**680,000,000**	**40**
Company				
GlencoreXstrata	2,300,000	14	n/a	n/a
CODELCO (Corporacion Nacional del Cobre de Chile)	1,758,000	10	132,600,000	75
Freeport-McMoran Copper & Gold	1,653,450	10	52,000,000	31

Sustainability

Reserves — M

Copper minerals occurring in vein deposits have been surpassed as sources of the metal by the mining of porphyries. These large orebodies, typically with grades of less than 1%, produce 50-60% of the world's supply. Copper reserves are widespread, with mining taking place in more than 50 countries. The Andean porphyries dominate and account for approximately 40% of the world's reserves.

Trade — L

Mining of copper dates back to at least Phoenician times around the Mediterranean, including Cyprus, from where the name originates. The Romans mined Parys Mountain, a complex polymetallic deposit in Anglesey, Wales, and mining was active there until the 19th century. The world's first cartel was reputedly set up in England by Cornish miners in an attempt to break the dominance of Parys producers.

Present-day production is dominated by large, open-pit operations in porphyry deposits with more than one third of the world's copper being produced by Chile. The mines in Chile and Peru are quoted as the largest man-made excavations of any type, with many millions of tonnes of material being moved weekly. The nationalization by Chile of its major US-owned mines around 1970 is a reminder of how politics can affect trade. Copper is traded on the main metal exchanges.

Ecological impact — M

Copper is one of the essential trace elements vital to the health of all living things and is widely distributed in the human body. An oversupply of copper, however, can lead to cirrhosis, especially in children. When copper ends up in acidic soil, it disseminates traces of copper ions, which are toxic to algae, bacteria and other organisms. Copper does not break down in the environment and, because of that, it can accumulate in plants and animals when it is found in soils. When concentrations exceed trace amounts, farm productivity (both of plants and animals) suffers, particularly milk yields in cattle and lack of weight gain in sheep.

Supply interruption indicators

Reserves	M
Trade	L
Ecological impact	M
Processing	L
Substitutability	L
Recyclability	L

Reserves-to-production ratio **40**

Processing — L

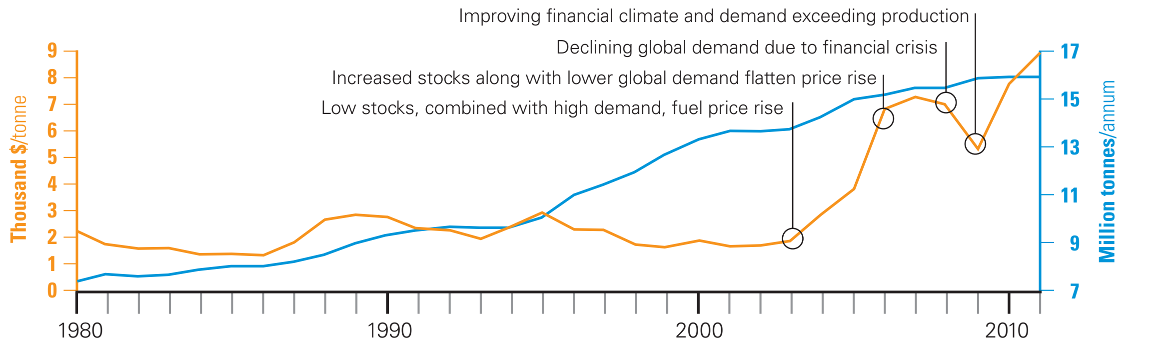
Copper ores often need extensive and potentially environmentally challenging treatment to reach concentrate stage. Comminution followed by froth flotation is used on a massive scale for both sulphide and oxide ores. The resulting concentrate is roasted, smelted and separated by electrolysis. Certain ores are treated by heap leaching, and electrowinning of the resulting copper-rich solutions produces metal for export. Copper processing is typically large-scale, both energy- and capital-intensive.

Substitutability — L

Most substitution for copper compromises performance, especially of electrical conductivity. Only silver has better electrical conductivity, but price excludes its large-scale use. Aluminium can substitute for copper in power cables and fibre optics are replacing copper in telecommunication. Steel and plastic have replaced much of the copper used in plumbing applications.

Recyclability — L

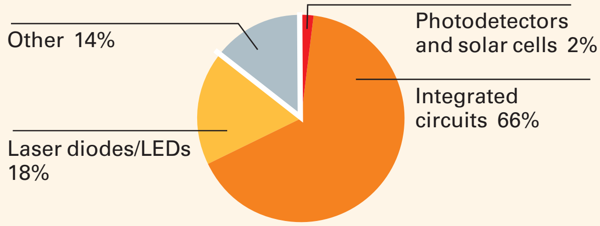
Copper is the third most recycled metal after iron and aluminium. The potential for increasing recycled copper is large, especially as the telecommunications industry expands the use of fibre optics and as cars are designed to be more efficiently recycled. At present, about 34% of copper demand is met from recycling. The EU Raw Materials Initiative states a recycling rate of about 47% for products that have reached the end of their useful life.



PRICE & PRODUCTION

Gallium Ga 31

A scarce metal with a bright future in high-performance LEDs and photovoltaics.



Uses in the energy sector

The global shift towards energy efficiency and lower-carbon energy has opened up opportunities for this metal in the production of high-brightness LEDs and PV cells. High-brightness LEDs are finding a growing number of applications, especially in lamps, computer notebook screens and backlit televisions. The market is expanding rapidly and was already estimated as being worth more than $8 billion in 2010. Gallium LEDs are prized for their ability to emit white and blue light.

The PV utilization is in the manufacture of thin-film cells based on copper-indium-gallium-selenide (CIGS) technology. The semiconductor CIGS absorbs sunlight much more effectively than crystalline silicon. This is why it can be used as a thin film (2 microns) compared to the 180-micron thick silicon wafers.

Multi-junction gallium-arsenide-based solar cells are presently the most efficient PV devices, making them attractive for space applications. They reach almost 39% efficiency under standard sunlight conditions and more than 44% under concentrated sunlight.

Uses outside the energy sector

The use of gallium outside the energy sector is limited. Gallium's largest use has been in microelectronics, where the semiconducting material gallium arsenide (GaAs) is vital for diodes, transistors, microwave systems and photocells on which cell phones, especially smartphones, are based. The smartphone market has grown spectacularly and is expected to continue growing at 15% to 25% annually.

GaAs is used in lasers for CD players and scanners. A radioactive salt of gallium is used in nuclear medicine and also has small-scale pharmaceutical uses. Gallium's low melting point, and the extreme temperature range at which it is a liquid, is exploited in specialist thermometers.

Properties and origins

Melting point	30°C
Density	5.91g/cm3

Gallium is a rare metal that will melt in the hand and actually wet the skin. In pure liquid form, it has a brilliant silvery colour and, when solid, is brittle and soft. Although predicted by Dmitri Mendeleev in his periodic table of 1871, it was first recognized by distinctive blue lines in the examination of zinc sulphide and first isolated in 1875.

It does not exist in a native form and only forms minerals that, because of their extreme rarity, cannot be considered of economic importance. Its abundance in the earth's crust is low at around 18ppm, but it is slightly concentrated in bauxite, an aluminium-bearing mineral. Bauxite is a product of the erosion of aluminium-bearing minerals, from igneous and volcanic rocks exposed in tropical climates. As suggested above, gallium is also found in sphalerite, zinc sulphide and in both sphalerite and bauxite, but concentrations are low, averaging 50ppm. Production is, therefore, as a minor by-product of zinc and aluminium processing.

Coal-forming swamps are known to accumulate gallium and some flue dusts have been found to contain significant concentrations, up to 1,000ppm, and could be regarded as potential future deposits.

Production and price

Annual production*	273 tonnes

Key producers 2012	**Annual production 2012***		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
China	n/a	n/a	n/a	n/a
Germany	n/a	n/a	n/a	n/a
Kazakhstan	n/a	n/a	n/a	n/a
Others	n/a	n/a	n/a	n/a
World	**273**		**n/a**	**n/a**
Company**				
n/a	n/a	n/a	n/a	n/a

* USGS does not report country data but estimates world capacity. Countries listed were last referenced by USGS in 2010. This illustrates the challenges around sourcing accurate data.

** Reliable company data not available.

Sustainability

Reserves M

Data on the reserves and production of gallium is difficult to find and unreliable, as the actual recoverable amount of gallium is proprietary information. There seem to be great uncertainties and possible misunderstandings when talking about figures, because similar terms such as primary production, refined gallium, recycling, secondary production or refinery capacity appear with contradictory numbers. It is thought that significant amounts of the element are produced as by-products of bauxite treatment in China, Russia and Japan. Reserves that could prove economic are based primarily on bauxite and large deposits of this mineral exist in several countries, including Guinea, Australia and Brazil. Extraction from coal-fired power station ash is potentially attractive, but has yet to be commercialized. Another important source for gallium production is the zinc processing chain. Next to these primary productions, new scrap is being recycled and forms secondary gallium. The numbers presented often show refinery capacity, which is not the same as actual production. This may be another reason for contradictory data sets.

Trade M

Demand for the element is growing rapidly, as the demand for LEDs and high-speed chips is escalating and use in CIGS-based PVs is projected to grow. Demand could well exceed supply in the near future. The Fraunhofer Institute, the largest organization for applied research in Europe, is estimating global demand at around 600 tonnes by 2030, some five to six times present annual production.

Ecological impact H

There is very limited information available on the effects of gallium in the environment because so little is released from human activities. The most significant bioactive effects observed on humans, however, are enlarged lymph nodes and renal damage similar to that caused by mercury. The compound GaAs is corrosive to metals and is a hazard both to humans and aquatic life, mainly due to the toxic characteristics of arsenic.

Supply interruption indicators

Reserves	M
Trade	M
Ecological impact	H
Processing	H
Substitutability	M
Recyclability	M
Reserves-to-production ratio	n/a

Processing H

Gallium is primarily recovered from bauxite and aluminium processing plants by electrolysis.

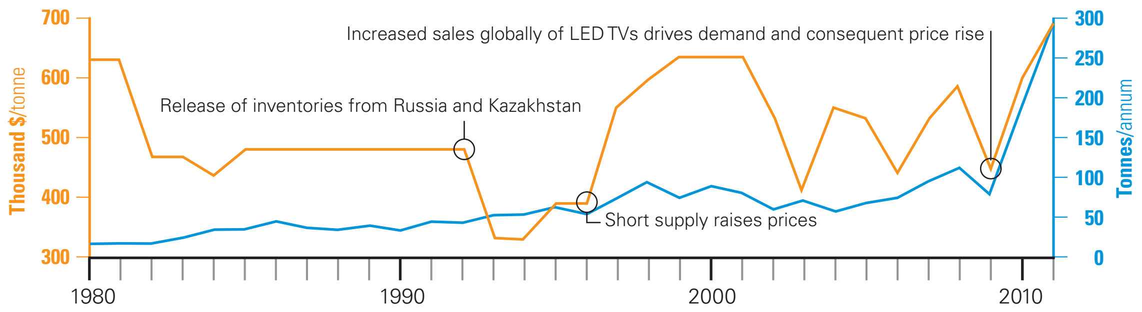
Substitutability M

A potential substitute of the current LED technology could be organic light-emitting diodes. These organic-based LEDs, which are currently under research, may compete with gallium-based compounds in the future.

Gallium in CIGS is a potential substitute to silicon-based solar technology and requires only 1/100th of the thickness of material compared to crystalline silicon cells. This substitution may increase if fabrication costs can be made competitive.

Recyclability M

At present, gallium is not recycled from old scrap and, because the majority of the metal ends up in extremely small quantities in manufactured articles, economically sensible recycling might be difficult to achieve. There is, however, a potential for recycling if and when gallium-containing products reach their 'end-of-life' time. No reliable data on the magnitude of recyclable material is available.



PRICE & PRODUCTION

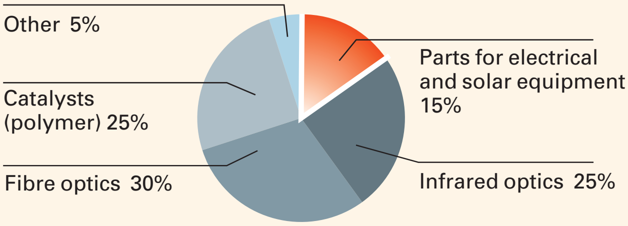
Germanium Ge 32

A rare metal with a big growth potential in the photovoltaic industry.

Uses in the energy sector

The semiconducting properties of germanium and the development of the germanium transistor opened the door to countless applications of solid-state electronics. Electronic chips containing germanium offer a lower consumption and higher speed, compared to silicon-chip technology. In 2006, IBM researchers demonstrated a germanium-based chip running at 500GHz, some 100 times faster than silicon chips of the time.

Uses in LED production are increasing, and there is a possible future application as a substrate and bottom cell in multi-junction concentrated PV (CPV) cells. Germanium-based PVs have been used in space applications for some years. These uses presently show modest quantities required.



Uses outside the energy sector

Germanium is mainly used in fibre optics: 30% of the entire germanium production is used in this application, as a dopant within the core of the optical fibre, to increase the refractive index of the pure silica glass core.

The second largest application area is germanium dioxide in lenses and windows used in infrared systems. Germanium dioxide is used as a polymerization catalyst for polyethylene terephthalate (PET) production – PET is the main material used in plastic bottle manufacture.

Properties and origins

Melting point 937°C
Density 5.32g/cm3

Germanium is a hard, greyish-white element. It has a metallic lustre, the same crystal structure as diamond and is brittle, like glass. Its most useful property is as a semiconductor, with electrical properties between those of a metal and an insulator.

Mendeleev predicted the properties of this element in his 1871 announcement of the periodic table, but discovery was not confirmed until 1886, when the chemist, Clemens Winkler, named the new element after his native Germany.

Germanium is not particularly rare and is estimated to represent 1.6ppm of the earth's crust. Few minerals, however, contain appreciable amounts and no mining for germanium itself is carried out. The majority of commercial extraction comes from lead zinc ores, especially the zinc sulphide mineral sphalerite, where it can reach concentrations of 0.3%. It is also known to be concentrated in coals, and some, in particular, have concentrations potentially of economic importance, with a deposit in Mongolia thought to contain around 1,600 tonnes of germanium.

Production and price

Annual production* 128 tonnes

Key producers 2012	Annual production 2012*		Reserves	R/P
Country	Tonnes	%	Tonnes	
China	90	70	n/a	n/a
Russia	5	4	n/a	n/a
US	3	2	450	150
Others	30	23	n/a	n/a
World	**128**		**n/a**	**n/a**
Company**				
n/a	n/a	n/a	n/a	n/a

* Refinery capacity quoted as actual production unknown.
** Reliable company data not available.

Sustainability

Reserves M

There is no published data available for germanium reserves, but working from the concentrations known to exist in certain lead-zinc ores and some coals, it is reasonable to assume a large resource. It is not possible to comment on economic reserves.

The combustion of coal is known to increase the concentration of germanium in the resulting ash by up to 10 times. China and Russia are reported to have used fly ash as a source of the material and EU-funded research is under way to find a method of extracting germanium from ash at a commercial scale.

Trade H

Production figures for germanium are cloaked in confidentiality, but it is commonly understood that trade in germanium is dominated by Chinese production, which is in the hands of only five or six companies. Canada is the home of another major producer, Teck Resources, which smelts more than 70,000 tonnes of lead and 270,000 tonnes of zinc ores per year at its huge plant in British Columbia, including concentrates from the world's largest lead-zinc mine in Alaska. The company was well known as a major producer, but has not reported germanium production since 2007.

The demand side of germanium is set to rise, mainly as a result of the growth of existing technologies, both fibre optic cables and LEDs. The expansion of national broadband networks will cause fibre optic cable demand to rise. Demand will also rise as the use of germanium-based LEDs in the automobile market becomes more widely adopted. The potential for an increase in germanium-based PV cells is restricted by price, because alternative technologies are cheaper to produce and it is difficult for manufacturers to justify the increased efficiencies. Germanium-based catalysts are declining, as PET is increasingly recycled. Germanium is not traded on any of the major commodity exchanges.

Ecological impact L

Germanium is thought to be essential to the health of plants and animals in the right concentrations. The health food industry has been promoting germanium supplements for years, although the UK's Department of Health warned against them in 1989, on the grounds that they had no nutritional or medical value and could be harmful at concentrations raised artificially. The production rates are so small that it is unlikely to be considered a threat to the environment.

Processing H

Germanium is separated from lead-zinc concentrates and coal ash by leaching.

Substitutability M

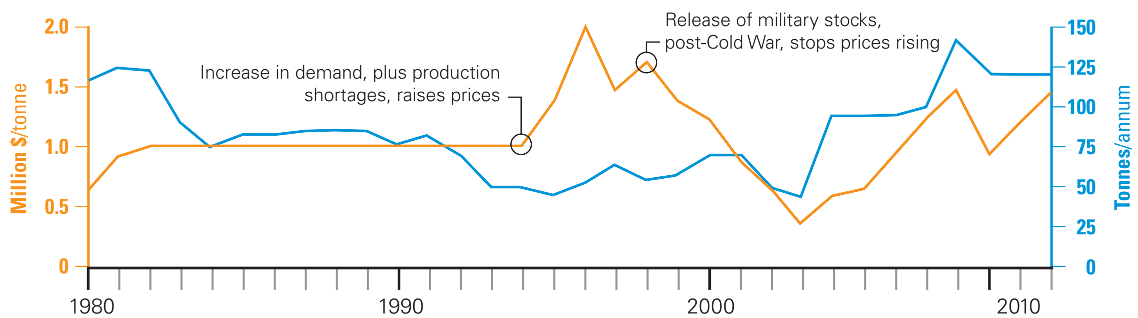
It is possible to substitute germanium in infrared systems with zinc and selenium, where performance is not critical and the same is true where germanium acts as a semiconductor. Germanium, however, is still considered more economic to use than the substitutes. For PET-production catalysis, other metals can be used as a substitute.

Recyclability M

Thirty per cent of the world's supply is produced from recycling. In particular, the recycling of fibre optics has increased over the past decade and there is a growing interest in developing recycling schemes for a range of germanium-bearing products.

Supply interruption indicators

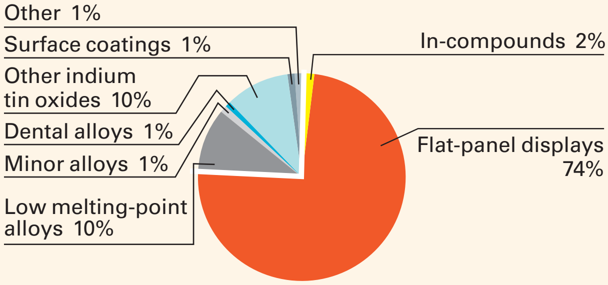
Reserves	M
Trade	H
Ecological impact	L
Processing	H
Substitutability	M
Recyclability	M
Reserves-to-production ratio	n/a



PRICE & PRODUCTION

Indium In 49

Essential to the LCD-production process and with a promising future in thin-film photovoltaics.



Uses in the energy sector

The largest contribution of indium to the energy sector is in the considerable saving of electricity made through its crucial role in liquid crystal display (LCD) screens. LCD-based televisions, computer monitors and many other displays are more energy efficient than cathode-ray-tube displays and are outselling them across the globe.

Indium is also found in the semiconductor copper–indium–gallium–selenide (CIGS) used to make thin-film PV cells that have high performance relative to other thin-film technologies. Today the production of CIGS cells is small but will potentially increase as the PV market grows. If manufacturing costs of these cells decreases, as happened for crystalline systems, their competitiveness will improve. The USGS estimates that 50 tonnes of indium are needed to produce one gigawatt of cells.

Indium is also used as a transparent conductor (indium-tin-oxide or ITO) in some crystalline silicon cells (hetero-junction cells), thin-film solar devices and in dye-sensitized and organic cells, which are potentially emerging into the market. Indium is also used in the control rods of nuclear reactors.

Uses outside the energy sector

Indium alloys have a number of relatively small-scale uses, including in the dental industry.

Properties and origins

Melting point 157°C
Density 7.31g/cm3

Indium is a soft, malleable metal with a bright lustre. It has the rare property that, when a bar of the pure metal is bent, a high-pitched squeal is emitted. The element is named after the indigo-blue line it displays when studied by spectroscopy. Some indium compounds are semiconductors.

Indium, which averages 0.15ppm in the earth's crust (approximately three times more than silver), is very rarely found in native form and usually occurs as compounds in zinc ores. Sphalerite, the main sulphide zinc ore, can contain more than 100ppm indium in some deposits. Although indium does form minerals, they are extremely rare and none has been of commercial interest.

Production and price

Annual production 670 tonnes

Key producers 2012	**Annual production 2012**		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
China	390	58	n/a	n/a
Canada	70	10	n/a	n/a
Japan	70	10	n/a	n/a
Others	140	21	n/a	n/a
World	**670**		**n/a**	**n/a**
Company*				
n/a	n/a	n/a	n/a	n/a

* Reliable company data not available.

In 49

Supply interruption indicators

Reserves	M
Trade	H
Ecological impact	L
Processing	H
Substitutability	H
Recyclability	M

Reserves-to-production ratio **n/a**

Reserves M

As indium is primarily produced in conjunction with zinc and to a lesser extent with copper and lead, it is difficult to gather accurate reserve data. There are considerable reserves of zinc, and indium producers report growing success at raising the extraction rates from sulphide ores other than zinc. Indium can also be extracted from the tailings at zinc mines. The implication is that there is a substantial resource of indium available.

Demand for the metal is presently dominated by its key role in LCD production. This continues to grow as LCD televisions replace conventional sets and LCD displays become the norm. If large-scale manufacture of CIGS PV cells takes off, there will be significant growth in demand.

Trade H

The production of indium is controlled by zinc demand. If indium demand continues to grow, and for any reason there is a downturn in zinc demand, there could be supply constraint. Supply has been interrupted in the recent past, as China has cracked down on metal smelters in a bid to improve environmental performance.

According to the USGS, China controls more than 50% of the world's refined indium production. The Chinese government restricts indium's export with duties.

Canada is another major producer, based on its large lead-zinc industry, especially the smelting of local as well as imported ores. The largest smelter, Teck Resources, in British Columbia, does not publish production figures, but some sources estimate it could be as high as 75 tonnes or 13% of global production per annum. Indium is not traded on any of the major commodity exchanges.

Ecological impact L

Indium reaches the environment through fumes and dust from zinc smelters. It is thought to have little effect as the quantities are small and it is unlikely to be encountered in toxic concentrations.

Processing H

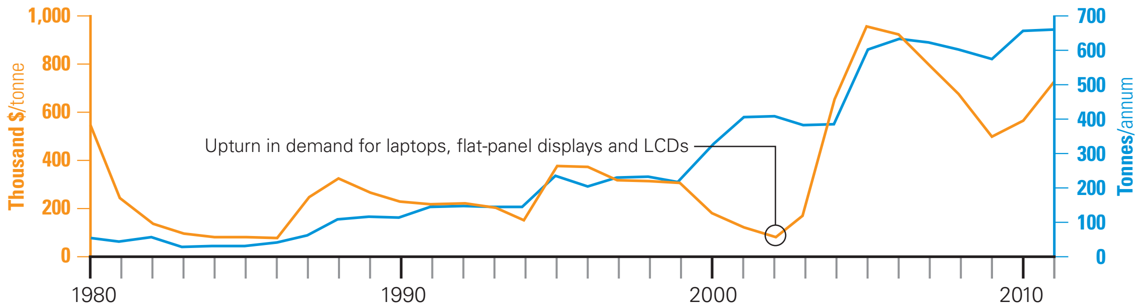
As mentioned above, indium primarily is a by-product of the zinc industry and is recovered from residues in smelters.

Substitutability H

Several substitutes for indium have already been developed. For flat-panel displays, it is possible to substitute ITO with antimony-tin oxide. Antimony, however, is itself a very rare element and is hazardous to human health. In the semiconductor industry, doped-tin-oxide and doped-zinc-oxide are possible substitutes for indium in transparent conductors but typically have inferior performance. For PV systems there are substitutes for indium. Where indium is used in alloys it may be substituted by gallium and hafnium, both of which are subject to supply constraints.

Recyclability M

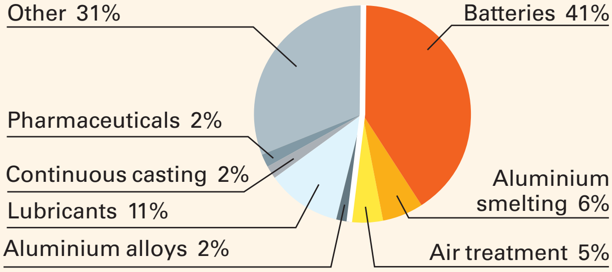
The majority of indium recycling is gained from production scrap. The Swiss Academy of Engineering Sciences estimates that approximately 60-65% of the indium contained in these wastes will be recycled. The global estimate for secondary production is 400 tonnes per annum with an increasing trend. Indium can also be recycled from PV modules and flat-panel displays and there is future potential for considerable quantities available for recycling – if appropriate processes can be invented and established. There remains, however, a challenge to make such processes economically viable since the indium content in a single device is very low. Increasing recovery from tailings could also expand production in the medium term.



PRICE & PRODUCTION

Lithium Li 3

The key to a revolution in vehicle technology.
Reserve scare stories oversold.



Uses in the energy sector

The Holy Grail of the electric car industry is increased battery performance and lithium is at the forefront of this technology. Lithium-ion batteries have exceptional power-to-weight ratios and are replacing the nickel-hydride batteries that were used in the first generation of hybrid electric vehicles such as the Toyota Prius. Fully electric cars, such as the Nissan Leaf, the Tesla and the Chevrolet Volt, are all based around lithium-ion. Lithium-ion batteries are also used for a wide range of electrical storage applications, including computers and video cameras.

Uses outside the energy sector

Lithium compounds were little more than a laboratory curiosity until the Second World War, when the properties of lithium stearate in high-temperature greases became vital to improve the performance of aero engines.

Uses in nuclear bomb manufacture raised demand and the discovery of lithium compounds that could withstand high temperatures led to the largest present-day use of lithium in the ceramic and glass industries. Pyrex glass and television screens are examples of household uses. Lithium compounds are used in pharmaceuticals, as a mood stabilizer, and as an alloying agent to lighten and increase the strength of a number of metals, especially those used in the aerospace industry.

Properties and origins

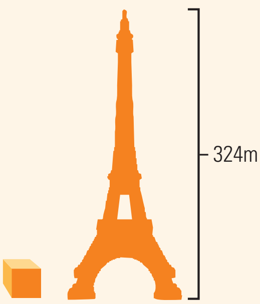
Melting point 181°C
Density 0.53g/cm3

Lithium is the lightest of metals and easily floats on water. It is soft enough to be cut with a knife and a freshly exposed surface exhibits a metallic silvery lustre. It rapidly corrodes in air to a dull grey. It is extremely reactive, so much so that it is normally stored under oil.

Lithium has the highest electrochemical potential of all elements. As it is so highly reactive, lithium is never found in its native form. At a concentration in the crust of about 18.5ppm, lithium is a relatively common element. Lithium is concentrated in magmatic processes that produce granites and to economic concentrations in pegmatites, essentially very-large-grained granitic rocks. In these rocks, lithium is found in the mineral spodumene – a complex lithium aluminium silicate. Weathering of lithium-rich igneous rocks in arid areas can result in further concentration as lithium-rich brines in evaporite deposits. Weathering in more humid conditions can concentrate lithium in clays.

Production and price

Annual production* 37,000 tonnes



Key producers 2012	**Annual production 2012***		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
Chile	13,000	35	7,500,000	577
Australia	13,000	35	1,000,000	77
China	6,000	16	3,500,000	583
Others	5,000	14	1,000,000	200
World	**37,000**		**13,000,000**	**351**
Company**				
Rockwood Holding (incl. Talison)	n/a	n/a	n/a	n/a
FMC Lithium	n/a	n/a	n/a	n/a
SQM	n/a	n/a	n/a	n/a

*Pure lithium metal.
** Known to be companies with largest production.

Sustainability

Reserves M

The reserves scare story has been completely oversold by the media. With known resources of more than 33 million tonnes worldwide, in addition to a substantial reserve base and a wealth of exploration opportunities, there is enough lithium available to meet even the most optimistic demands for the growth of electric cars. Even certain oilfield and geothermal brines are being investigated as potential sources of the element.

Trade H

Production, initially from mining spodumene and other lithium-rich minerals in pegmatites, rapidly moved to extraction from evaporite deposits when they were discovered to be lithium-rich. More than 50% of present production is by solar evaporation of brines in the salars – evaporite basins in the high Andes of Chile and Argentina – where production costs are lower than conventional mining methods, despite the complexity of separating lithium from the other components of the brines.

Production rates are a constraint. With an estimated 100 million light vehicles being produced annually by 2020, assuming 3% to be full electric cars, 2% plug-in hybrids and 15% full hybrids, the corresponding lithium demand would be 60,000 tonnes per year, three times the present production. A potential complication is that large reserves lie in Bolivia, a country that has recently nationalized strategic natural resources assets and industries. Another constraint is the high percentage of production in the hands of a very small group of companies, raising the possibility of cartels.

Ecological impact M

In its elemental form, lithium is corrosive. However, as it is so reactive, any ecological impacts will only originate with lithium compounds. The volume of lithium released into the environment by human actions has, to date, been very small. Lithium is readily absorbed by plants and is known through pharmaceutical experiences to be toxic to humans in high concentrations. A route to deliver such concentrations seems unlikely.

Supply interruption indicators

Reserves	M
Trade	H
Ecological impact	M
Processing	L
Substitutability	M
Recyclability	M

Reserves-to-production ratio **351**

Processing L

Pegmatites are crushed and ground before the lithium-bearing minerals are separated by froth flotation or gravity techniques. The concentrate is calcined and then leached to produce lithium chemicals, typically lithium carbonate.

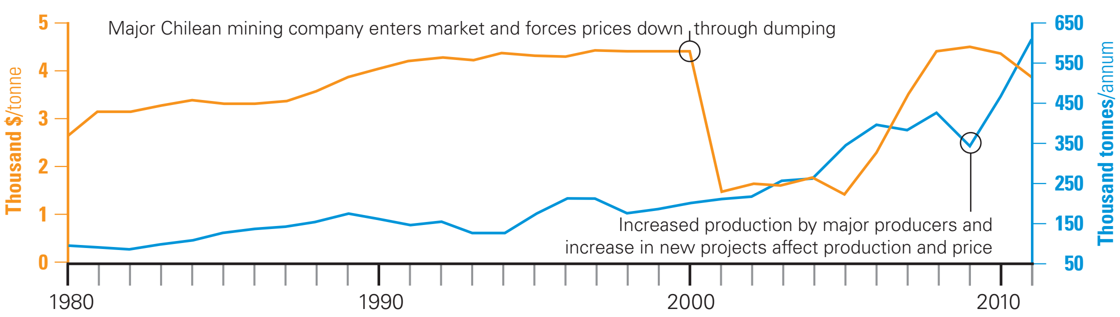
Brines pumped to the surface, for lithium extraction, contain 600 – 700mg per litre of lithium. At the surface, the brines are concentrated by solar evaporation. The processes required to isolate lithium vary widely in complexity, depending on the quantities of other salts present.

Substitutability M

The high specific energy capacity requirement for batteries that will enable the electric car dream to become reality relies now, and for the foreseeable future, on the unique chemical and physical properties of lithium. For stationary energy storage, alternative technologies such as compressed air energy storage (CAES) systems, sodium-sulphide batteries and nickel-metal hydride batteries already exist and can be substituted albeit with some performance loss. Substitution is possible for the majority of the non-energy uses of lithium.

Recyclability M

Recycling of lithium-ion batteries, previously restricted in scale by economics, is expected to start soon in Europe and rise significantly as technology developed by Umicore Group is deployed and worthwhile quantities become available at the end-of-life of electric cars.

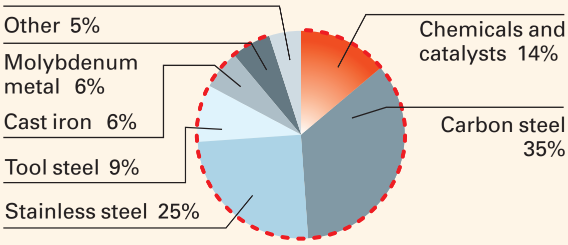


PRICE & PRODUCTION*

*Production figures indicate lithium minerals and brines. Dividing by 15 will give an approximate value for pure lithium.

Molybdenum Mo 42

A vital component of specialist alloys used in many energy pathways and with a promising future as a catalyst in oil and coal refining.



Uses in the energy sector

Wherever ordinary carbon steels have performance limitations, stainless steels and other alloys containing molybdenum can provide the physical and chemical properties required, especially strength at high temperatures and resistance to acids. For example, along the oil energy pathway, molybdenum is found in alloys and coatings from the exploration phase, right through to end-users. Molybdenum alloys are used in drill pipes and risers for high-temperature wells, where hydrogen sulphide is a problem, in the refinery vessels where sulphur is stripped from crudes, and in the coatings of piston rings of vehicles.

As the supply of low-sulphur crudes reduces, molybdenum-based catalysts will increase in use, not only facilitating economical refining, but also reducing sulphur emissions. In coal gasification and liquefaction, thought to be a growing market, molybdenum catalysts are used in desulphurization processes. In the nuclear industry, molybdenum alloys are used extensively in reactor cooling systems.

Molybdenum is used as the back contact material in copper-indium-gallium-selenide thin-film PV cells.

Uses outside the energy sector

Apart from the countless applications of stainless steels and alloys containing molybdenum, particularly lightweight steels for the automotive industry, the material has a wide range of applications. Its lubricating properties are applied in a range of high-temperature settings, primarily in the form of oil-soluble molybdenum sulphides. Molybdenum's high thermal conductivity and low expansion make it the material of choice as a substrate in many semiconductor applications and for lamps, especially in the automotive industry. Catalysts containing molybdenum are used in the fibre and plastics industries. The material is used in some fertilizers as molybdenum is an essential component of the enzyme nitrogenase that all plants need.

Properties and origins

Melting point 2,617°C
Density 10.28g/cm3

Molybdenum is a silvery-white metal with one of the highest melting temperatures of any element. It has a very low coefficient of thermal expansion, the lowest of the engineering materials, and, when alloyed in steels, it greatly increases their strength and resistance to corrosion.

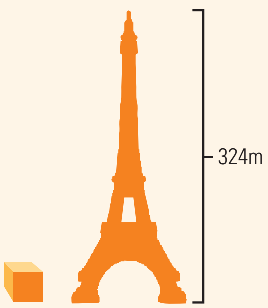
Although the element was not isolated until 1782, the commonest molybdenum-bearing mineral, the sulphide molybdenite, was known in ancient civilizations – a 14th century Japanese steel sword has been found containing molybdenum. Until commercially attractive separation technology was developed in the late 19th century, molybdenum remained mainly a laboratory curiosity.

Molybdenum, a relatively rare element with an average crustal concentration of only 1.5ppm, is concentrated by a variety of igneous processes into a range of minerals. The sulphide molybdenite, a product of high-temperature hydrothermal mineralization is the mineral of commercial interest. It occurs in veins, stockworks and porphyries, often associated with copper. Viable concentrations range from 0.01% to 0.25%.

Molybdenum is sought as a prime product in mines, particularly in the US and Canada, but the majority of the world's supply is as a by- or co-product of copper mining.

Production and price

Annual production 250,000 tonnes



Key producers 2012	**Annual production 2012**		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
China	105,000	42	4,300,000	41
USA	57,000	23	2,700,000	47
Chile	35,300	14	2,300,000	65
Others	52,700	21	1,700,000	32
World	**250,000**		**11,000,000**	**44**
Company				
Freeport-McMoran Copper & Gold	37,600	15	1,540,000	41
Codelco	20,000	8	n/a	n/a
Grupo Mexico	18,220	7	1,283,400	69

Sustainability

Reserves M

The combination of molybdenum as a prime ore and as by- and co-products of copper found in a large number of deposits, leads the USGS to report that resources of molybdenum are adequate to supply world needs for the foreseeable future. With reserves and production distributed mainly in China, the US and Chile, there is little risk of geopolitical supply constraint.

Trade L

The demand for molybdenum has been growing steadily for years, in line with the growth in economies and the rise in use of specialist steels and catalysts. There is no expected rapid change in demand.

Ecological impact M

Molybdenum is essential to all species. As with other trace metals, what is essential in tiny amounts can be highly toxic at larger doses. No harmful effects have been reported from workers in the molybdenum mining and processing industries. The element is excreted rapidly and, therefore, build-up in the body is thought to be unlikely, unless massive doses are absorbed. Some molybdenum compounds are known to be toxic. However, in the main uses – as an alloying agent and in catalysts – there is no obvious route to the biosphere of anything but minuscule quantities.

Processing M

The route from ore to metal is straightforward and should not present any supply constraints. Molybdenite-bearing ores are comminuted before being fed to froth flotation cells, where the mineral is separated from other metal sulphides and gangue minerals. Acid leaching can dissolve impurities if necessary and, then, the resulting material is roasted in air to produce an oxide, which is the normal feedstock for a range of further chemical processes chosen according to the end product required.

Mo 42

Supply interruption indicators

Reserves	M
Trade	L
Ecological impact	M
Processing	M
Substitutability	H
Recyclability	M

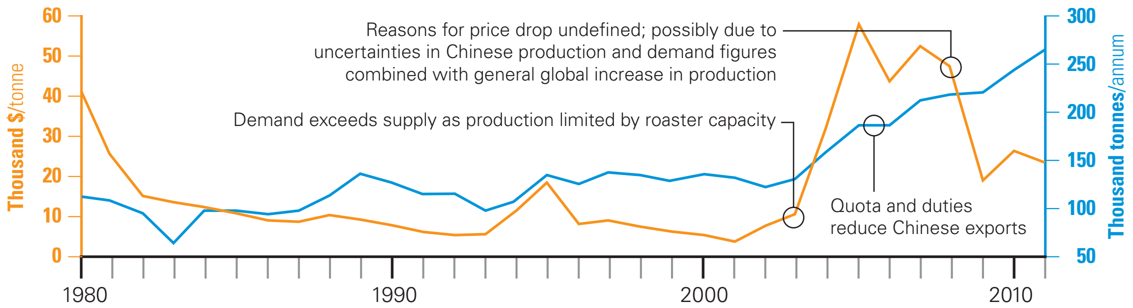
Reserves-to-production ratio **44**

Substitutability H

For alloying, there is little substitution for molybdenum and, in fact, such are the essential properties of alloys made with this element that new materials are being developed. The ready availability of molybdenum also lessens the need to find substitutes. Potential substitutes for molybdenum include chromium, vanadium, niobium and boron in alloy steels, and tungsten in tool steels.

Recyclability M

It is difficult to quantify the amount of molybdenum recycled, but steels and other alloys containing the metal are frequently recycled and may account for as much as 30% of demand.

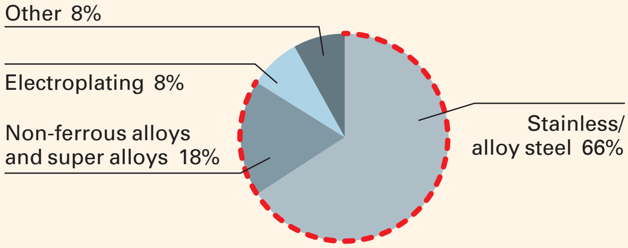


PRICE & PRODUCTION

Nickel Ni 28

A metal that literally supports the energy industry as a vital constituent of corrosion resistant steels.

Uses in the energy sector



Stainless steels and super alloys containing nickel are the principal materials that can be used in high-temperature settings such as thermal power station boilers, gas turbines, heat exchangers and refinery vessels. Corrosion-resistant nickel steels are the metal of choice for tubing in deep oil and gas wells, especially where hydrogen sulphide is likely to be encountered, and for many down-hole tools used in drilling.

At low temperatures, most metals become brittle, so finding a material from which large storage vessels could be constructed to store and transport liquefied natural gas (LNG) was a challenge at the beginning of that industry. Research in the 1940s led to the development of a steel containing 9% nickel that was far less brittle than carbon steels at low temperatures.The market for nickel steel that can perform at cryogenic temperatures is increasing alongside the rise in LNG.

Nickel-cadmium batteries have been in common use since the 1960s. Now, they are being replaced with nickel-metal hydride (NiMH) batteries, which are used in hybrid vehicles. The affinity that nickel has with hydrogen makes it useful as a catalyst in oil refining.

Uses outside the energy sector

Nickel-based super alloys are also used in turbines for civilian and military airplanes and marine vessels. Corrosion resistance and workability are qualities that make nickel-bearing steels invaluable in many settings across industry and architecture. The iconic Chrysler building in New York is partly clad in nickel-rich stainless steels.

Properties and origins

Melting point 1,453 °C
Density 8.9g/cm^3

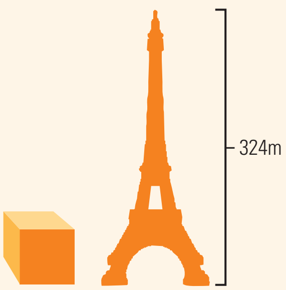
Nickel is a silvery, lustrous metal that is malleable, ductile, magnetic at room temperature and corrosion resistant. Although it is the fifth most common element on earth, most of the metal is thought to be in the core and so it is only the 23rd most common element in the crust, averaging around 50ppm. The metal is found in plants, animals and seawater with much of this being thought to have accumulated from space-derived meteoritic dust.

Nickel forms many minerals, with the chief economic varieties being sulphides. The metal is found principally in two types of geological setting: magmatic sulphides and laterites. Magmatic sulphides form when molten rock fractionates deep in the crust or in large-scale lava flows, and laterites are the result of tropical or sub-tropical weathering of nickel bearing rocks. Examples of large-scale magmatic deposits include the Bushveld complex in South Africa and the Norilsk complex in Siberia, with economic grades ranging from 0.2% to 3%. Sudbury in Canada is the setting for a major deposit formed by a giant meteor impact that caused crustal and, possibly, upper-mantle melting. Large-scale laterite deposits are known in many tropical settings such as Indonesia, the Philippines, Cuba and New Caledonia.

In the deep oceans, remote from sediment sources, extensive deposits of nodules rich in manganese, cobalt and nickel have been found.

Production and price

Annual production 2,100,000 tonnes



Key producers 2012	Annual production 2012		Reserves	R/P
Country	Tonnes	%	Tonnes	
Phillipines	330,000	16	1,100,000	3
Indonesia	320,000	15	3,900,000	12
Russia	270,000	13	6,100,000	23
Others	1,180,000	56	63,900,000	54
World	**2,100,000**		**75,000,000**	**36**
Company				
Norilsk	300,340	14	6,000,000	20
Vale	237,000	11	6,926,310	29
GlencoreXstrata	210,200	10	13,700,000	65
BHP Billiton Group	157,900	8	2,700,000	17
Jinchuan	150,000	7	n/a	n/a

Sustainability

Reserves — M

Land-based resources, grading 1% nickel or greater, are known to contain more than 130 million tonnes, of which about 70% are in laterites, according to the British Geological Survey, and the rest primarily in sulphides. These resources are distributed among many countries, although the depletion of reserves and the lack of new discoveries in the traditional mining districts are causing exploration teams to focus on more difficult regions. This resource of nickel in seafloor manganese nodules is enormous, but politics and economics have, to date, ruled out production.

Trade — L

Nickel is traded on the main metals markets, including the LME, and demand reflects the global economy as steel consumption fluctuates. The volatility in prices in recent years has been affected by factors as diverse as the slowdown of the Chinese economy, earthquakes and tsunami in Japan and the European debt situation.

Ecological Impact — H

Nickel can present health hazards to humans both by skin contact and when nickel dust is inhaled. The metal can causes dermatitis when it is used in stainless steel watch bracelets, spectacle frames, garment fasteners and jewellery. Dust presents problems in mining and processing facilities, as inhalation is known to cause lung and nasal cancers. One of the main processes used to purify nickel involves the production of nickel carbonyl. Inhaling the vapour of this compound, even in tiny amounts, can prove fatal.

Processing — L

Nickel ores are concentrated, after comminution, by suitable physical and chemical processes before smelting with the choice of process influenced by ore type. Froth flotation of sulphide ores separates nickel-rich material from copper-rich. This is followed by smelting and refining, either by using heat to separate metals of different melting temperatures or by leaching, which exploits the differences in chemical properties of nickel and the metals it is usually found with. Some nickel is still purified after smelting using the Mond process that involves the production of highly toxic nickel carbonyl.

Recently, solvent extraction of ultra finely ground ores has been developed and research is being carried out in bioleaching to exploit low-grade ores.

Laterite ores, which normally need minimal crushing, are either smelted in electric arc furnaces or subjected to hydrometallurgic processes, primarily pressure acid leaching, in which a slurry of ore is reacted with concentrated sulphuric acid.

Substitutability — M

Nickel's unique properties limit the opportunities for substitution without decreasing performance. The main efforts are directed at replacing nickel steels with nickel-plated steel and reducing the use of stainless steels in construction. Steel producers are producing low-nickel steels with higher chromium and manganese contents.

Recyclability — L

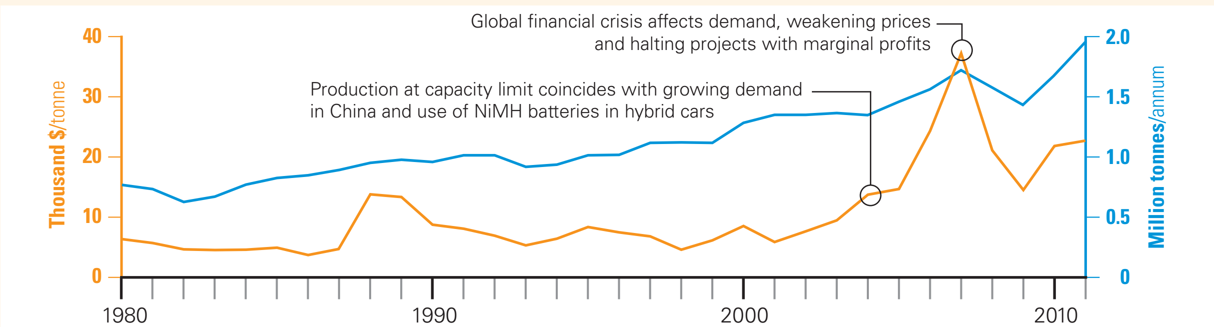
The high price of nickel provides an incentive for recycling and the corrosion resistance makes it suitable. Special alloys are recycled into the same alloy, but most nickel-containing steels are blended to provide a consistent quality of feed to the recycling process. Batteries containing nickel are increasingly being recycled, partly because of legislation aimed at preventing cadmium going into landfill.

Ni 28

Supply interruption indicators

Reserves	M
Trade	L
Ecological Impact	H
Processing	L
Substitutability	M
Recyclability	L

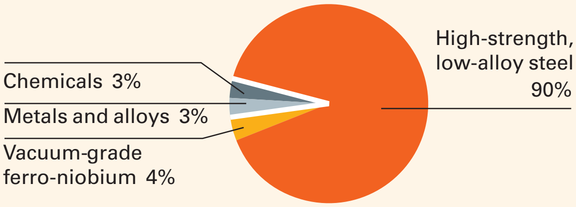
Reserves-to-production ratio **36**



PRICE & PRODUCTION

Niobium Nb 41

A metal valued for its ability to strengthen steel used for offshore platforms and electricity pylons.



Uses in the energy sector

Niobium is a vital element in the production of high-strength steels that are extensively used in the manufacture of oil and gas pipelines, offshore platforms and electricity pylons. The addition of niobium to steel increases strength, reduces weight and improves the resistance to fatigue. Niobium alloys are used in cathodic protection systems, which pass electrical currents through the components of offshore structures to reduce corrosion. In the nuclear industry, the metal is used, when alloyed with uranium and zirconium, to coat fuel rods.

Uses outside the energy sector

Light-weight, high-strength, niobium-rich steels are used extensively in car manufacture, high-performance ships and in the production of reinforcing bars for the construction industry.

Superconducting magnets based on niobium alloy wires are at the heart of magnetic resonance imaging (MRI) machines and nuclear magnetic resonance scanners.

Since the invention of MRI machines in the 1970s, this method of imaging has become a widely used diagnostic tool in hospitals across the developed world. Niobium-based superconducting magnets are also used in particle accelerators including the Large Hadron Collider at CERN. The International Thermonuclear Experimental Reactor (ITER), currently under construction in the south of France, which is the latest step in fusion research, has ordered magnets containing more than 220 tonnes of niobium-tin and niobium-titanium alloy wire.

Super alloys that contain niobium are able to operate at high temperatures, leading to their use in jet engine and turbine manufacture. As niobium is known to cause less allergic reaction than most metals, it is valued as a coating for jewellery and also for coating medical implants, including pacemakers.

Properties and origins

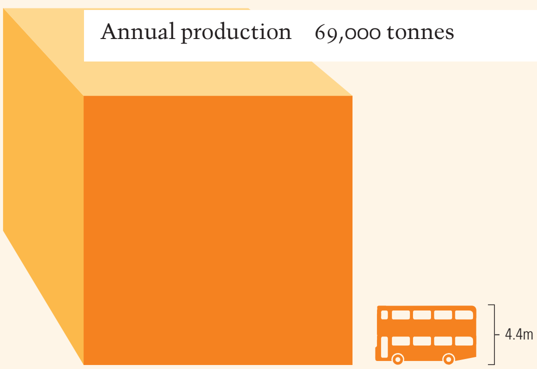
Melting point 2,468 C
Density 8.6g/cm^3

Niobium is a soft, malleable, light-grey metal that is stable in air. Initially, the metal was called columbium by the English chemist Charles Hatchett, who discovered it in 1801 while analysing a mineral in the British Museum known to come from Connecticut, US, and labelled columbite. It was only given its present name in 1846 by the German chemist Heinrich Rose, who isolated the element from tantalum, which has very similar properties. The metal does not occur in its native form but it is an essential component of many minerals, the majority of which are oxides such as columbite, where it is combined with tantalum.

The main economic source of niobium is in the group of minerals known as pyrochlores, where it forms oxides with calcium and sodium. Pyrochlores are found in igneous rocks including granites and their large-grain counterparts, pegmatites. However, by far the largest economic deposits of pyrochlores found to date occur in carbonatites, which are igneous rocks with a carbonate mineral content of more than 50%. The majority of the world's supply of niobium comes from carbonatites exploited in two surface mines in south-east Brazil. The largest active niobium mine, outside Brazil, is an underground mine in Quebec, Canada, which is working another carbonatite-hosted pyrochlore orebody.

Production and price

Annual production 69,000 tonnes



Key producers 2012	Annual production 2012		Reserves	R/P
Country	Tonnes	%	Tonnes	
Brazil	63,300	92	4,100,000	65
Canada	5,000	7	200,000	40
Others	700	1	n/a	
World	**69,000**		**> 4,000,000**	**> 58**
Company*				
CBMM	64,535	88	n/a	n/a
IAMGOLD	4,707	6	2,563,000	n/a
Anglo American	4,400	6	1,540,000	350

* Production data from companies' annual reports do not match global production data from USGS and the percentages noted are based on the total production reported from the three listed companies.

Sustainability

Reserves — H

The British Geological Survey briefing on niobium mentions some 58 carbonatite bodies around the world known to contain niobium, some of them with huge resources of the metal. The Morro dos Lagos deposit in Brazil is reported to contain nearly three billion tonnes of the metal and the 12km² Tomtor deposit in Siberia has a lower-ore deposit that contains 12% niobium. The following quote from the USGS summarizes the situation: "world resources of niobium are more than adequate to supply projected needs".

Trade — H

Production of niobium is dominated by the Brazilian company CBMM, which controls more than 90% of the global niobium market as a result of owning Araxa, the biggest niobium mine in the world. CBMM is an integrated company that mines and processes niobium into a comprehensive range of products and has been instrumental in promoting the use of the metal in steelmaking.

Outside Brazil, the Canadian company IAMGOLD, produces more than 5% of the world supply from the Niobec mine in Quebec. Small-scale niobium mining operations exist in several other countries, including Australia and Mozambique.

Ecological impact — L

Apart from the impact of mining, especially via open pits, no known ecological impacts exist.

Processing — H

After the run-of-mine ore is crushed and milled, the resulting slurry is concentrated using a number of methods chosen to handle the particular chemical and physical properties. These include gravity separation, froth flotation, magnetic separation and acid leaching. The concentrate is converted to metal by digestion in acids, followed by solvent extraction, precipitation and calcining to produce niobium oxide, which is reduced into the pure metal using a thermal process involving aluminium compounds. Ferro-niobium is produced by adding iron oxide powder. Niobium can be extracted as a by-product of tin-smelter waste.

Supply interruption indicators

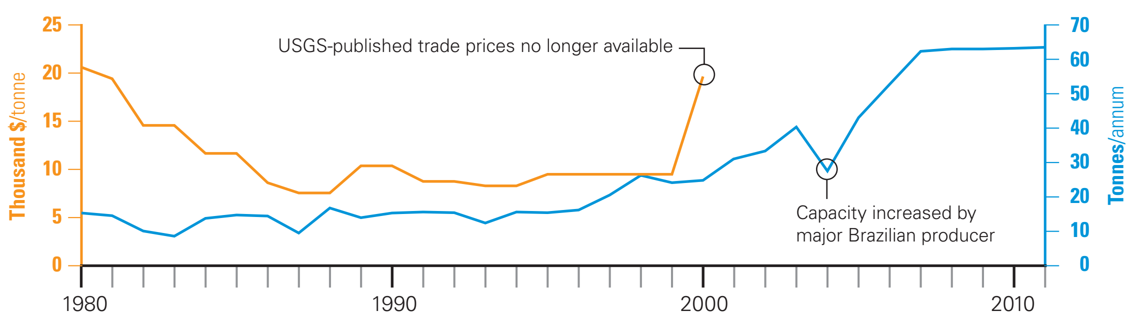
Reserves	H
Trade	H
Ecological Impact	L
Processing	H
Substitutability	M
Recyclability	M
Reserves-to-production ratio	>58

Substitutability — M

Substitutes for niobium are available but carry cost and performance penalties. In high-strength, low-alloy steels, molybdenum and vanadium can be used, while in high-strength and stainless steels, tantalum and titanium are possible substitutes. The similarity of properties between tantalum and niobium alloys enables substitution in applications for corrosion resistant coatings.

Recyclability — M

The metal can be recovered from niobium-bearing steels and super-alloys, although recycling specifically to recover niobium is not currently carried out. The USGS reports that as much as 20% of current consumption may come from recycling.



PRICE & PRODUCTION

Palladium Pd 46

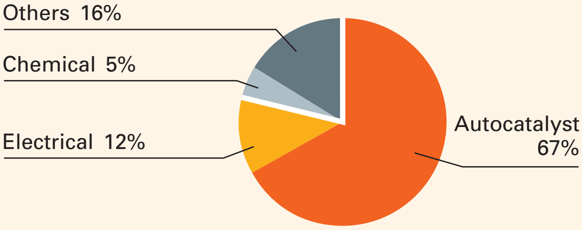
A platinum group metal (PGM) valued as an autocatalyst and as potential mainstay of the fuel-cell industry.

Uses in the energy sector

Today more than 85% of all new vehicles worldwide are fitted with a catalyst, each containing on average some 10 grams of PGM, in order to help reduce carbon monoxide, unburned hydrocarbons and NOx emissions.

Palladium has been effective in gasoline vehicle catalysts, but the sulphur content of diesel and the highly oxidizing conditions in diesel exhaust systems precluded wide-scale use in these vehicles. However, this has changed in recent years as the sulphur content of diesel fuel has been drastically reduced and palladium-platinum catalysts entered the market in 2005. The increased use of diesel-particulate filters has also driven palladium demand, because the high exhaust temperatures needed to clean the filter require the addition of the metal to stabilize the platinum used in the catalyst, and so stop it sintering into large and ineffective particles.

A potential major demand for palladium is expected by researchers working on novel low-temperature fuel-cells, where expensive platinum is replaced by cheaper palladium.



Uses outside the energy sector

The chemical stability and conductivity of the metal make it a useful alternative to gold for plating contacts in electronic components. The catalytic properties of palladium are used in oil refining and in the chemical industry, often in place of platinum, in processes including the production of nitric acid and polyester. The metal is also used in dentistry and for jewellery.

Properties and origins

Melting point 1,552°C
Density 12.02g/cm³

Palladium is a soft, silver-white metal with the lowest density and the lowest melting point of the PGMs. It is soft and ductile when annealed and has its strength and hardness greatly increased when it is cold-worked. It was discovered in 1803 by the English polymath William Wollaston, who had been working on the residue left when platinum-bearing ore was dissolved. His work was rewarded with prestigious awards from the Royal Society and having the highest award of the Geological Society of London named in his honour. The original Wollaston medal was cast in palladium.

The metal is about as abundant as gold and forms around 0.006ppm of the earth's crust. Palladium is found in a number of geological settings, with the three commercially most important all having different origins. The Siberian Norilsk deposit, rich in nickel and copper is hosted in flood basalts; the Canadian Sudbury deposit is thought to have resulted from local crustal melting associated with a meteorite impact; and the Bushveld complex in South Africa is a huge ultrabasic layered igneous intrusion. Palladium is also concentrated when rocks bearing the metal are weathered and eroded, forming placers.

Production and price

Annual production 195 tonnes

Key producers 2012	**Annual production 2012**		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
Russia	82	42	n/a	n/a
South Africa	72	37	n/a	n/a
North America	28	14	n/a	n/a
Others	13	7		
World	**195**		**n/a**	**n/a**
Company				
Norilsk Nickel	84	44	1,760	21
Anglo American	43	22	n/a	n/a
Implats	30	15	4,603	153

Sustainability

Reserves M

The Merensky reef, an ancient placer deposit in the Bushveld complex in South Africa dominates global PGM reserves and current estimates from the USGS quote 63,000 tonnes, although the proportion of palladium is not mentioned. Significant reserves are known in Russia at Norilsk, Canada at Sudbury and at the Stillwater complex in Montana, USA. Given the huge potential of the Bushveld complex and the massive volumes of potentially palladium-rich rock in ultrabasic complexes around the world, reserves appear adequate for the foreseeable future.

Trade M

Palladium is traded on the world's main exchanges. The supply side of palladium is dominated by Russia and South Africa and the very few companies operating large operations in those countries. The Norilsk Nickel company, the world's leading palladium producer, reports 2.7 million ounces (84 tonnes) of production in 2012, which equates to more than 40% of the global production quoted by the USGS.

The three main South African mining houses account for more than 35% of global palladium production, and are all at risk of interruptions to the electricity supply. There was significant loss of production repeatedly in 2008, from power shortages and from labour disputes in 2012.

The demand side is dictated by the health of automotive industries. The current global financial crisis caused a large drop in new-car production and a consequent fall in autocatalyst requirements, leading to periods of oversupply. However, the increasing substitution of palladium for platinum in autocatalysts has boosted demand.

Ecological impact L

Palladium is known to cause some people to develop dermatitis in a manner similar to nickel. Limited data is available on the effects of exposure to the metal. It is pyrophoric and can spontaneously combust when finely divided.

Supply interruption indicators

Reserves	M
Trade	M
Ecological Impact	L
Processing	M
Substitutability	H
Recyclability	M
Reserves-to-production ratio	n/a

Processing M

The processes used to extract palladium differ considerably between Bushveld ores and the sulphide-rich, nickel-copper-dominated varieties. In the Bushveld, following the concentration of PGMs by comminution, froth flotation or gravity separation followed by smelting, palladium is isolated by selective solvent extraction. Nickel-copper ores undergo a far more complicated process involving a pressure-leaching phase in which the two primary metals are removed, followed by two further smeltings separated by electrolysis, ending with solvent extraction to separate out the PGMs and other high-value metals.

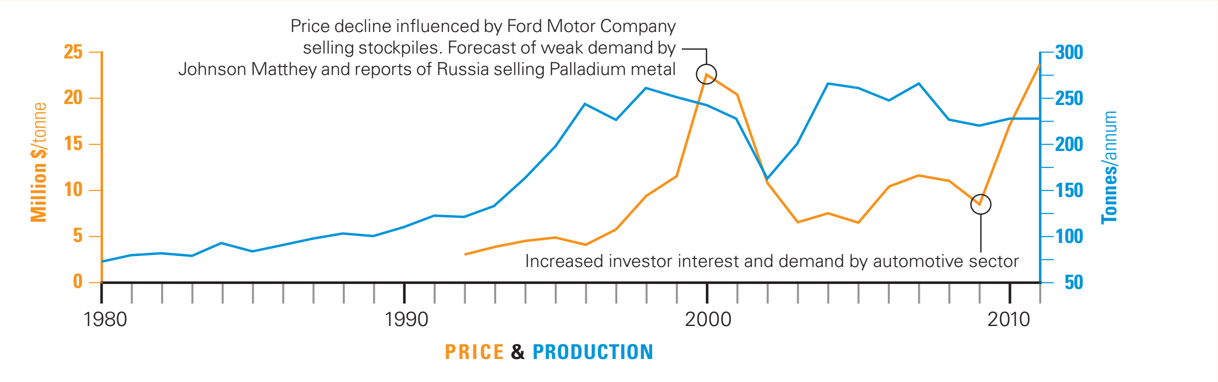
The small number of mining companies that control the extraction of the ore, also control the processing. Crushing, grinding and froth flotation are followed by smelting in electric furnaces. Leaching is used to remove base metals and this, plus ion exchange, allows platinum to be refined from other PGMs.

Substitutability H

The high price of palladium has prompted the substitution by nickel in capacitor manufacture, but in catalysts no adequate substitutes have been developed.

Recyclability M

Much palladium will be dissipated in vehicle exhausts. The high price commanded by palladium and the other PGMs used in autocatalysts have driven the efforts to recycle them from exhaust systems. It was reported in 2012 that recycling resulted in 71 tonnes.



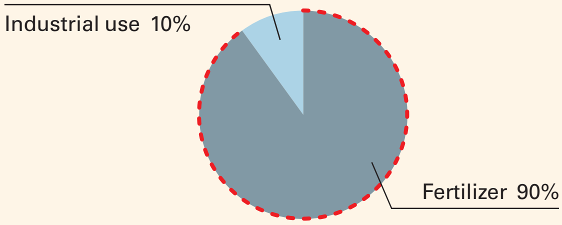
Phosphorus P 15

A major fertilizer mineral indispensable to the growth of the biofuels business.

Uses in the energy sector

Phosphorus, in the form of phosphoric acid, is the key fertilizer spread together with potassium and nitrogen to raise production of crops used as biofuel feedstock. The fertilizer replaces the phosphorus taken up by plants from the soil.

Across the world, the demand for biofuels is growing, with targets being drawn up by numerous governments anxious to reduce greenhouse gas emissions from transport fuels. The IEA Biofuels for Transport Technology (2011) report predicts that biofuels are set to replace 9% of transport fuels by 2030 and crops that are in demand include corn, wheat, sugarcane and energy grasses. The use of phosphorus-based fertilizers for biofuels is seen as possible competition for their use in food production.



Uses outside the energy sector

The majority of phosphorus use is within the agriculture sector. Phosphorus fertilizers are vital to meeting the world's demand for food. The use of fertilizers has been at the heart of increased agricultural yields, along with the use of pesticides, many of which are prepared using phosphorus-bearing compounds. Phosphorus compounds have a wide range of uses, from producing alloys, such as phosphor bronze, to baking soda, pyrotechnics and ordnance.

Properties and origins

Phosphorus has several allotropes, or natural forms, which display different properties. The two most common are red and white phosphorus.

Melting point 44°C
Density 1.82g/cm3

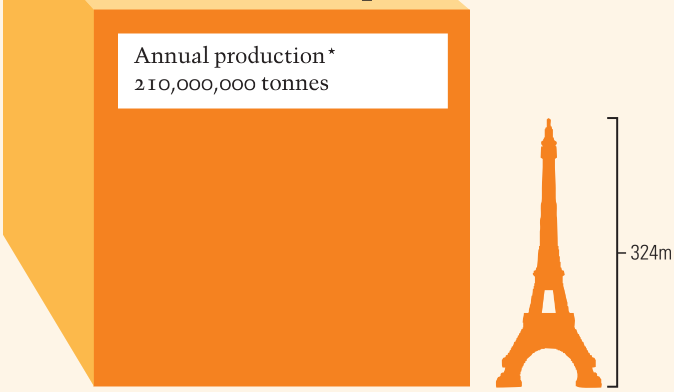
Phosphorus, a non-metal, is highly reactive and is never found in nature as a free element but always as phosphates, where each atom is bonded to four oxygen atoms. The element gives its name to the phenomenon of emitting light when exposed to the air.

Although phosphorus is found in many minerals, only two forms of phosphate are commercially mined:

1 Apatite is a mineral found in some pegmatites and in some other igneous rocks, usually in very small concentrations. When weathered out, this mineral starts the cycle whereby phosphorus enters the hydrological cycle, the biosphere and eventually the ocean.

2 Phosphates are sedimentary rocks that accumulate either by chemical deposition in enclosed marine basins or as a result of biological concentrations, the most important being seabird excreta, known as guano. Phosphorus dissolved out of either igneous or sedimentary settings can be redeposited in limestones and marls, replacing the calcite with calcium phosphate. Phosphates are the main source of the material as they are often large, flat-lying and easily mineable deposits, often having concentrations of calcium phosphate exceeding 70%.

Production and price



Key producers 2012	Annual production 2012*		Reserves	R/P
Country	Tonnes	%	Tonnes	
China	89,000,000	42	3,700,000,000	42
US	29,200,000	14	1,400,000,000	48
Morocco/Western Sahara	28,000,000	13	50,000,000,000	1,786
Others	63,800,000	30	11,900,000,000	187
World	**210,000,000**		**67,000,000,000**	**319**
Company				
OCP (2011 data)	28,100,000	13	n/a	n/a
The Mosaic Company	12,100,000	6	n/a	n/a
PotashCorp	6,821,000	3	145,700,000	21

* Phosphate.

Sustainability

Reserves L

At present consumption rates, reserves are estimated to be sufficient for about 300 years. All projections for the future suggest rising demand, as the need to feed a growing population requires more fertilizer.

Trade M

China has risen, in the past decade, to overtake the US and Morocco as the largest producer of phosphate rock. It is currently retaining the material in the country by levying export tariffs. This could be a trend that other countries adopt, but is unlikely to affect Morocco and Tunisia, where production far exceeds local demand. However, questions about political stability arise in these and some other producing countries. As most of phosphate rock mining takes place in open pits or open cast mines, there is a growing awareness of the environmental impact of these operations. Phosphorus is not traded on any of the major commodity exchanges.

The demand for phosphate fertilizers is inextricably linked to the need to produce food. In addition to a growing population, the demands imposed by dietary changes will increase the need for fertilizers. Biofuels are an additional factor.

Ecological impact M

Phosphorus is an essential element for plant growth and for human health. The average human body has around 0.7 kilogrammes of the element, mainly in bones and teeth. However, the natural cycle, whereby phosphorus is taken up by plants from the soil and held until they die, has been disrupted by human use of fertilizers. Overuse of these can, through run-off from fields, lead to concentrations in watercourses that cause eutrophication, or overproduction of micro-organisms, and the resulting shortage of oxygen in the water leads to the death of other life forms.

Supply interruption indicators

Reserves	L
Trade	M
Ecological impact	M
Processing	L
Substitutability	H
Recyclability	H

Reserves-to-production ratio **319**

Processing L

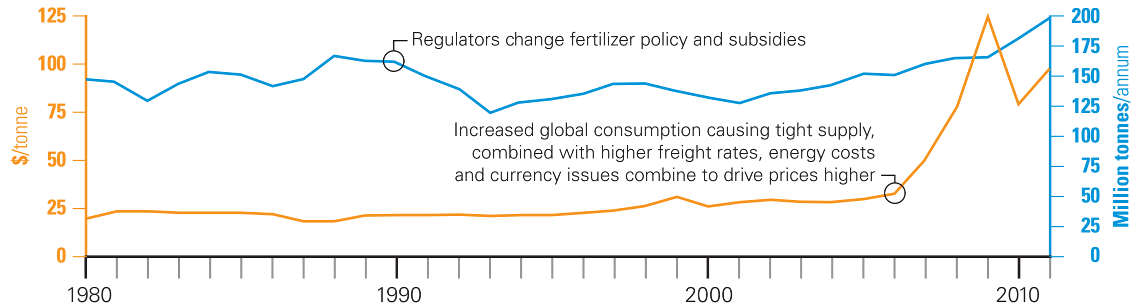
Phosphate containing on average in excess of 30% phosphorus pentoxide is ground and dissolved in sulphuric acid to produce phosphoric acid. This is added to more phosphate rock to produce superphosphate fertilizer.

Substitutability H

There are no substitutes for phosphorus in agriculture and, therefore, none in biofuels.

Recyclability H

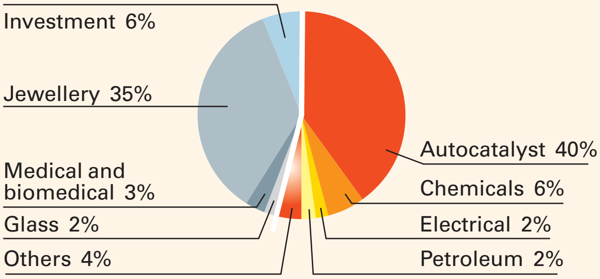
As the vast majority of phosphorus is used as fertilizers, which mostly end up being captured by plants or washed out to sea, there is virtually no opportunity to recycle the material.



PRICE & PRODUCTION

Platinum Pt 78

Platinum literally cleaned up the automobile and without it there would not be sufficient gasoline to meet demand.



Uses in the energy sector

- **Oil refining:** Since the early 1950s, platinum has been the principal catalyst used in refineries that upgrade low-octane naptha into high-octane gasoline. Current demand for high-octane fuels could not be met without platinum. The demand for more gasoline, and hence more platinum catalyst, has been balanced by the development of new catalysts that require less of the metal.
- **Autocatalysts:** The drive to reduce pollution from car exhausts led to the introduction of autocatalysts on light vehicles in California in 1975. Now, more than 85% of all new vehicles worldwide are fitted with one. As the catalyst for the average car holds between 2 and 10 grammes of platinum group metals (PGMs – platinum, palladium and rhodium, used in various combinations), this sector is the biggest single consumer.

  The autocatalyst, a fine honeycomb mesh coated with PGMs that sits in a container between the engine and the silencer, significantly reduces the quantities of harmful emissions in both gasoline and diesel engines. Catalysts for diesel cars originally only used platinum, but now, increasingly, use a combination of platinum, palladium and rhodium. Additional demand could come from fuel-cell technology.

Uses outside the energy sector

The biggest single use of platinum, outside the energy sector, is in the jewellery sector and it has also been successfully promoted as an investment metal. Platinum-based catalysts are used in the chemical industry and, in recent years, platinum's use in anti-cancer drugs and in medical devices has risen sharply.

Properties and origins

Melting point 1,772°C
Density 21.45g/cm3

Platinum is a steel-grey element with a metallic shine, catalytic properties and a high resistance to chemical attack. It does not oxidize when heated in air and is highly resistant to corrosion, thus counted as a noble metal.

Platinum, which makes up around 0.004ppm of the earth's crust, is primarily found in its native form. It is found in ultrabasic igneous rocks and can be concentrated by magmatic processes, especially those leading to layered complexes. Another path is based on erosion of such rocks, which frees the metal from the other minerals present. The erosion products will be sorted by alluvial processes and, because of its high density, platinum will be concentrated into placer deposits. The metal was first discovered in deposits of this type in South America, but was initially discarded as worthless by the Spanish conquistadors. Platinum is often found in association with other PGMs as well as nickel, copper and chromium.

Production and price

Annual production 176 tonnes

Key producers 2012	Annual production 2012		Reserves	R/P
Country	Tonnes	%	Tonnes	
South Africa	127	72	n/a	n/a
Russia	25	14	n/a	n/a
Zimbabwe	11	6	n/a	n/a
Others	13	7	n/a	n/a
World	**176**		**n/a**	**n/a**
Company				
Anglo American Platinum	74	42	n/a	n/a
Norilsk Nickel	21	12	467	22
Implats	45	26	7,153	n/a

Pt 78

Supply interruption indicators

Reserves	M
Trade	M
Ecological impact	H
Processing	M
Substitutability	H
Recyclability	M
Reserves-to-production ratio	n/a

Sustainability

Reserves — M

Platinum is mined as a prime ore, principally in the Bushveld complex in South Africa, thought to hold up to 85% of the world's reserves, where it is concentrated to grades exceeding 10ppm for example, within the Merenksy Reef. At the Norilsk complex in Siberia and at Sudbury in Canada, it is mined as a by-product of other metal mining operations, such as copper-nickel operations, with grades of typically only 0.5ppm. The reserves are difficult to specify as most mines report figures for PGMs and not just platinum. The USGS quotes a global reserve figure for PGMs at 66 million kilogrammes and Johnson Matthey quotes more than 6 million kilogrammes of platinum reserves in the Bushveld.

Trade — M

The figures above demonstrate the dominance of just two countries and three companies for the majority of production. South Africa has experienced production problems in recent years, both in mining and in processing with strikes in 2012 and 2014 stopping production and resulting in price rises. With low ore grades, processing is energy intensive. South Africa is suffering electricity generating shortfalls and continuing risk of power cuts. Russian production has been subject to strong political influence and natural resources are still considered as assets in which the state takes a direct interest. Exports have been controlled by the government agency Almazjuvelirexport who appear to publish little data on production.

Jewellery sector demand is erratic as is the investment market. Increases in car production and more stringent regulations, especially for diesels, will lead the growth in demand. The development of fuel-cells could demand significant quantities if this sector fulfills its potential.

Ecological impact — H

At present, the bioactivity of metallic platinum has not been proved and there are no available toxicity values. Only platinum compounds are known to be highly bioactive and are used in cancer therapy. However, there is known to be some dissipation of platinum particles into the environment from autocatalysts, which could pose a potential risk if they were bioactive.

Processing — M

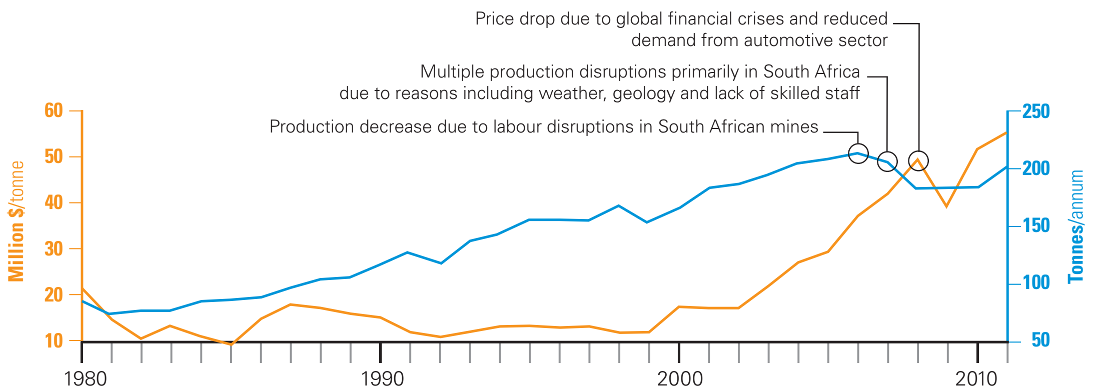
The mining companies control processing, with similar risks as for production. With low ore grades and complex metallurgy, processing is capital and energy intensive. Crushing, grinding and froth flotation is followed by smelting in electric furnaces. Leaching is used to remove base metals and this and ion exchange allow platinum to be refined from other PGMs.

Substitutability — H

Within the automotive sector, platinum can be fully substituted by palladium in gasoline engines. For diesel vehicles, only a partial substitution by palladium is possible, with platinum remaining the main component. For jewellery, fashion and sentimentality hold sway and therefore the potential for substitution is difficult to estimate.

Recyclability — M

The recycling of platinum in industrial applications, for example, petrochemical catalysts, is known to be highly effective and rates are estimated to be more than 90%. For consumer products, especially products with a long life, such as autocatalysts, only about 50 – 60% of the platinum is recycled. The reason is that many of the vehicles with catalysts end their lives in countries that do not have adequate recycling.



PRICE & PRODUCTION

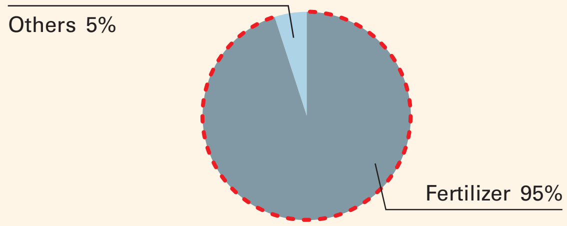
Potassium K 19

One of the key plant nutrients, without which biofuels would be a non-starter.

Uses in the energy sector

Potash, spread as a fertilizer, provides potassium, one of the three primary plant nutrients along with phosphorus and nitrogen. Without it, the yields of crops grown for biofuels would be drastically reduced and the economics of this energy pathway compromised.

Across the world, the demand for biofuels is growing, with targets being drawn up by numerous governments anxious to reduce greenhouse gas emissions from transport fuels. As mentioned in the phosphorus section, the IEA Biofuels for Transport Technology (2011) report predicts that biofuels are set to replace 9% of transport fuels by 2030 and crops that are in demand include corn, wheat, sugarcane and energy grasses. The use of potassium-based fertilizers for biofuels is seen as possible competition for their use in food production.



Uses outside the energy sector

Beyond their vital use as fertilizers, which accounts for some 95% of world production, potassium compounds have many uses, ranging from photographically sensitive chemicals to a primary constituent of gunpowder.

Properties and origins

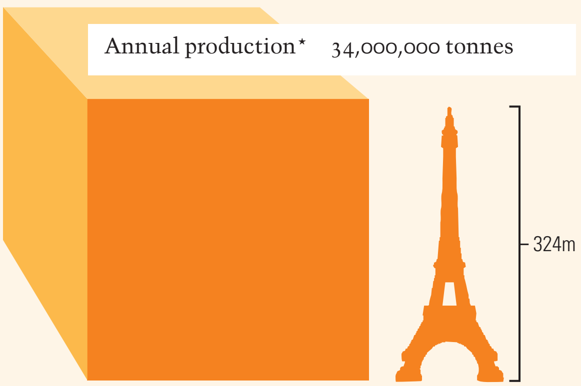
Melting point 64°C
Density 0.86g/cm^3

Potash is not an element. It is the name given to a range of potassium-bearing materials, the most common being potassium chloride. The name comes from the ancient practice of obtaining potassium by leaching wood-ash in large iron pots. Spreading wood-ash leachate replaces the potassium plants obtain from the soil, which they need for growth and strength. Naturally occurring potash salts were discovered in Germany in 1861, during the sinking of a shaft to explore for common salt, and mined potash rapidly replaced wood burning as the source. Large deposits have subsequently been found in many parts of the world, with particularly large deposits in the Williston Basin that spreads across southern Saskatchewan and into North Dakota, spanning the Canadian – US border.

Most potash is found in marine evaporites, not surprisingly, as seawater contains around 0.04% potassium. Potassium chloride minerals are formed along with common salt and other rarer salts when shallow seas or lakes are subject to drying out in arid areas. Evaporites often stretch over many square kilometres and can be tens of metres thick. The potassium content of potash is always quoted as potassium oxide (K_2O) equivalent. The large sheet-like deposits of potash lend themselves to room and pillar mining. In some locations, deep deposits are exploited by solution mining, a process where a leachate solution is pumped into the potash-rich layer via a borehole, dissolving it. The resulting solution is recovered through a second borehole and then evaporated to produce the material.

Production and price

Annual production* 34,000,000 tonnes



Key producers 2012	**Annual production 2012***		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
Canada	9,000,000	26	4,400,000,000	489
Russia	6,500,000	19	3,300,000,000	508
Belarus	5,650,000	17	750,000,000	133
Others	12,850,000	38	1,050,000,000	82
World	**34,000,000**		**9,500,000,0000**	**279**
Company				
Urakali United Company	9,362,000	28	1,622,600,000	173
PotashCorp	7,724,000	23	n/a	n/a
The Mosaic Company	7,422,000	22	n/a	n/a

*In K_2O equivalent.

Sustainability

Reserves L

Potash reserves are widespread globally with individual deposits, such as the Williston Basin, containing several billion tonnes. Large deposits are now known to exist in several countries, although reserves, and certainly production, are dominated by Canada, Russia and Belarus. This was not always the case, as demonstrated by the extraordinary rise in prices of the material in January 1915, when the price in the US raced from $35 to $600 per tonne, as the wartime blockade of Germany, then the world's major source, cut off supplies. This led to feverish exploration efforts and the discovery of reserves in the US and later in Canada. Potash, despite its widespread availability, is still regarded as a strategically important mineral. In 2010, the international mining company BHP Billiton made a series of bids to acquire the Canada-based company PotashCorp, the world's leading producer. The bid was blocked when the Canadian government ruled that the sale would not be in the best interest of Canada. PotashCorp holds large shareholdings in various top-producing companies, rather than operating as a single mining company itself, and hence does not appear in the key producers table below.

Trade M

Potash trade is dominated or, some commentators claim, controlled by companies acting together. Canpotex, which trades the products of three large Saskatchewan miners, sells more than a third of global production. Critics have, in the past, accused Canpotex and Belaruskali, a Russia–Belarus based organization, of being in league to control prices. World prices certainly have the potential to be influenced by the commanding position these organizations hold. Developing nations, in particular India, have to provide subsidies to farmers in order to purchase the potash needed to feed the growing population. The use of potash fertilizers in the biofuels sector is growing and opponents of this energy pathway are quick to point out that use of fertilizers for energy crops competes with fertilizer demand for food production.

K 19

Supply interruption indicators

Reserves	L
Trade	M
Ecological impact	M
Processing	L
Substitutability	H
Recyclability	H

Reserves-to-production ratio **279**

Ecological impact M

According to the International Potash Institute, "potassium has no known deleterious effect on the quality of natural and drinking waters and it does not induce eutrophication in rivers and lakes. Under regular agricultural practices, small amounts of potassium ions are leached into deeper soil layers and finally reach the aquifers, which presents no ecological threat. Potassium in drinking water and/or food is no hazard for human health provided renal function is normal. A diet high in potassium has no harmful effect and is recommended for people suffering from hypertension."

Processing L

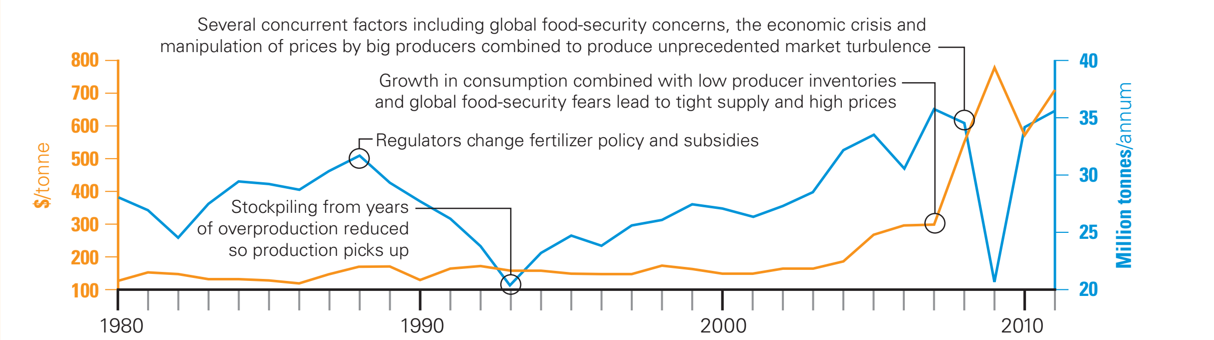
Processing of potash for agricultural use is straightforward and consists mainly of removing clays in the run-of-mine material and then separating off common salt.

Substitutability H

There are no substitutes for potassium as an essential plant nutrient and an essential nutritional requirement for animals and humans.

Recyclability H

Burning plant material and spreading the resulting ash on the soil to replace potassium taken up by the plants was an early form of recycling. Mineral-based potash is not recycled after use.

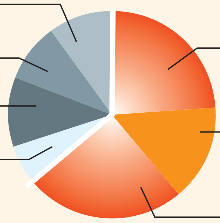


PRICE & PRODUCTION

Rare earth elements

See page 57 for more information.

A set of 17 elements with a range of unique physical and chemical properties essential for a range of green technologies and numerous other uses, from magnetic toys to control rods in nuclear reactors.



Uses in the energy sector

Of the 17 REEs, each of the 10 that have direct uses in the energy sector are described on page 57. REE use is centred around five main areas:

- Lanthanum in battery storage.
- Neodymium, praseodymium dysprosium and terbium in permanent magnets within electric motors and generators.
- Lanthanum and cerium used as oil-cracking catalysts.
- Lanthanum, cerium, neodymium and praseodymium in autocatalysts.
- Yttrium, cerium, europium and terbium as phosphors in lighting.

In the energy sector, the first large-scale use of an REE was the production of nickel-metal hydride batteries (NiMH) that required lanthanum. These batteries have been at the heart of the electric and hybrid car revolution since the late 1990s and are only now being superseded by lithium-ion batteries. Batteries containing lanthanum are still produced in large numbers for a variety of uses.

As the world moves towards a lower-carbon economy, REEs have found significant new uses in electrical generators and motors. To improve the performance of the motors in electric and hybrid cars, REE-based permanent neodymium-iron-boron magnets (NdFeB) are used. A commonly quoted figure is that every Toyota Prius needs one kilogramme of permanent magnets, with neodymium comprising about 30%. The addition of approximately 5% dysprosium is presently indispensable to raise the temperature resistance.

There is a large research effort under way to reduce the car industry's dependence on REE-based permanent magnets, especially for the substitution of the critical elements dysprosium and terbium, the only substitute presently suitable for dysprosium. In some direct-drive (i.e. gearless) wind turbines, NdFeB magnets are essential. The global market share of this type of wind turbine is about 10% with the majority presently being manufactured by Chinese companies. This technology uses fewer parts and therefore potentially requires less maintenance making them well suited to offshore applications. Presently some 200 kilogrammes of neodymium are required for every megawatt of generating capacity in wind turbines using REE-based permanent magnets.

Certain REEs are required in autocatalysts and in oil refining as cracking catalysts. In the production of steel, additions of small amounts, usually less than 1%, of REEs improve stability useful in the production of lightweight steels, which in turn reduces energy consumption. Some REEs are also indispensable as phosphors in high-efficiency light bulbs and display panels. Selected REEs are utilized in several areas of nuclear reactors, mainly in control rods and protective coatings.

Production and price

Annual production
110,000 tonnes

Key producers 2012	Annual production 2012		Reserves	R/P
Country	Tonnes	%	Tonnes	
China	95,000	86	55,000,000	579
USA	7,000	6	13,000,000	1,857
Australia	4,000	4	1,600,000	400
Others	4,000	4	40,400,000	10,100
World (total)	**110,000**		**110,000,000**	**1,000**
Company*				
Zibo Jiahua Advanced Material Resources Co.	1,491 export quota	n/a	n/a	n/a
Inner Mongolia Baotou Steel Rare Earth Hi-Tech Co.	1,265 export quota	n/a	n/a	n/a
Inner Mongolia Baotou Hefa Rare Earth Co.	1,045 export quota	n/a	n/a	n/a

* The biggest producers are Chinese companies subject to government quotas on exports.

Uses outside the energy sector

REEs have an extremely wide use in all areas of life. Magnetic applications are seen in industry (pumps, compressors), public and domestic life (air conditioning, electric toothbrushes, fans), the medical field (selected MRI scanners, contrast agents), buildings (elevators, escalators), the automotive industry (ignition coils, seat height adjustment), lifestyle products (speakers in mobile phones, eBikes) as well as in military equipment. Moreover, REEs are required for a multitude of non-magnetic uses including laser manufacturing, for colouring glass and adding UV protection, as signal amplifiers and many more.

The magnetic properties of samarium and neodymium led to the development of extremely strong permanent magnets, which were rapidly adopted by manufacturers for miniature applications, such as loudspeakers and hard-drive coil motors.

Rare earth elements

Supply interruption indicators

Reserves	M
Trade	H
Ecological impact	M
Processing	L
Substitutability	M
Recyclability	M

Reserves-to-production ratio **1,000**

Properties and origins

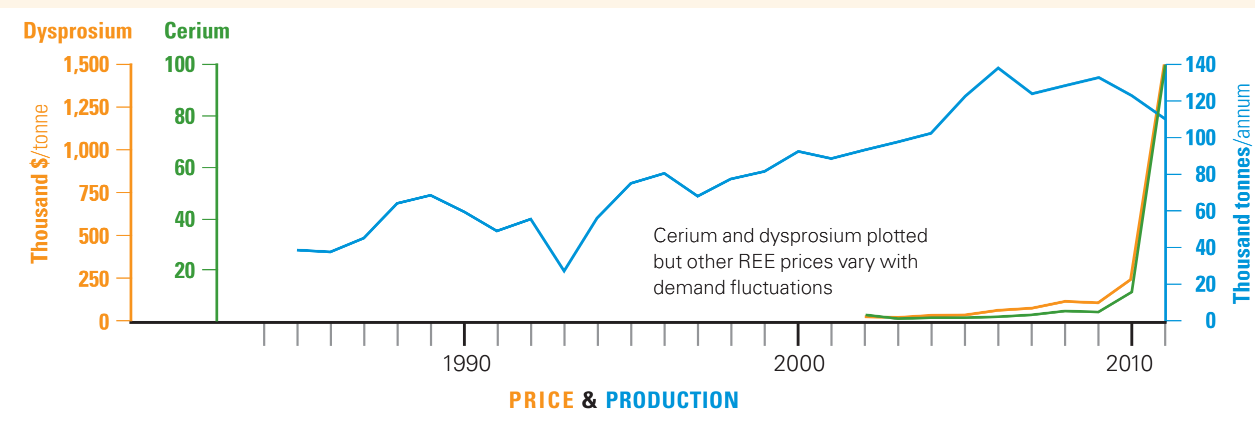
Melting point 822°C – 1,658°C
Density 2.99 – 9.84g/cm³

The term 'rare earth elements' is a misnomer, with the radioactive promethium being the only one that really is rare. Most are well represented in the crust: cerium, for instance, is as common as copper at 68ppm. They are not often found, however, in economically attractive concentrations, hence the collective name, although they are constituents of a variety of oxides previously called 'earths'. The discoveries of these elements started in 1787, with yttrium named after the village Ytterby in Sweden, where the mineral that contained it was first described.

Discoveries guided by predictions in the periodic table continued well into the 20th century and pure dysprosium was only produced for the first time in the early 1950s.

The elemental forms of REEs are iron-grey to silvery metals, usually soft and ductile. They are mostly reactive, especially when powdered or at high temperatures.

REEs are often found together and the principal sources are the complex minerals, bastnäsite and monazite, usually found as a placer derived from pegmatites. REEs with relatively high grades of dysprosium and terbium are also found in lateritic clays. Some ores of REEs, especially placers and monazite ores, introduce complications to mining and processing as they contain radioactive thorium.



Sustainability

Reserves M

REE deposits are known in many countries and exist in a variety of geological settings. Reserves are thought to be large and the USGS quotes more than 110 million tonnes of reserves.

The possible constraint on REE consumption comes from the present concentration of some 97% of global production in China. This is a relatively recent phenomenon and one that appears to be changing rapidly. Until the 1980s, the Mountain Pass mine in California produced the majority of the world's REEs. Numerous Chinese operations, many of them artisanal and said to be unregistered and unregulated, began to undercut the US operation. The pressure from these new operations, and the need for Mountain Pass to invest heavily in order to meet environmental legislation, challenged profitability and this Californian mine shut in 2002, leaving Chinese producers in a dominant position. Factors, however, including government-driven efforts to improve the environment, a vigorous growth in domestic demand and the natural tendency for Chinese suppliers to maintain value in the country have led to restrictions on exports and a rise in prices.

These actions, and the recognition of the demand growth that is accompanying moves to a lower-carbon economy, have spurred exploration and development activities around the world and new ventures are starting in several countries, which should ease concerns over supplies. This upturn in interest has also seen the owners of Mountain Pass reopening the mine in 2012 with ongoing investment in new technology designed to improve efficiency and lower costs. The large Mount Weld mine in Australia, described by the owners as the richest REE deposit in the world, started production of rare earth oxides in 2013, through its advanced materials plant in Malaysia. Worldwide, there are estimated to be several hundred rare-earth mining projects in development but price fluctuations threaten many of them.

Trade H

As described above, China has an extraordinarily dominant position on the supply side and has been observed to restrict exports. Even though export restrictions have been in effect since around 2000, this caused no concern because quota was never reached. REEs attracted enormous media attention but reports did not always publish correct numbers. Speculation possibly added to the publicity and fuelled debate that contributed to considerable and rapid price fluctuations. But there does not appear to be a direct relationship between the price variation and supply and demand. The real problem is the uncertainty and lack of transparency around supply, demand and use. Certainly this situation is unfavourable and concern over the sustainability of supply has caused Japan and manufacturing companies such as Toyota and Siemens to seek supplies elsewhere, by forming agreements with Vietnam, Australia and Mongolia to develop new mines. Concern over supply interruptions has also increased interest in recycling.

The increasing demand for REEs is largely being driven by their use in magnets and energy-efficient lighting, and this growth is expected to continue as wind-turbine, electric-vehicle, compact-fluorescent and LED demand grows. LEDs need fewer REEs per unit of light output than fluorescents. Growth in fluorescent use currently drives up the demand, but as LEDs take over that will be ameliorated to some extent.

Ecological impact M

The major impact of REEs has been at mining and processing sites, both regulated and illegal. Mountain Pass mine was ordered to undertake a number of environmental clean-ups before its shutdown. Monazite mining and processing require particular attention due to the radioactive nature of many of the ores.

For all REEs, the processing is technically extremely difficult and highly time and energy consuming. The leaches, acids and other chemicals needed for the separation and refining are problematic as is their subsequent disposal.

Illegal mining in China is known to be causing severe environmental damage and, although the Chinese government tries to stop this type of mining, it has as yet only been partially successful.

Processing L

Processing and separation of the very similar chemical elements require many steps to isolate each individual element and, as mentioned previously, this involves environmentally challenging chemistry.

Substitutability M

Presently, there are no suitable substitutes available for lanthanum and cerium as catalysts, nor for neodymium and none for dysprosium for magnet production. The number of research programmes started in 2012 indicates the effort being made to find substitutes especially in the magnets market.

It should be kept in mind that the REEs are 17 individual elements that have to be considered separately. The most common REEs, lanthanum and cerium, are not substitutable and do not suffer supply shortages. The enormous price jumps in 2012 are thought to be caused by speculators.

Recyclability M

The technology to recycle REEs bound into magnets exists but needs to be developed. The French chemical company Rhodia announced in 2011 that it was developing a commercial magnet recycling process as well as a separate process to recover the REEs in compact fluorescent lamps primarily for the recovery of europium, terbium and yttrium. Collection of phosphor powder from recycled lamps is facilitated in the US, aided by the fact that the lamps are already required to be recycled to keep the mercury that they contain out of the environment. On top of the technical issue, the actually available quantity of REEs is another unknown factor, as is whether it is worth trying to recycle the low percentages of REEs used in steels.

REEs used in the energy sector

Scandium Sc 21

Scandium is about as abundant as niobium and yet the total global consumption is estimated by the USGS to be around only 10 tonnes. There is a low concentration of scandium in many ores and little information is available about its production. The element is used in the production of specialized lamps and it is predicted that there will be a future demand in fuel-cell production.

Yttrium Y 39

Yttrium belongs to the group of the heavy REEs (HREEs) and is more abundant in the earth's crust than cobalt but less than copper. The annual global production is close to 9,000 tonnes. Yttrium is found in placer deposits or in low concentrations in other REE minerals.

The major applications are as host for phosphors in fluorescent lamps, monitors, television and LCD screens. Yttrium-stabilized zirconium dioxide is used in electronic sensors in automobiles, structural ceramics and thermal barrier coatings in turbines and aircraft engines. Potential future applications are in high-temperature superconductors for power transmission lines and wind turbines.

Lanthanum La 57

Lanthanum has a lower crustal abundance than copper, at 31ppm, but is difficult to isolate from the other lanthanides. It is commonly one of the major REE constituents of the placer desposit minerals monazite and bastnäsite and is not considered to be endangered by supply shortages.

Lanthanum is important as a refining catalyst and is also used in automotive catalysts and in NiMH batteries for hybrid vehicles. The element also forms cathodes in solid-oxide fuel cells, a demand for which is set to rise. Other REEs can be substituted for lanthanum but usually with a drop in performance. Systemic substitutes are available for some applications such as Li-ion batteries in place of NiMH batteries. Although the element can be recycled from some applications, there are uses, such as in autocatalysts, where it is simply dissipated.

Cerium Ce 58

Cerium is the most abundant of the REEs and more abundant in the crust than copper. As with all other REEs it does not occur in a native state and although its concentration in REE-bearing ores is low, the annual global production is around 40,000 tonnes.

Cerium has numerous applications with the most important being as a catalyst both in petroleum cracking (fluid catalytic cracking) and in autocatalysts. In the lighting industries, cerium is used as phosphor for lamps and scintillation counters. The uses include some dissipative and low-concentrated uses. In principal cerium can be recycled and this is done in some applications. Accurate data is not available but the recycling share is thought to be low because, to date, recycling has shown little or no economic advantage.

Praseodymium Pr 59

The main use of praseodymium in energy-related areas is for the production of permanent magnets. In NdFeB permanent magnets, praseodymium can be substituted for a portion of neodymium. The characteristics will remain the same but as praseodymium usually is cheaper than neodymium, total production cost can be reduced.

Neodymium Nd 60

By far the dominant use of neodymium in the energy sector is as an indispensable ingredient of the powerful NdFeB permanent magnets. The field strength of this type of magnetic alloy allows for considerable performance from even small magnets leading to a wide range of applications. These include electric motors in e-mobility, speaker magnets in numerous lifestyle products such as smartphones, and direct-drive wind turbine generators. Although the market for direct-drive wind turbine generators is growing, particularly for offshore applications, in 2010 about 90% of the roughly 200GW installed global windpower was based on classic gearbox and generator systems not containing REE-based permanent magnets. Disadvantages of the NdFeB magnets are their susceptibility to corrosion, their brittleness and the low temperature resistance. If an NdFeB magnet gets too hot, it will lose its remanence (i.e. magnetic property).

Substitutes for neodymium in magnets are, at a systemic level, samarium cobalt magnets. However, they do not achieve the same performance. A partial substitution of neodymium by praseodymium is possible. Neodymium is the third most abundant REE and therefore, despite press speculation, a shortage seems unlikely. Recycling of magnets is possible but problems arise in the logistics chain when collecting and removing them from the products they are embedded in.

Samarium Sm 62

Samarium and cobalt are combined to produce permanent magnets, which have lower performance than NdFeB magnets, but are more corrosion and temperature resistant. Additionally samarium is used in nuclear reactors as radiation shielding material.

Europium Eu 63

The main use is as an energy-efficient phosphor for television, fluorescent lamp and LED production. Substitutes are not available yet. Europium is also used in the nuclear industries as radiation shielding material.

Gadolinium Gd 64

Gadolinium is used mainly as a host for phosphors in fluorescent lamps. In the nuclear industry gadolinium is added as a safety additive in fuel rods.

Terbium Tb 65

The main application is as a (green) phosphor in lamps, monitors, television screens and LEDs. Its efficiency as a phosphor contributes to energy savings. It can also be used in x-ray intensifying screens. Terbium can act as a (partial) substitute for dysprosium in permanent magnets although the relatively low abundance and availability of the element precludes large-scale substitution.

Dysprosium Dy 66

Dysprosium belongs to the group of the HREEs and is one of the least abundant REEs. The most important use in energy applications is as an addition to NdFeB magnets. This addition enhances the temperature resistance of NdFeB magnets so that they can be used in automotive electric traction motors. If e-vehicle production grows there is a risk of supply shortage. Dysprosium is also used as a phosphor and in the nuclear industry as radiation shielding.

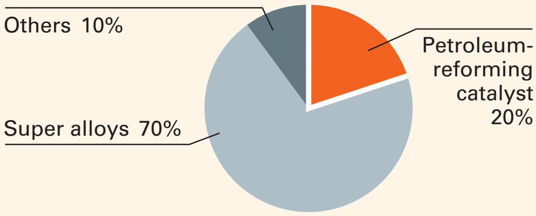
Rhenium Re 75

The catalyst that enables high-octane lead-free gasoline to be produced.

Uses in the energy sector

The extraordinary resistance to creep at high temperatures makes rhenium invaluable in alloys used to make single-crystal turbine blades for industrial gas turbines used in power generation. Creep resistance allows engines to be manufactured with closer tolerances and run at higher temperatures. These factors significantly improve performance and efficiency, while prolonging engine life. As blade technology has advanced, rhenium now constitutes up to 6% of the nickel-based alloys used in modern turbines.

The use of rhenium-platinum catalysts in the refinery process of petroleum reforming enables the production of high-octane hydrocarbons used in the formulation of lead-free gasoline. Rhenium catalysts allow refineries to run processes at higher temperatures and lower pressures, leading to higher octane ratings and better yields. Rhenium coatings are used by researchers working on thermophotovoltaic power generation systems.



Uses outside the energy sector

The increase in performance offered by rhenium in turbine blade alloys described here has led to the uptake of the metal in modern jet engines. Some 70% of the world's rhenium is used in turbine blade manufacture. The high melting temperature of the metal drives its use in a wide range of manufacturing including jet engine nozzles, electrical contacts, crucibles and x-ray tubes.

Properties and origins

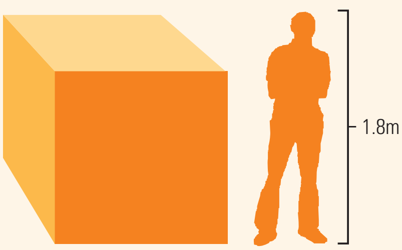
Melting point 3,180 °C
Density 21.03g/cm^3

Rhenium, the last stable element to be discovered, is a silvery-white metal with the second highest melting temperature and the fourth highest density of all metals. It is also one of the rarest elements with a crustal concentration reported to be between 0.5 and 1ppb. Although Mendeleev predicted element 75, it was not discovered until 1925 by the German chemists Ida Tacke, Otto Berg and Walter Nodack, who isolated the element from the molybdenum bearing ore, molybdenite.

The metal is not known to occur in its native state and the only commercial source is from molybdenite found in copper porphyry orebodies. Copper porphyries are disseminated concentrations of copper sulphide minerals resulting from the percolation of igneous fluids through rock overlying or surrounding an igneous intrusion.

Production and price

Annual production 52 tonnes



Key producers 2012	Annual production 2012		Reserves	R/P
Country	Tonnes	%	Tonnes	
Chile	27	52	1,300	48
USA	9	17	390	43
Poland	6	12	n/a	n/a
Others	10	19	810	81
World	**52**		**2,500**	**48**
Company				
Molymet	25	48	n/a	n/a
Freeport McMoRan / Climax Molybdenum	9	17	n/a	n/a
KGHM	4	7	n/a	n/a

Sustainability

Re 75

Supply interruption indicators

Reserves	H
Trade	H
Ecological Impact	L
Processing	H
Substitutability	M
Recyclability	M

Reserves-to-production ratio **48**

Reserves H

As the sole economic source of rhenium is as a by-product of molybdenum in copper mines, the reserves are totally linked to the availability of these metals.

Trade H

Trade in rhenium is controlled by copper/molybdenum producers who exploit copper porphyry deposits. There are a limited number of companies in this position and by far the largest is Molymet, based in Chile, who produces almost half the world's supply. Large-scale porphyry mining also takes place in the US but data is not currently available. The Polish company KGHM has joined the ranks of producers, fairly recently, with metal derived from its copper workings; the company reports an annual production capacity of 4 tonnes, equivalent to nearly 7% of world production.

Ecological Impact L

The minute volumes of rhenium that are used result in extremely limited human exposure to the metal and little is known about its toxicity. The ecological impact of the metal itself is therefore considered to be low to non-existent, although, as it is mostly produced as a by-product of molybdenum and copper mining, it could be associated indirectly with the impacts caused by the extraction of those metals.

Processing H

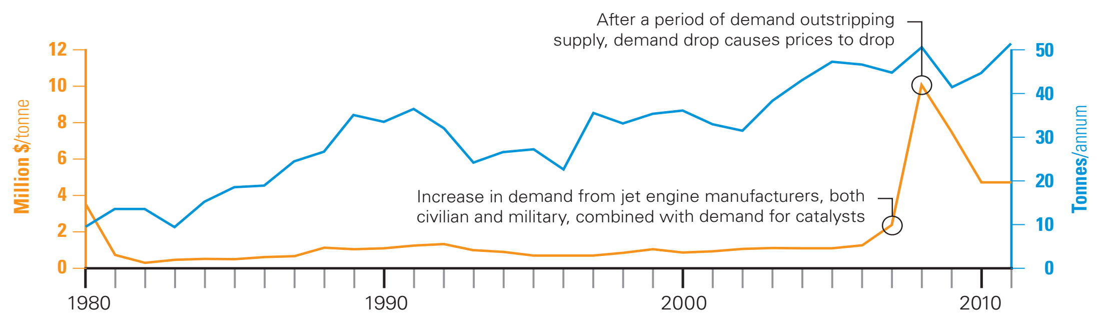
As mentioned above, most rhenium is extracted from molybdenum that is found in copper deposits. During the roasting of molybdenum, rhenium converts to rhenium pentoxide, which becomes deposited in the exhaust stacks of the roasting plant. This material is extracted by intensive washing and an ion-exchange process is used to recover rhenium. Copper roasting can also lead to the accumulation of rhenium pentoxide in the exhaust stack.

Substitutability M

The scarcity and price of rhenium have long driven efforts by major users to find substitutes but with limited success. Aero engine manufacturers, including GE, have reduced the proportion of the metal needed in super alloys but have not been able to replace it. For use as a catalyst, rhenium can be substituted by elements including gallium, germanium, indium and selenium, unfortunately all critical materials themselves. The USGS reported in 2013 that for one catalyst application a tin-iridium alloy has proved a commercial success.

Recyclability M

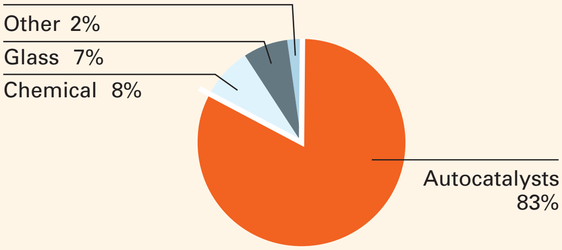
Rhenium recycling rates are reported to be steadily increasing, driven by the high cost of the metal and the supply rate being controlled by the copper and molybdenum industries. Recycling rhenium is facilitated by the fact that much of the metal is used in aero engines, which are fully accounted for throughout their existence.



PRICE & PRODUCTION

Rhodium Rh 45

A rare platinum group metal (PGM), essential in autocatalysts.



Uses in the energy sector

The introduction of catalytic converters on gasoline engine vehicles has reduced their harmful emissions by vast amounts. It is estimated that autocatalysts save 15 tonnes of emissions over the 10-year life of the average car. The three-way catalyst that is fitted to the majority of the world's new vehicles reduces nitrogen oxides, carbon monoxide and unburned hydrocarbons. Rhodium is the key element required to catalyse the reactions that reduce the nitrogen oxides. Now, more than 85% of all new vehicles worldwide are fitted with a catalyst, resulting in considerable emissions. The high cost of the metal has driven research to reduce the amount of rhodium used in each catalyst, below today's average level of less than 1 gramme in each car. Diesel cars do not use rhodium.

Rhodium is also used in detectors in the nuclear industry.

Uses outside the energy sector

Since rhodium is extremely expensive and produced in small amounts, it is only used for specialist purposes where substitution is impossible. These include catalysts in the chemical industry, applications in glass and fibreglass manufacturing, high-temperature thermocouples, filters in mammography and electroplated optical instrument components. It is also used as a protective coating for some gold and silver jewellery items.

Properties and origins

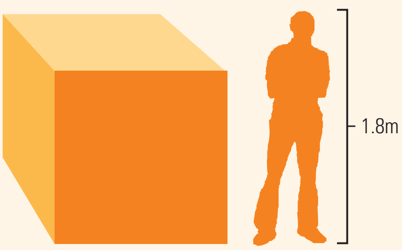
Melting point 1,966°C
Density 12.41g/cm3

Rhodium, one of the PGMs, is a hard, silvery metal that is highly resistant to corrosion and does not form an oxide even when heated. It has a higher melting point than platinum and it does not dissolve in most acids.

The metal, which only forms 0.0001ppm of the earth's crust, is found in association with other PGMs and with other metal ores, including silver and gold. PGMs are principally found in ultrabasic igneous rocks and can be concentrated by magmatic processes, especially those leading to layered complexes. Another path is based on erosion of such rocks, which frees the metal from the other minerals present. The erosion products will be sorted by alluvial processes and, because of its high density, rhodium will be concentrated into placer deposits.

Production and price

Annual production 22 tonnes



Key producers 2012	**Annual production 2012**		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
South Africa	18	80	n/a	n/a
Russia	3	12	n/a	n/a
Zimbabwe	1	4	n/a	n/a
Others	1	4	n/a	n/a
World	**22**		**n/a**	**n/a**
Company				
Anglo American Platinum (Amplats)	10	45	n/a	n/a
Lonmin	4	18	n/a	n/a
Implats	7	31	840	n/a

Rh 45

Supply interruption indicators

Reserves	M
Trade	H
Ecological impact	L
Processing	H
Substitutability	H
Recyclability	M

Reserves-to-production ratio **n/a**

Sustainability

Reserves — M

Rhodium is principally mined as a by-product of platinum mining, with by far the largest production coming from the Bushveld complex in South Africa, thought to hold up to 85% of the world's reserves. Here it is concentrated to grades exceeding 10ppm, in 30 – 90 centimetre-thick layers, like within the Merenksy Reef. It is mined as a by-product of other metal mining operations, for example, at the copper-nickel operations at Sudbury in Canada. The reserves are difficult to specify, as most mines report figures for PGMs and not just rhodium.

Trade — H

The supply side of rhodium is dominated by the mining of PGMs by the three main South African mining houses (Anglo American, Impala, Lonmin), which together account for more than 70% of global rhodium production. Their output is subject to constraint by restrictions to electricity supply, necessary to drive the energy-intensive mining and processing operations. Some commentators mention up to 25% production loss due to breakdown of electricity supply. Production is also feeling the impact of HIV/AIDS, causing considerable loss of experienced staff.

Russian production of PGMs has been subject to strong political influence in the past and natural resources are still considered as assets in which the state takes a direct interest.

The demand side is dictated by the health of automotive industries. The recent global financial crisis caused a large drop in new car production and a consequent fall in autocatalyst requirements, leading to periods of oversupply. Such swings in demand, combined with speculations, have led to dramatic volatility in prices.

Ecological impact — L

As a noble metal, rhodium is inert and is harmless to humans. However, the compounds are reactive and potentially harmful. The only route into the environment for the metal, as a result of human activities, is in particulates ejected from autocatalysts. Given the quantities of the metal used and the fact that autocatalysts are successfully recycled, the exposure to the average human is thought to be minute. The effects of such low-level exposure to nanoparticles of rhodium could be a potential risk, if they were proven to be bioactive.

Processing — H

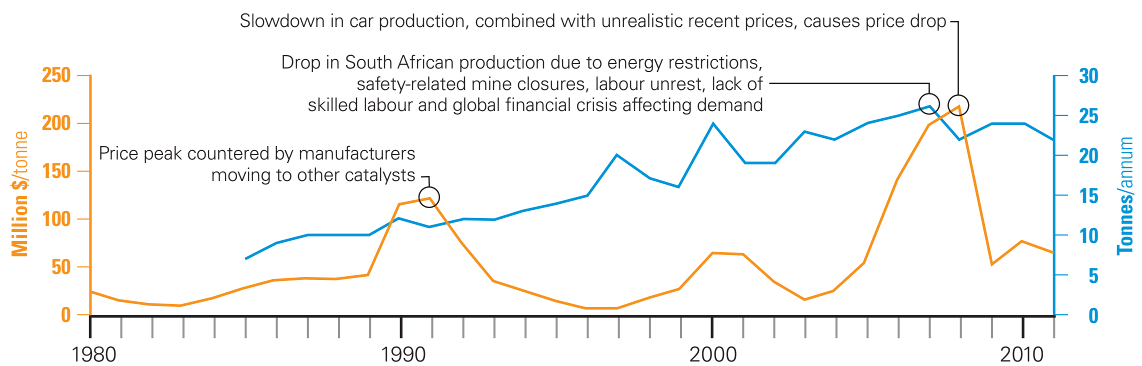
Rhodium is isolated from other PGMs following their concentration and smelting from ores by energy-intensive comminution and smelting.

Substitutability — H

The high price of the metal has underpinned research into substitutes, but, to date, none has been found for the metal's prime use in autocatalysts. However, manufacturers have developed devices that use less of the metal.

Recyclability — M

The recycling of autocatalysts is estimated to be capable of providing up to 50% of the global demand. These numbers are highly speculative because of the enormous growth rates of autocatalysts and their long life cycle.

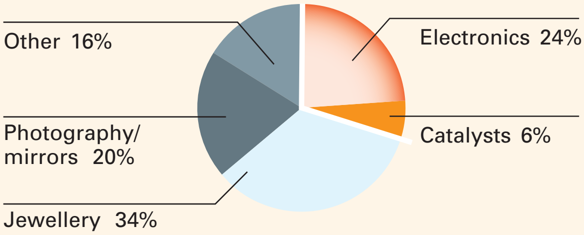


PRICE & PRODUCTION*

*Production figures are incomplete, as no reliable data is available.

Silver Ag 47

An invaluable metal in the photovoltaic world.



Uses in the energy sector

The extraordinary electrical conductivity of silver makes it valuable in many electronic applications, from the contacts of transmission voltage switchgear, to contacts on microprocessors. The metal is used for contacts (conductors) in both crystalline and thin-film silicon cells; in the latter case it helps reflect some light back into the cell to increase light collection. The share of silicon thin-film systems, however, is modest and accounts for about 2% of the global share, compared with about 90% market share of crystalline silicon cells. Solar-cell producers see aluminum and silver as critical to the growth of this market.

New announcements about the potential use of silver in energy applications show up frequently, but the actual breakthrough in mass production cannot be estimated reliably.

Silver-zinc and silver-oxide batteries are manufactured for use where space is at a premium, such as in watches.

Uses outside the energy sector

The traditional uses of silver for tableware, coinage, medals and jewellery are still substantial and account for more than 40% of world production. Use in photography is declining, but industrial use is diversifying, with applications in manufacturing and consumer products. Medical uses continue to expand, ranging from dentistry, where the silver-mercury amalgam is still popular, to antimicrobial agents on dressings. One rapidly expanding use is as antenna material in radio frequency identification (RFID) chips. The chips improve logistics organization and control, but most RFID chips will result in dissipation of the silver, without recycling.

Properties and origins

Melting point 962°C
Density 10.49g/cm3

Silver is a dense, highly ductile and malleable metal with a brilliant lustre. It has the greatest electrical and thermal conductivity of all metals and one of the highest optical reflectivities. It reacts readily with ozone or hydrogen sulphide – remember what happens if you use a silver spoon to eat a boiled egg – and the halides are photosensitive, a property that led to photography.

Silver is found in native form: as an alloy with gold; and in ores containing sulphur, arsenic, antimony or chlorine, especially in conjunction with other metals, such as copper, lead and zinc. Most silver deposits are the result of replacement or cavity-filling by hydrothermal solutions and, consequently, have a wide variety of size and shape, ranging from small, discrete veins to large stockworks.

Production and price

Annual production 24,000 tonnes

Key producers 2012	**Annual production 2012**		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
Mexico	4,250	18	37,000	9
China	3,800	16	43,000	11
Peru	3,450	14	120,000	35
Others	12,500	52	340,000	27
World	**24,000**		**540,000**	**23**
Company				
Penoles	1,527	6	23,000	n/a
KGHM Polska	1,274	5	n/a	n/a
BHP Billiton Group (Cannington mine, Australia)	1,063	4	n/a	n/a

Sustainability

Reserves M

The majority of silver is produced as a by-product of copper, lead and zinc. Ore grades vary greatly and the economics of mines will depend on the grades of all the marketable metals in the ore. Calculating reserves, therefore, for specific metals is hazardous. Also, the economics of silver mining are subject to environmental pressures, because low-grade sulphide ores are increasingly being processed with cyanide leaching, a process that many authorities are banning. Production levels will depend on the demand for the main metals. The published reserves show it to be widespread, with little risk of political constraint.

The demand for silver has been dominated by jewellery, silverware and coinage, but industrial uses are set to grow. Price is a major factor in many of these uses, as there are substitutes available.

Trade L

Silver has had an exciting trading history, particularly in 1979-80, when the two American Hunt brothers came very close to cornering the global market by buying up large quantities of physical silver. The metal has been traded on the London Bullion Market Association since 1897 and is subject to a daily fix. However, the main market is COMEX in New York. To be traded on a major market, the metal has to reach an agreed purity, usually at least 99.9%.

Ecological impact H

Silver is used in the foods of many cultures as a colouring agent and in thin-leaf form. Silver is not toxic but some of the compounds are. The main risk to the environment is from the use of cyanide in some mine processes.

Processing M

Silver is primarily produced as a by-product of copper from anode slimes in electrolytic refining. Silver can also be recovered from some lead concentrates by adding zinc to produce a zinc-silver float from which the zinc can be driven off by heat.

Ag 47

Supply interruption indicators

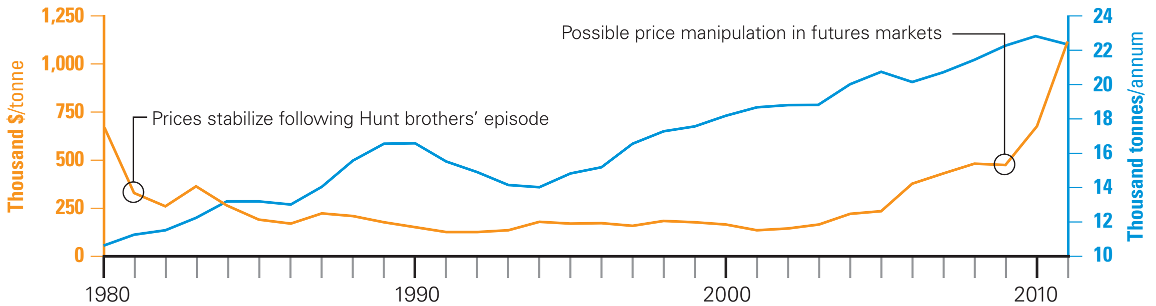
Reserves	M
Trade	L
Ecological impact	H
Processing	M
Substitutability	L
Recyclability	M
Reserves-to-production ratio	23

Substitutability L

Silver has experienced a classic case of substitution, as digital photography has overwhelmed traditional forms. Use in medical appliances, primarily in silver alloy catheters and tracheal tubes, could be met by tantalum and titanium. Lithium-ion batteries are taking the place of silver-based batteries in many applications. The use of silver in coins and jewellery could, of course, be completely substituted, but the public worldwide seems increasingly attracted to silver jewellery. Copper is beginning to be used as an alternative to silver in crystalline-silicon solar cells.

Recyclability M

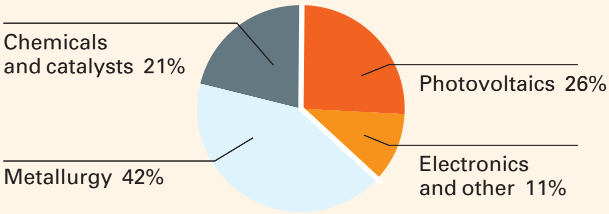
Global recycling rates are estimated to be around 10% of the total gross silver demand, according to the 2013 United Nations Environment Programme report on metals recycling. The recycling efficiency is very high and can achieve up to 98%, depending on the selection and preparation of the products. Logistics to gather the products remains the decisive factor for recycling. Jewellery, coinage, catalysts and electronics are natural contenders for recycling. Sadly, some historical film libraries have also been sold off for their scrap silver value.



PRICE & PRODUCTION

Tellurium Te 52

When combined with cadmium, tellurium is the most promising material for thin-film PV production.



Uses in the energy sector

Tellurium, when combined with cadmium (CdTe), has shown great promise as a material for producing high-efficiency thin-film PV cells. Efficiencies of up to 13% are being achieved in commercial products, with more than 19% cell efficiency reported in laboratory settings. CdTe can offer low production. The US-based company First Solar uses CdTe as its prime PV technology and this accounted for about 5% of the global market in 2012.

Uses outside the energy sector

The main use of tellurium is as an additive to metals, especially in steel and with copper, to improve machinability. The next biggest application is found in chemicals and catalysts, which is declining because of recent price increases of tellurium.

Tellurium is used as a vulcanizing agent and as an accelerator in the processing of rubber, in catalysts for synthetic fibre production, and as an additive in lubricants. Other applications include the use of tellurium in blasting caps and as a pigment to produce blue and brown colours in ceramics and glass.

Emerging technologies, including Blu-Ray discs and thermoelectric coolers in thermal imagers and solar cells that use the Peltier solid state cooling effect, are providing new demands for high-purity tellurium in alloys.

Properties and origins

Melting point 450°C
Density 6.25g/cm3

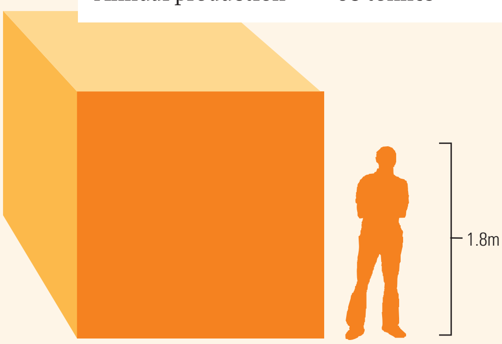
Tellurium belongs to a small group of elements that are referred to as metalloids. It is stable, silver-white, brittle and has a metallic lustre. It is a semiconductor, showing great electrical conductivity in certain directions. When exposed to light, that conductivity increases slightly.

Tellurium is one of the rarest elements in the earth's crust, averaging 0.005ppm. Although it has been found native, it is usually in the form of tellurides formed with metals, including gold and copper. The majority of annual production of tellurium results from refining of the sludges, which accumulate in the electrowinning of copper.

Tellurium has the property, unique among the elements, of causing the skin and breath of people who have absorbed it to smell of garlic. This occurs in miners extracting tellurium-rich gold veins.

Production and price

Annual production* ~ 80 tonnes



Key producers 2012	Annual production 2012*		Reserves	R/P
Country	Tonnes	%	Tonnes	
Japan	35	44	n/a	n/a
Russia	35	44	n/a	n/a
Canada	10	13	800	80
Other	n/a	n/a	23,100	n/a
World	**~ 80**		**n/a**	**n/a**
Company**				
n/a	n/a	n/a	n/a	n/a

* Production and reserves figures are incomplete, as no reliable data is available.
** Reliable company data not available.

Sustainability

Supply interruption indicators

Reserves	M
Trade	M
Ecological impact	L
Processing	H
Substitutability	M
Recyclability	M
Reserves-to-production ratio	n/a

Reserves — M

The production and reserves estimates for tellurium are closely tied to copper, from which it is mainly produced. It is thought that the recovery rates of tellurium, from the residues of electrowinning, could be increased for some ore types. Other copper extraction processes, however, that are becoming more common for particular ores, do not capture tellurium. Research is being carried out into other sources, such as some gold and lead sulphide ores, where tellurium is known to occur in higher concentrations. Production from these latter sources is being raised, especially when high gold prices increase demand. In its 2012 annual report, the Swedish mining company Boliden announced that it had brought a new gold and tellurium mine onstream capable of producing 40 tonnes per annum and that it has already agreed a long-term supply agreement with an unnamed party. Also in 2012, it was reported that First Solar had invested in starting its own mine in Mexico; this is despite the fact that Mexico is not listed by the USGS as having reserves.

In general, production figures are extremely difficult to obtain and the tellurium required in the annual production of CdTe alone is thought to exceed the production figures quoted by USGS. Supply will be a major constraint on growth in the use of tellurium.

Trade — M

The rising demand for tellurium caused by the growth in PV production has exposed the potential for supply deficit. Estimates see the demand for tellurium required in PV as equal to about the annual primary production, i.e. excluding recycling. Accurate and reliable data is not available. In this context the market share of CdTe systems has to be kept in mind. This is in the order of 5% with a cumulative global installed share of less than 7% (2011). Tellurium is not traded on any of the major commodity exchanges.

Ecological impact — L

Tellurium is generally considered toxic, but the general population is unlikely to be exposed to it.

Contact during production does include both the hazard of malodorous sweat and breath mentioned earlier and gastrointestinal problems.

Processing — H

More than 90% of tellurium is produced from anode slimes collected from electrolytic copper refining, and the remainder is derived from skimmings at lead refineries and from flue dusts and gases generated during the smelting of bismuth, copper and lead ores. In copper production, tellurium is recovered only from the electrolytic refining of smelted copper.

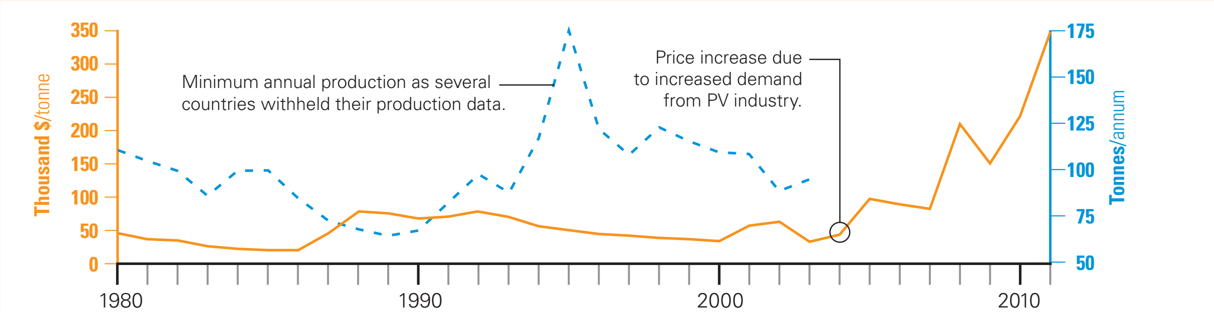
Substitutability — M

A substitute for the Te in CdTe cells is not known; however, other PV systems based on other elements such as silicon thin-film and CIGS could be used.

Apart from its use in CdTe cells, several materials can replace tellurium in most applications, but usually with losses in production efficiency or product characteristics.

Recyclability — M

Small amounts of tellurium are recovered during the manufacture of tellurium-bearing electronics, but the percentage of recycling is low because the majority of the use, to date, has been dissipative. In the future, CdTe PV cells will be recyclable and the quantities recovered should, therefore, increase from the current 7% level. Recycling, however, will only be substantial in about 20 years' time, when the first solar cells will reach their end-of-life.

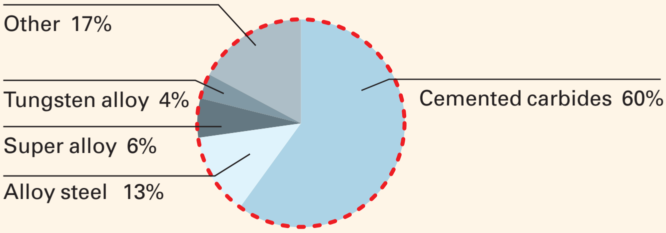


PRICE & PRODUCTION*

*Production figures are incomplete, as no reliable data is available.

Tungsten W 74

An essential and irreplaceable industrial element dominated by Chinese production and reserves.



Uses in the energy sector

The most widely used form of tungsten is the carbide, formed by reacting the metal as a powder with pure carbon powder at high temperatures. Tungsten carbide is extremely hard and is formed into a vast range of cutting and grinding tools, without which drilling and cutting operations in oil and mining would be severely restricted. Thirty per cent of tungsten carbide is used in mining and 20% in the oil industry. Tungsten alloys fulfil vital roles in high-temperature refinery furnaces and in industrial turbines, where the metal's outstanding strength when hot is invaluable. They are also used in high-voltage electrical circuits for contact breakers and as heat sinks in electronic applications. The once-familiar use as the elements of incandescent light bulbs is declining as energy-efficient types replace them.

Uses outside the energy sector

In common with its use in the energy sector, tungsten carbide is invaluable as a hard material from which to form tools and instruments. Tungsten alloys have a wide range of applications and are used where their extreme strength, thermal and electrical conductivities and resistance to wear are needed. Tungsten is also used as the basis for specialized pigments. In the Second World War, the allies were estimated to have more than 15,000 uses for tungsten, including armour plate and armour-piercing ammunition.

Properties and origins

Melting point 3,407°C
Density 19.26g/cm3

Tungsten is a grey-white metal with the highest melting point of any metal, the lowest coefficient of expansion and one of the highest densities, similar to uranium or gold. It also has high electrical and thermal conductivity. Its density gave rise to its name, tungsten or 'heavy stone'.

In the earth's crust, the element averages around 1.2ppm. It does not occur as a native metal and is found in a variety of oxide minerals, where the metal can reach concentrations of between 0.1% and 1% tungsten trioxide. The commonest ore mineral is scheelite, $CaWO_4$, known for emitting a range of fluorescent colours under UV light. All tungsten deposits are associated with granitic intrusions or medium-to-high grade metamorphic rocks usually found in subduction-related orogenic belts.

Examples of major deposits can be found in orogenic belts of the Far East, particularly China, as well as southern Siberia, Kazakhstan, the Caucasus, the Alps, the Rockies and the Andes. Weathering of tungsten mineral-bearing rocks can result in placer and even evaporite deposits.

Mining methods are, of course, chosen to suit the style of mineralization and range from open pit, for large near-surface stockworks, through to dredging for placer recovery, and stoping and block caving for deep deposits. Run-of-mine material is normally comminuted and then concentrated by froth flotation, gravity, magnetic or electrostatic methods, depending on the ore composition. Concentrates of tungsten minerals can be added directly to some steelmaking processes or tungsten metal can be produced from concentrates, by a number of leaching and oxidizing processes.

Production and price

Annual production 73,000 tonnes

Key producers 2012	Annual production 2012		Reserves	R/P
Country	Tonnes	%	Tonnes	
China	62,000	85	1,900,000	31
Russia	3,500	5	250,000	71
Canada	2,000	3	120,000	60
Others	5,500	8	930,000	169
World	**73,000**		**3,200,000**	**44**
Company*				
n/a	n/a	n/a	n/a	n/a

* Reliable company data not available.

Sustainability

Supply interruption indicators

Reserves	H
Trade	H
Ecological impact	L
Processing	L
Substitutability	M
Recyclability	L

Reserves-to-production ratio **44**

Reserves H

As of 2011, the USGS quotes the known reserves of tungsten to be just less than 3 million tonnes and China is thought to hold two-thirds of those. Russia has significant reserves and Kazakhstan is believed also to be rich in tungsten. Production is dominated by China, with more than 85% of the global production in 2010.

The recent financial crisis stopped the development of a number of mines, but there are exciting discoveries that, when in operation, could ease the monopolistic position that China holds. Most prominent among these is a high-grade metamorphic deposit in Western Australia that is due to come onstream in 2013 and produce approximately 7% of the world's tungsten.

In addition to being the world's largest producer, China is also the largest consumer and the government has recently been controlling exports.

Trade H

Tungsten is traded in a variety of forms, chiefly as ores and concentrates. Because China restricts exports, the biggest exporters are Russia, Canada and Bolivia. The increase in demand for the metal, especially in China, has driven prices higher in the past few years, with a doubling between 2004 and 2010. The fear of a shortage has caused the EU to classify tungsten as a critical raw material. Tungsten is not traded on any of the major commodity exchanges.

Ecological impact L

Tungsten is an essential element for some bacteria and is the heaviest element used by any living organism. The metal toxicity is low, but some forms may be mobile in the environment and may inhibit certain plant and animal functions. It is known to be hazardous to humans when exposed to large amounts of tungsten dust particles.

Processing L

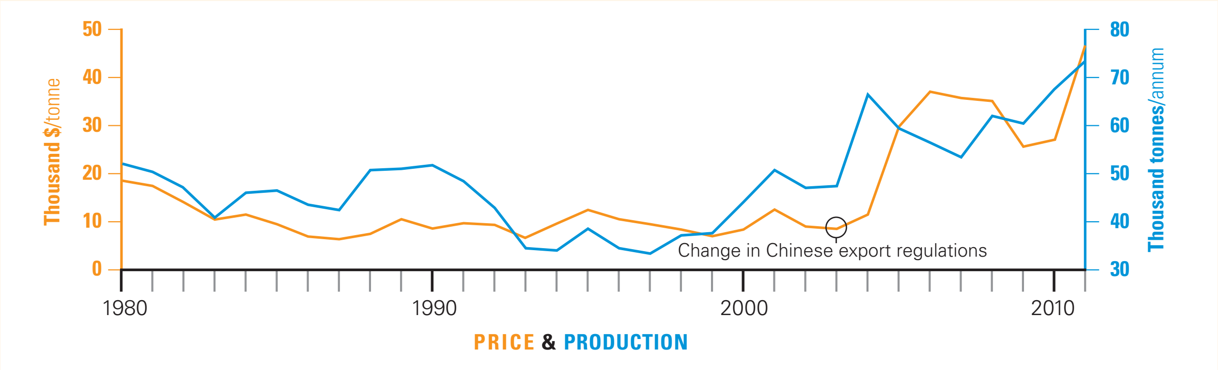
Unlike many metals, tungsten can be processed from concentrate near to the point of end use, for example, in specialist steel manufacturers. There are not thought to be any serious constraints caused by lack of processing capacity.

Substitutability M

Because of tungsten's unique range of properties, the possibilities of substitution are small, especially where performance at high temperatures is critical. Tungsten carbide can be replaced by diamond tools with additional cost, or a small variety of other metal carbides with reduced performance. Molybdenum alloys can substitute for some tungsten steels and depleted uranium can replace the metal in counterweights or armour-piercing ammunition, where health and environmental concerns can be overcome.

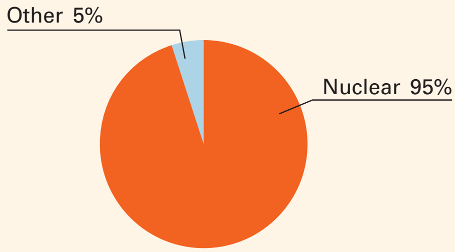
Recyclability L

Tungsten is among the most highly recycled of all metals, at a rate of between 30% and 40%. The metal is lost when used in carbide forms and in chemical applications, but alloys and steels can be recycled.



Uranium U 92

A true energy material. A single element providing 11% of the world's electricity.



Uses in the energy sector

By far the most significant end use of uranium is as a fuel for nuclear reactors and the vast majority of those are providing steam for electricity generation. As of July 2011, there were 440 nuclear reactors producing electricity in the world, 61 under construction, 154 planned and 343 proposed. Electricity production from nuclear reactors totalled 2,630 billion kWh in 2010.

The navies of the US, Russia, China, France and the UK have used uranium-fuelled reactors to power surface ships and submarines since the 1960s. A small number of civilian ships have been powered by reactors including a handful of nuclear-powered icebreakers.

Uses outside the energy sector

In the 19th century, uranium was used as a colouring agent for glass and ceramics, providing a range of vibrant reds, oranges and yellows.

Use in the manufacture of domestic items stopped when the toxicity of uranium was recognized but, since the advent of the nuclear age, new uses have emerged. Depleted uranium, the residue left when the isotope U235 has been extracted for civil or military applications, is used as ballast in planes and yachts, as a shield for nuclear reactors and, controversially, as armour-piercing ordnance. It is impossible to gain accurate statistics on these uses.

Properties and origins

Melting point 1,132°C
Density 18.97g/cm3

Uranium is a very dense metal that is radioactive. At 2.4ppm, it is a fairly common element of the crust but is never found in its native form, because it is highly reactive and soluble. There are several naturally occurring isotopes of the element, with U238 representing some 99.3% of the naturally occurring minerals. Approximately 0.7% of natural uranium is the fissile isotope U235.

There are more than 200 known uranium minerals, but only 10 economic varieties, with oxides being the most important. Uranium is initially concentrated in minerals within both granitic and volcanic rocks. The element is readily released from these rocks due to its solubility and is further concentrated as uranium-rich minerals fall out of solution.

The richest deposits in the world occur at unconformities, where hot metal-bearing fluids, rising from intrusive rocks, encounter reducing conditions. Some of these deposits have grades averaging 5,000ppm and locally 200,000ppm. Sandstones provide a number of settings where reducing conditions cause uranium-rich fluids from nearby granitic or volcanic rocks to be deposited, producing grades averaging between 400ppm and 4,000ppm.

Production and price

Annual production* 58,394 tonnes

Key producers 2012	Annual production 2012*		Reserves	R/P
Country	Tonnes	%	Tonnes	
Kazakhstan	21,317	37	629,000	30
Canada	8,999	15	468,700	52
Australia	6,991	12	1,661,000	238
Others	21,087	36	2,568,500	122
World	**58,394**		**5,327,200**	**91**
Company				
KazAtomProm	8,863	15	n/a	n/a
Areva	8,641	15	n/a	n/a
Cameco	8,437	14	n/a	n/a

*U_3O_8 – triuranium octoxide

Sustainability

U 92

Supply interruption indicators

Reserves	L
Trade	M
Ecological impact	H
Processing	L
Substitutability	H
Recyclability	L
Reserves-to-production ratio	91

Reserves L

Approximately 90% of uranium is mined as a prime ore, with the style and scale of the mining varying widely to reflect the variety of deposit type. Open-pit and underground mines have been joined by in-situ leaching, which, in 2009, accounted for some 36% of production. Leaching can only be used in deposits where the mineral is hosted by porous and permeable rocks, mainly sandstones. Depending on the rock chemistry, either acid or alkali solutions are pumped into the mineralized formation through wells. The solution dissolves the uranium minerals and is then recovered through a further set of wells. At the surface, the mineral is removed from the solution, which is then re-injected for further work.

In both open-pit and, particularly, in underground mines, exposure to high-grade radioactive minerals has to be avoided, and mechanization and automation is increasingly being used. At McArthur River in Canada, the world's largest uranium mine, much of the extraction, loading and milling is carried out using systems that are controlled remotely.

In recent years, demand has risen faster than supply from mines and the shortfall has been met by material recycled from nuclear weapons. The move to lower-carbon electricity has renewed interest in nuclear power and demand is set to remain strong worldwide despite the reservations expressed by many after the Fukushima event in March 2011.

Trade M

Although the reserves of uranium are not overly concentrated geographically, the control of the mining and processing operations is in the hands of a small number of companies, and processing into useable fuel in the hands of even fewer. There are only eight companies worldwide that are involved in commercial-scale conversion.

Uranium is not traded through organized commodity markets but mainly through private contracts. More than 85% of contracts are believed to be long term, three to 10 years, but there is a small spot market. To enhance the security of supply, a trend has emerged whereby utilities buy uranium from different suppliers across the processing chain, from mine, through to mills and enrichment plants and, finally, fuel rod manufacturers.

For mainly historical and political reasons, trade has developed into two distinct markets: (i) the Western world and (ii) Russia, the former Soviet Union countries and China.

Ecological impact H

In addition to its radioactivity, uranium presents a toxic hazard. It is readily absorbed by plants and animals and is known to affect many organs and the immune system. Exposure can be limited by tight controls on mining, on processing and use in the energy sector. However, recent tragic events in Japan show that controls can be breached when affected by natural phenomena, such as a tsunami.

Depleted uranium ordnance also remains controversial.

Processing L

Comminution of oxide ores is followed by leaching in hot acids. Precipitation results in a concentrate of up to 80% uranium oxide, often referred to as 'yellowcake'. The waste materials, or tailings, need to be stored in isolation from the environment, because they are still radioactive.

To produce useful fuel from yellowcake, the U235 content needs to be enriched from approximately 0.7% to between 2% and 5%. This involves a complex series of chemical and physical processes that are undertaken in a very small number of plants around the world. The residual material from these processes is depleted uranium. Fortunately, the steps needed to produce weapons-grade uranium are even more dependent on specialist equipment. The manufacturers of such equipment are monitored by international regulators and, therefore, it is known which countries are involved or plan to be involved in such work.

Substitutability H

At present, uranium is the main fuel supplied to nuclear reactors. Mixed oxide fuel, made from reprocessed plutonium and uranium, is an alternative supplying around 2% of the nuclear fuel used today and thorium could be utilized as a fuel in reactors built especially for it. The latter has been done with demonstration plants in the past, but it is not yet happening on a commercial scale. Given the known resources of the element, thorium could prove attractive in the future.

Recyclability L

Uranium is a widely but controversially recycled material. Fuel from reactors is reprocessed to recover unused U235, which is reformed into new fuel rods and returned for use in power generation. Some 2,000 tonnes per annum of uranium is sourced by this route. As countries agree to reduce their stocks of nuclear weapons, these have become a major source of recycled uranium, supplying up to 15% of the world's civil requirements.

Note: A price and production graph could not be plotted as no reliable data is available.

Vanadium V 23

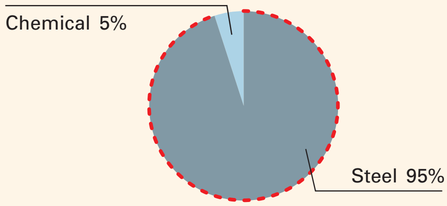
Key to a potential revolution in energy storage technology.

Uses in the energy sector

Apart from its role as an alloying agent in specialist steels that are formed into components and tools across most energy pathways, vanadium has had little use to date in the energy sector. This, some commentators believe, is about to change as vanadium-redox batteries (VRBs) may become an essential key to fulfilling the vision of a fully decarbonized electricity system. One of the recurring barriers to optimizing the deployment of solar, wind and wave generation is the difficulty of storing energy when these systems are working, so that it can be used at night or when wind speeds are low.

Vanadium batteries exploit the fact that the metal has multiple oxidation states. Batteries consist of two tanks filled with electrolyte, liquids that conduct electricity, in which vanadium ions float, one for each ionic state. When the two liquids are mixed, a chemical reaction causes the ions to change their charge and electricity is created. The battery is charged by passing electricity through it, thus restoring the original charge of the vanadium ions. The electrolytes are pumped back to the storage tank for storage, until they are needed again to produce electricity.

Vanadium batteries have no theoretical storage limit (this depends on the size of the tanks for the electrolytes)



and their performance does not decrease as they are repeatedly charged and discharged. Early versions suffered from the need to be cooled, which reduced efficiency and restricted the operating window, but research published in March 2011 by the US Department of Energy suggests that new formulation of the electrolytes will overcome this limitation. Scaling up and commercial viability has to be demonstrated yet, because the main VRB developer (VRB Power) filed for bankruptcy in 2009.

Vanadium is also used in the cathodes of some lithium-ion batteries and this use may increase dramatically.

Uses outside the energy sector

Vanadium is a commonly used alloying agent in steels, familiar to anyone who has ever used a modern set of spanners. An early advocate of vanadium was Henry Ford, who promoted the lighter steels containing the metal for use in his iconic Model T. Vanadium also has uses as a catalyst in the chemical industry and in ceramic manufacture.

Properties and origins

Melting point 1,890 °C
Density 6.09gm/cm³

Vanadium is a relatively low-density, soft and ductile silvery-grey metal. When exposed to air, a rapidly forming oxide layer stops it corroding. Adding it to steel increases the strength and hardness, leading to the manufacture of lighter, longer-lasting components, such as crankshafts. Typically, steel alloys contain 1–4% vanadium.

The element, which at about 160ppm is not rare in the crust, does not occur native but is found in some 65 minerals. Vanadium was first isolated in the early 19th century by the Spanish mineralogist, Andres Manuel del Rio, from the lead chlorovanadate, vanadinite.

Some deposits of magnetite, a common oxide of iron, are often rich in vanadium and the slags resulting from smelting such ores are a major source. The metal is also found in significant quantities in carbonaceous deposits, including coal and oil. Some crude oils are reported to contain up to 1,200ppm and it is possible that, in the future, the metal could be extracted in quantity from residues in refineries or from power station ash. According to the trade body, VANITEC, vanadium was recovered from the Alberta tar sands in the 1990s and could become an economically viable source in the future.

Production and price

Annual production 63,000 tonnes

Key producers 2012	**Annual production 2012**		**Reserves**	**R/P**
Country	Tonnes	%	Tonnes	
China	23,000	37	5,100,000	222
South Africa	22,000	35	3,500,000	159
Russia	16,000	25	5,000,000	313
Others	2,000	3	400,000	200
World	**63,000**		**14,000,000**	**222**
Company*				
EVRAZ	n/a	n/a	n/a	n/a
Xstrata Rhovan	n/a	n/a	n/a	n/a
Panzhihua	n/a	n/a	n/a	n/a

* Known to be companies with largest production.

Supply interruption indicators

Reserves	M
Trade	H
Ecological impact	H
Processing	L
Substitutability	M
Recyclability	L
Reserves-to-production ratio	222

Sustainability

Reserves — M

The production and reserves of vanadium are dominated by just three countries: China, Russia and South Africa. The reserves figures quoted by the USGS suggest an adequate supply for many years, based on current production rates, but a rapid increase in demand could be constrained by lack of capacity or export restrictions by producing countries, especially China.

A guide to the possible rise in demand is provided by scaling up the quoted storage capacity of vanadium-redox batteries at around 20 watt-hours per litre of electrolyte, to the size of battery required to be useful in a wind farm application. A battery capable of storing eight hours of output from a typical three megawatt wind installation, i.e. 24 megawatt-hours, would need more than 240 tonnes of vanadium. If the predictions about the growth in the use of lithium-ion batteries with vanadium cathodes are taken into account, as well as the continued rise in the use of vanadium in steels, demand could well exceed supply in the near future.

Trade — H

Trade is controlled by a small number of large companies, such as the Russia-based Evraz Corporation, which provides vanadium to meet more than 20% of the world's demand, and Panzhihua of China, controlled by the Hebei Iron & Steel Group. Neither of these companies provides readily accessible production data.

Ecological impact — H

Vanadium is an essential trace element in humans and some organisms, particularly fish, naturally concentrate the element, but the compounds are universally regarded as toxic. The main route into the environment is unintentional, through flue gases from coal- and oil-fired power stations.

Processing — L

Vanadium from the magnetite ores of China and Russia, and a large proportion of the vanadium from the magnetite ore in South Africa, is extracted as a co-product with iron, which is converted to steel. The iron from these operations contains about 1.5% vanadium, which is removed as slag by low-temperature treatment with oxygen.

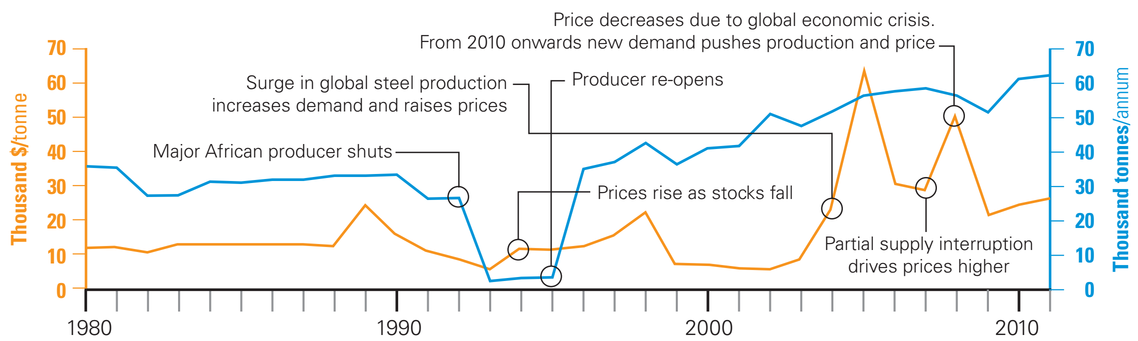
In those refineries that process vanadium-rich crude oil, especially in Venezuela, the metal is recovered from cokes that form as a refining residue. A similar process is used at power stations that burn vanadium-bearing fuels. In some cases, the vanadium-rich ash is added to feedstock of steelmaking processes and recovered along with the vanadium originally present in the magnetite ore.

Substitutability — M

Except for vanadium's use in titanium alloys for the aerospace industry, its substitution is to some degree possible. However, possible substitutes do not have the same characteristics and are themselves similarly critical: manganese, molybdenum, niobium, titanium and tungsten. In redox-flow batteries, vanadium can only be substituted with a loss of efficiency. Possible substitutes are zinc-bromine-flow batteries and potential new technologies based on iron-chromium or zinc-cerium.

Recyclability — L

Recycling of vanadium is possible, but the actual percentage of recycled metal is small. Vanadium is primarily recycled from tool steel scrap and from spent chemical process catalysts. Usually, vanadium is lost during the recycling process.



PRICE & PRODUCTION

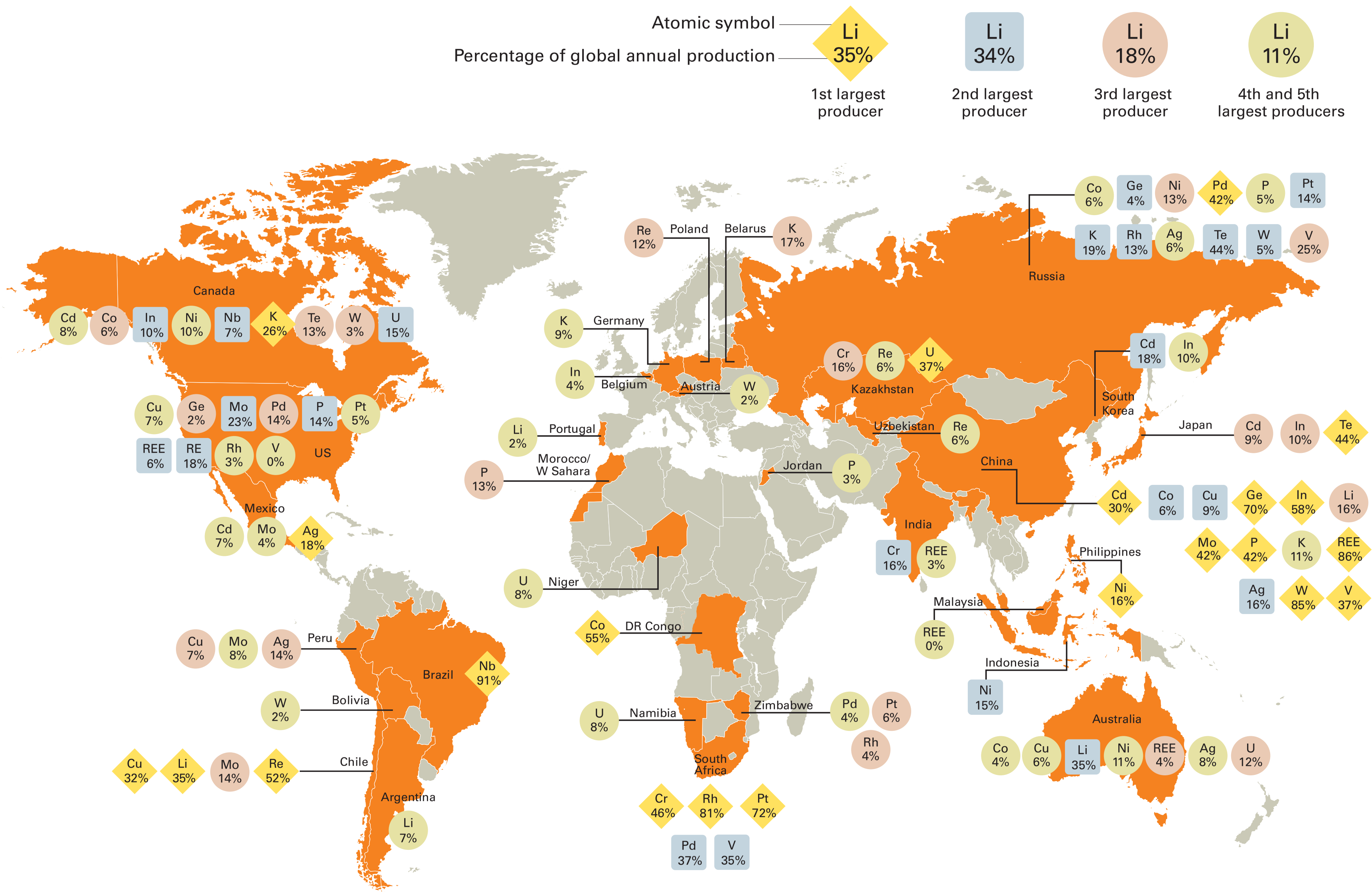
Materials data and references

Annual **production** 2012 in tonnes with percentages of world total

Materials	World	Argentina	Australia	Austria	Belarus	Belgium	Bolivia	Brazil	Canada	Chile	China	DR Congo	Germany	India	Indonesia	Japan	Jordan	Kazakhstan	Malaysia	Mexico	Morocco/ W Sahara	Namibia	Niger	Peru	Philippines	Poland	Portugal	Russia	South Africa	South Korea	USA	Uzbekistan	Zimbabwe
Cd Cadmium	23,000								1,780 8%		7,000 30%					2,130 9%				1,610 7%										4,100 18%			
Cr* Chromium	24M													3.8M 16%				3.8M 16%											11M 46%				
Co Cobalt	110,000		4,500 4%						6,700 6%		7,000 6%	60,000 55%																6,200 6%					
Cu Copper	17M		970,000 6%							5.37M 32%	1.5M 9%													1.24M 7%							1.15M 7%		
Ga Gallium	273										n/a		n/a					n/a															
Ge Germanium	128										90 70%																	5 4%			3 2%		
In Indium	670					30 4%			70 10%		390 58%					70 10%														70 10%			
Li Lithium	37,000	2,700 7%	13,000 35%							13,000 35%	6,000 16%																820 2%						
Mo Molybdenum	250,000									35,300 14%	105,000 42%									10,900 4%				19,500 8%							57,000 23%		
Ni Nickel	2.1M		230,000 11%						220,000 10%						320,000 15%										330,000 16%			270,000 13%					
Nb Niobium	69,000							63,000 91%	5,000 7%																								
Pd Palladium	195																											82 42%	72 37%		28 14%		8 4%
P** Phosphorus	210M										89M 42%						6.5M 3%				28M 13%							11.3M 5%			29.2M 14%		
Pt Platinum	176																											25 14%	127 72%		9 5%		11 6%
K*** Potassium	34M				5.65M 17%				9M 26%		3.9M 11%		3M 9%															6.5M 19%					
REE Rare earth elements	110,000		4,000 4%								95,000 86%			2,800 3%					350 0%												7,000 6%		
Re Rhenium	52									27 52%								3 6%								6 12%					9 18%	3 6%	
Rh Rhodium	22																											2 13%	18 81%		1 3%		1 4%
Ag Silver	24,000		1,900 8%								3,800 16%									4,250 18%				3,450 14%				1,500 6%					
Te† Tellurium	80‡								10 13%							35 44%												35 44%					
W Tungsten	73,000			1,100 2%			1,100 2%		2,000 3%		62,000 85%																	3,500 5%					
U Uranium	58,394		6,991 12%						8,999 15%									21,317 37%				4,495 8%	4,667 8%										
V Vanadium	63,000										23,000 37%																	16,000 25%	22,000 35%		270 0%		

*Marketable chromite ore. ** Phosphate. *** K_2O equivalent. † Refinery production. M = Million. n/a = No reliable data available. ‡ Withheld data, actual world production larger.

Top producing countries



Reserves percentages of world total and reserves-to-production ratios (R/P)

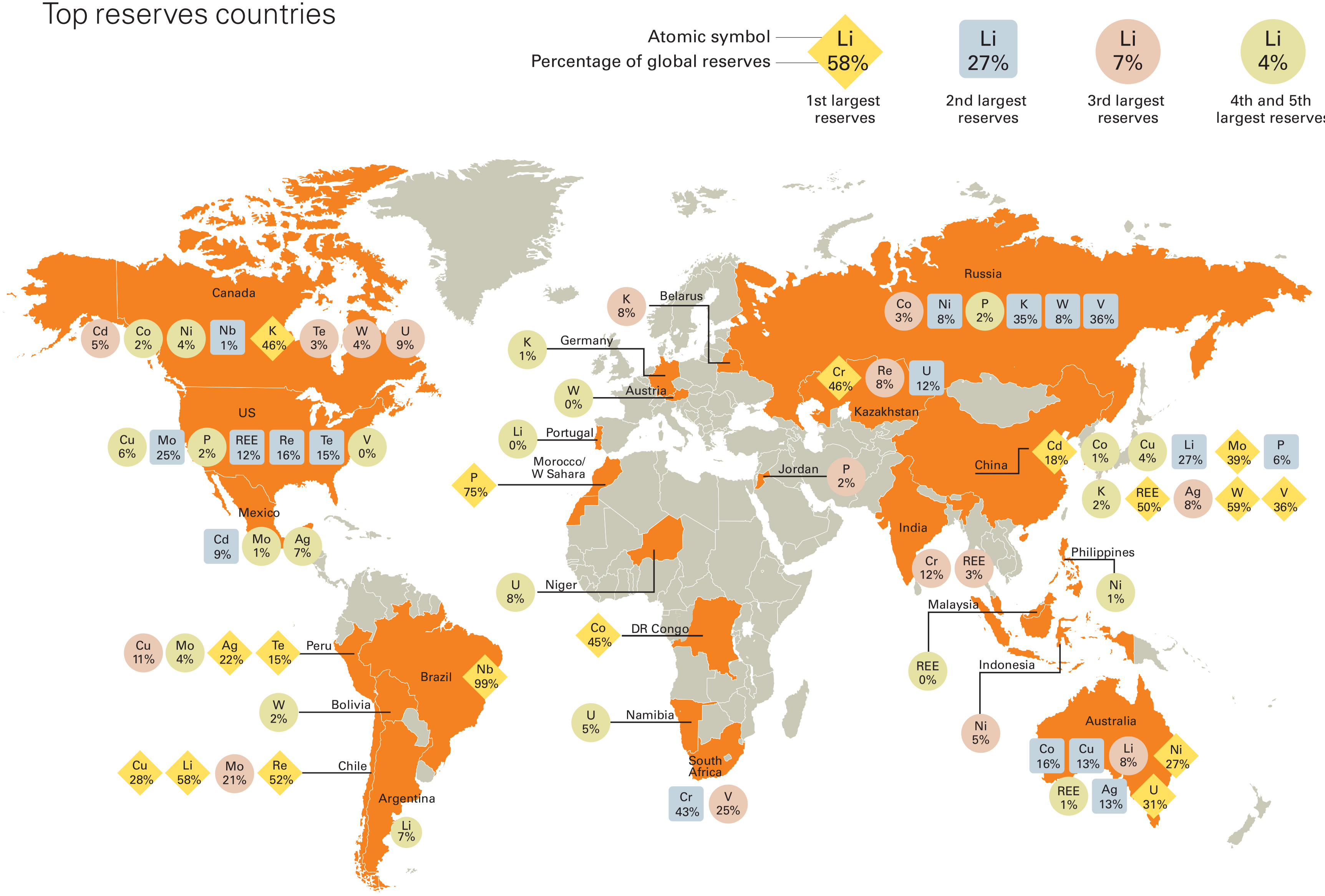
R/P is calculated for each country according to its annual production and reserves.

Materials	Global reserves (tonnes)	Argentina	Australia	Austria	Belarus	Belgium	Bolivia	Brazil	Canada	Chile	China	DR Congo	Germany	India	Indonesia	Japan	Jordan
Cd Cadmium	500,000								5% 13		18% 13					n/a	
Cr* Chromium	460M													12% 14			
Co Cobalt	7.5M		16% 267						2% 21		1% 11	45% 57					
Cu Copper	680M		13% 89							28% 35	4% 20						
Ga Gallium	n/a										n/a		n/a				
Ge Germanium	n/a										n/a						
In Indium	n/a					n/a			n/a		n/a					n/a	
Li Lithium	13M	7% 315	8% 77							58% 577	27% 583						
Mo Molybdenum	11M									21% 65	39% 41						
Ni Nickel	75M		27% 87						4% 15						5% 12		
Nb Niobium	>4M							99% n/a	1% n/a								
Pd Palladium	n/a																
P** Phosphorus	67BN										6% 42						2% 231
Pt Platinum	n/a																
K*** Potassium	9.5BN				8% 133				46% 489		2% 54		1% 47				
REE Rare earth elements	110M		1% 400								50% 579			3% 1107			
Re Rhenium	2,500									52% 48							
Rh Rhodium	n/a																
Ag Silver	540,000		13% 36								8% 11						
Te† Tellurium	24,000								3%							n/a	
W Tungsten	3.2M			0% 9			2% 48		4% 60		59% 31						
U Uranium	5.3M		31% 238						9% 52								
V Vanadium	14M										36% 222						

Materials	Global reserves (tonnes)	Kazakhstan	Korea	Malaysia	Mexico	Morocco/ W Sahara	Namibia	Niger	Peru	Philippines	Poland	Portugal	Russia	South Africa	USA	Uzbekistan	Zimbabwe
Cd Cadmium	500,000		n/a		9% 29												
Cr* Chromium	460M	46% 55												43% 18			
Co Cobalt	7.5M												3% 40				
Cu Copper	680M								11% 61						6% 34		
Ga Gallium	n/a	n/a															
Ge Germanium	n/a												n/a		n/a		
In Indium	n/a		n/a														
Li Lithium	13M											0% 12					
Mo Molybdenum	11M				1% 12				4% 23						25% 47		
Ni Nickel	75M									1% 3			8% 23				
Nb Niobium	>4M																
Pd Palladium	n/a												n/a	n/a	n/a		n/a
P** Phosphorus	67BN					75% 1786							2% 115		2% 48		
Pt Platinum	n/a												n/a	n/a	n/a		n/a
K*** Potassium	9.5BN												35% 508				
REE Rare earth elements	110M			0% 86											12% 1857		
Re Rhenium	2,500	8% 63									n/a				16% 41	n/a	
Rh Rhodium	n/a												n/a	n/a	n/a	n/a	
Ag Silver	540,000				7% 9				22% 35				n/a				
Te† Tellurium	24,000								15%				n/a		15%		
W Tungsten	3.2M												8% 71				
U Uranium	5.3M	12% 30					5% 58	8% 90									
V Vanadium	14M												36% 313	25% 159	0% 167		

*Marketable chromite ore. ** Phosphate. *** K_2O equivalent. † Refinery production. M=Million. BN=Billion. n/a = No reliable data available.

Top reserves countries



Elements, for which no reliable reserves data are available, are not depicted on the map, as ranking not possible.

Materials comparison 2012 data

Materials	Atomic number	Atomic weight (g/mol)	Melting point (°C)	Boiling point (°C)	Density (g/cm³)	Composition of the upper continental crust (ppm)	Toxicity and other impacts	Annual production (tonnes)	Reserves (tonnes)	R/P (years)	$/tonne (latest figure 2011)	Dissipation †	Recycling today †	Recycling potential †	Producing countries	Producing companies
Data source/ notes		Merck PSE	Merck PSE	Merck PSE	Merck PSE	Rudnick & Gao 2003		USGS MCS 2013	USGS MCS 2013	Calculated	USGS 140 series	Risk	Status	Potential	Share of top 3 (2012)	Share of top 3 (2012)
Cd Cadmium	48	112.41	321	765	8.64	0.09	Toxic	23,000	500,000	22	2,760	Orange	Orange	Green	58	n/a
Cr Chromium	24	52.00	1,857	2,672	7.14	92	Chromium VI toxic	24M	460M	19	2,680	Green	Green	Green	78	n/a
Co Cobalt	27	58.93	1,495	2,870	8.89	17.3	Mildly toxic	110,000	7.5M	68	36,100	Green	Green	Green	67	34
Cu Copper	29	63.55	1,083	2,567	8.92	28	Mildly toxic	17M	680M	40	8,950	Green	Green	Green	48	34
Ga Gallium	31	69.72	30	2,403	5.91	17.5	Mildly toxic	273	n/a	n/a	688,000	Orange	Orange	Green	n/a	n/a
Ge Germanium	32	72.64	937	2,830	5.32	1.4	Mildly toxic	128	n/a	n/a	1,450,000	Orange	Green	Green	77	n/a
In Indium	49	114.82	156	2,080	7.31	0.056	Unknown (treat with caution)	670	n/a	n/a	720,000	Orange	Orange	Green	79	n/a
Li Lithium	3	6.94	181	1,347	0.53	24	Corrosive and flammable	37,000	13M	351	3,870	Orange	Orange	Green	86	n/a
Mo Molybdenum	42	95.94	2,617	4,612	10.28	1.1	Carcinogenic	250,000	11M	44	34,100	Green	Green	Green	79	30
Ni Nickel	28	58.69	1,453	2,732	8.91	47	Mildly toxic and carcinogenic	2.1M	75M	36	22,890	Orange	Green	Green	44	35
Nb Niobium	41	92.91	2,468	4,742	8.58	12	Unknown (treat with caution)	69,000	>4M	58	n/a	Green	Green	Green	99	100
Pd Palladium	46	106.42	1,552	3,140	12.02	0.00052	Corrosive and flammable	203**	66,000	n/a	23,729,652**	Orange	Orange	Orange	93	81
P Phosphorus	15	30.97	44	280	1.82	1,500	White P toxic and flammable	210M	67BN	319	97	Red	Red	Orange	69	22
Pt Platinum	78	195.08	1,772	3,827	21.45	0.0005	None	176**	66,000	363	45,626,526**	Orange	Orange	Orange	92	80
K Potassium	19	39.10	64	774	0.86	28,000	Corrosive and flammable	34M	9.5BN	279	709	Red	Red	Orange	62	73
Re Rhenium	75	186.21	3,180	5,627	21.03	0.000198	None	52	2,500	48	4,670,000	Orange	Orange	Orange	81	>50
Rh Rhodium	45	102.91	1,966	3,727	12.41	0.0001*	Flammable	22**	66,000	n/a	33,504,468**	Red	Orange	Orange	96	94

* Binder 2008. ** Johnson Matthey 2014. M = Million. BN = Billion. † See table page 81. n/a = No reliable data available.

Materials	Atomic number	Atomic weight (g/mol)	Melting point (°C)	Boiling point (°C)	Density (g/cm³)	Composition of the upper continental crust (ppm)	Toxicity and other impacts	Annual production (tonnes)	Reserves (tonnes)	R/P (years)	$/tonne (latest figure 2011)	Dissipation †	Recycling today †	Recycling potential †	Producing countries	Producing companies
Data source/ notes		Merck PSE	Merck PSE	Merck PSE	Merck PSE	Rudnick and Gao, 2003		USGS MCS 2013	USGS MCS 2013	Calculated	USGS 140 series	Risk	Status	Potential	Share of top 3 (2012)	Share of top 3 (2012)
Ag Silver	47	107.87	962	2,212	10.49	0.053	None	24,000	540,000	23	1,130,000	● red	● orange	● orange	48	15
Te Tellurium	52	127.60	450	990	6.25	0.005*	Toxic	80	24,000	300	349,000	● red	● red	● orange	100	n/a
W Tungsten	74	183.84	3,410	5,660	19.26	1.9	Unknown (treat with caution)	73,000	3.2 M	44	46,700	● green	● green	● green	92	n/a
U Uranium	92	238.03	1,132	3,818	18.97	2.7	Very toxic and radioactive	58,394	5.3M	91	n/a	n/a	n/a	n/a	64	44
V Vanadium	23	50.94	1,890	3,380	6.09	97	Mildly toxic	63,000	14 M	222	26,600	● green	● green	● green	97	n/a

Rare earth elements								110,000**	110 M**	1000**	***				96**	
Sc Scandium	21	44.96	1,541	2,831	2.99	14	None	n/a	n/a	n/a	n/a	n/a	n/a	n/a	96	n/a
Y Yttrium	39	88.91	1,522	3,338	4.47	21	None	8,900	540,000	61	170,000	● red	● orange	● orange	96	n/a
La Lanthanum	57	138.91	921	3,457	6.16	31	None	n/a	n/a	n/a	69,000	● orange	● orange	● orange	96	n/a
Ce Cerium	58	140.12	799	3,426	6.77	63	None	n/a	n/a	n/a	81,000	● orange	● orange	● orange	96	n/a
Pr Praseodymium	59	140.91	931	3,512	6.48	7.1	Flammable	n/a	n/a	n/a	255,000	n/a	n/a	n/a	96	n/a
Nd Neodymium	60	144.24	1,021	3,068	7.00	27	None	n/a	n/a	n/a	275,000	● green	● orange	● green	96	n/a
Sm Samarium	62	150.36	1,077	1,791	7.54	4.7	None	n/a	n/a	n/a	150,500	n/a	n/a	n/a	96	n/a
Eu Europium	63	151.96	822	1,597	5.25	1	None	n/a	n/a	n/a	5,210,000	n/a	n/a	n/a	96	n/a
Tb Terbium	65	158.93	1,356	3,123	8.25	0.7	Toxic	n/a	n/a	n/a	4,010,000	n/a	n/a	n/a	96	n/a
Dy Dysprosium	66	162.50	1,412	2,562	8.56	3.9	None	n/a	n/a	n/a	2,760,000	● red	● red	● green	96	n/a

* Binder 2008. M = Million. BN = Billion. **REEs grouped. ***metal-pages.com, minimum 99% Freight On Board (FOB) China. † See table page 81. n/a = No reliable data available

Resource and reserve definitions adapted from USGS

Resource A concentration of naturally occurring solid, liquid or gaseous material in or on the earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.

Identified resources Resources whose location, grade, quality and quantity are known or estimated from specific geological evidence. Identified resources include economic, marginally economic and sub-economic components. To reflect varying degrees of geological certainty, these economic divisions can be subdivided into measured, indicated and inferred.

Measured Quantity is computed from dimensions revealed in outcrops, trenches, workings or drill holes; grade and/or quality are computed from the results of detailed sampling. The sites for inspection, sampling and measurements are spaced so closely and the geologic character is so well defined that size, shape, depth and mineral content of the resource are well established.

Indicated Quantity and grade and/or quality are computed from information similar to that used for measured resources, but the sites for inspection, sampling and measurement are farther apart or are otherwise less adequately spaced. The degree of assurance, although lower than that for measured resources, is high enough to assume continuity between points of observation.

Inferred Estimates are based on a presumed continuity beyond measured and/or indicated resources, for which there is geological evidence.

Undiscovered resources Resources, the existence of which is only postulated, comprising deposits that are separate from identified resources. To reflect varying degrees of geological certainty, undiscovered resources may be divided into two parts:

1 **Hypothetical resources** Discovered resources that are similar to known mineral bodies and that may be reasonably expected to exist in the same producing district or region under analogous geological conditions. If exploration confirms their existence and reveals enough information about their quality, grade and quantity, they will be reclassified as identified resources.

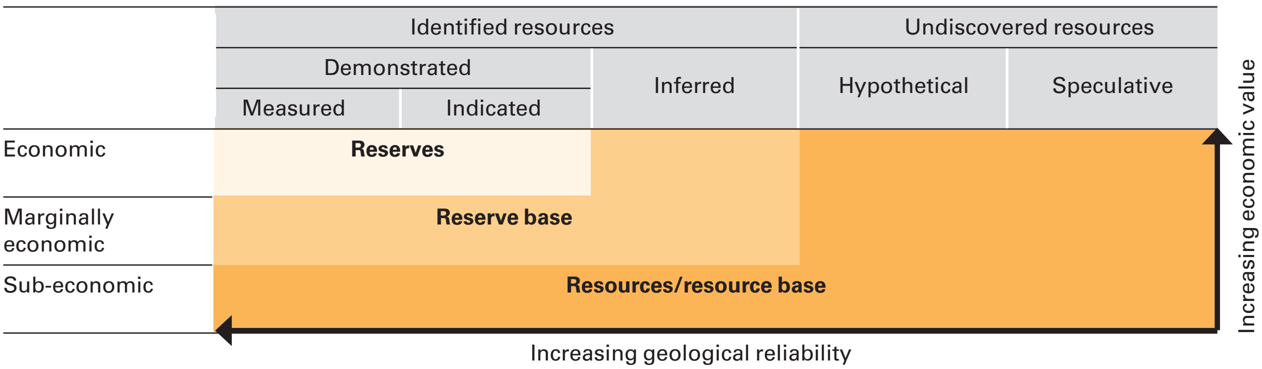
2 **Speculative resources** Undiscovered resources that may occur either in known types of deposits in favourable geologic settings, where mineral discoveries have not been made, or in types of deposits as yet unrecognized for their economic potential. If exploration confirms their existence and reveals enough information about their quantity, grade and quality, they will be reclassified as identified resources.

Reserve base That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness and depth.

Reserves The part of the reserve base that could be economically extracted or produced at the time of determination. The term 'reserves' does not signify that extraction facilities are in place and operative.

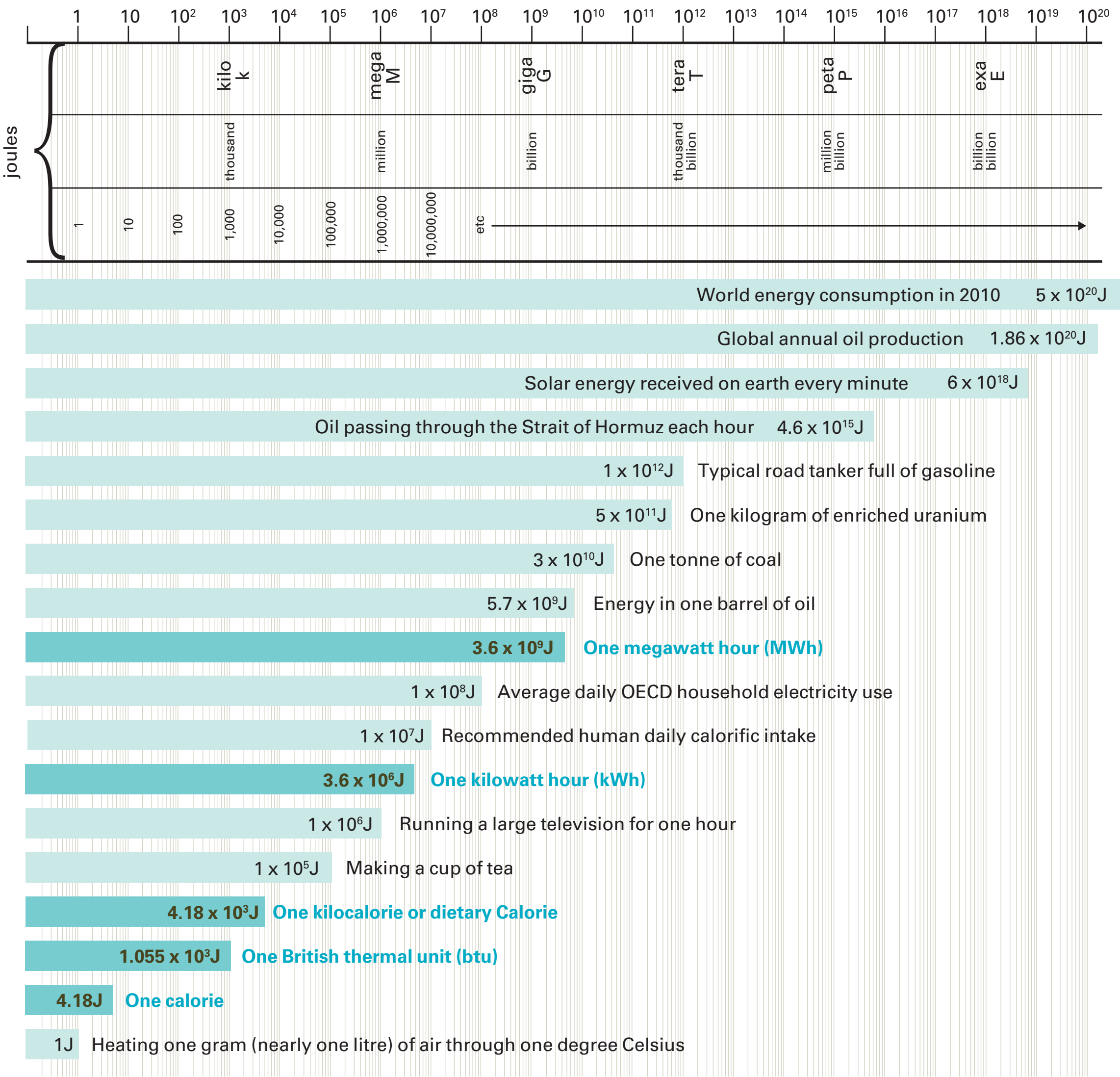
Economic Implies that profitable extraction or production under defined investment assumptions has been established, analytically demonstrated, or assumed with reasonable certainty.

Relationship between resources and reserves



Source: Adapted from USGS Bulletin 1450–A.

Units of energy



N.B. Data may vary from report to report, thus data inconsistencies may occur, as well as rounding errors.

Factors used to assess dissipation and recycling of materials as shown on pages 78 and 79

	Green	Orange	Red
Dissipation risk is considered to be	Low if material is used in bulk or is a main constituent of an alloy	Medium if the data is uncertain or dissipative use between 30% and 70%	High if material is a minor constituent of an alloy or used as a fuel additive
Current recycling status is considered to be	Good if recycling technology is in place and global recycling quota > 20%	Fair if recycling technology known but data uncertain and recycling quota <20%	Poor if no recycling technology is in place or known
Future recycling potential is considered to be	Promising if recycling technology is proven	Neutral if the data is uncertain	Low if the main use is as a fuel additive

Glossary

Adits Horizontal openings that allow access to a mine.

Alloying Combining or modifying metals.

Alluvial Deposited by flowing water.

Autocatalyst Device to clean up internal combustion engine exhaust gases.

Basic magmas Molten rock low in silica.

Bauxite Main ore of aluminium.

Biofuels Man-made fuel derived from plant material.

Black smoker A seafloor vent emitting mineral-rich, volcanically heated water.

Block caving A method for mining massive, steeply dipping orebodies by undercutting the orebody and blasting it down into galleries.

BTU Abbreviation for British Thermal Unit (see Units of energy on page 81).

By-product A secondary material produced as a result of the treatment of an ore rich in a prime mineral.

Calcined Subjected to a heat treatment that drives off volatile matter and causes thermal decomposition.

Calorie A unit of energy where 1 calorie = 4.18J (1 dietry Calorie = 4.18kJ, see Units of energy on page 81).

Carbide A compound of carbon and a less electronegative element.

Carbonatite An intrusive or extrusive igneous rock rich in carbonate minerals.

Cavitation A process where bubbles in liquids collapse, which can lead to erosion of engineered components in the liquid, such as propellers or turbine blades.

Chalcogenides Binary compounds consisting of one of the chalcogen elements, those in group 16 of the periodic table, plus one other element.

CIGS Copper Indium Gallium (Di) Selenide.

Comminution The process of breaking into small particles.

Concentrate The product that results when ore is comminuted and the gangue removed.

Conflict mineral A mineral whose exploitation is used to support illegal actions, e.g. tantalum or coltan that is/was extracted in the eastern DR Congo to support rebel groups.

Co-product A material produced in a process where more than one valuable product results.

Critical element A term widely used but with a range of definitions. Usually it identifies elements or materials that are deemed of high economic importance and at the same time show various signs of potential supply interruption or shortage. Some studies also include environmental and political factors.

Ductile The property of a metal allowing it be drawn out into thin wire.

Electrowinning A process for recovering metals by passing an electric current through a solution containing the metal.

Energy pathway A practical route from energy source to a useful application of energy.

EOL End-of-Life (of a product). A term used to specifiy the end phase of a product's use.

Evaporites Sediments resulting from the evaporation of saline waters.

Flux A substance added in the smelting process to facilitate the purging of impurities and lowering the melting temperature of the slag.

Fly ash Fine residue resulting from the burning of pulverized coal, usually in power stations.

Froth flotation Process for separating ore from gangue that exploits the property of relative attraction of finely ground materials to water.

Gangue Valueless material associated with ore.

Grade A measure of the concentration of ore in a deposit.

Halide A binary compound of which one part is halogen.

Heap leaching A process for concentrating ore by running leach solution over heaps of comminuted run-of-mine material. The leachate, the resulting liquid, is collected and the metal extracted by chemical or electrowinning processes.

HREE See REE.

Hydride A hydrogen-bearing compound.

Hydrometallurgical Processes to concentrate metals that involve aqueous chemicals, including leaching and solution.

Hydrothermal (process) The circulation of water driven by igneous activity. The term is normally used when describing processes that carry minerals in solution.

Ion exchange Process that concentrates metals from solution.

ISL Abbreviation for in-situ leaching, a mining method where an element or material is extracted using aqueous solutions or dilute acids.

J Joule, SI unit for energy, work and heat.

Laterite A residual deposit often containing iron oxides and bauxite, formed as a result of special climate conditions in tropical conditions.

Layered complexes Large igneous rock masses with distinct layering.

LREE See REE.

Lb Imperial pound = 453.6 grammes.

LNG Abbreviation for liquefied natural gas.

Leaching A process for extracting metals by solution in aqueous media.

Magmatic Of/or associated with molten rock.

Malleable The property of metal that allows it to be fashioned or shaped.

Metamorphic Rock that has been altered by heat and/or pressure.

Metasomatic Rock altered by contact with hydrothermal fluids.

Naphtha A range of hydrocarbons with boiling points between 30°C and 200°C

Native An element that occurs naturally in its free state as a mineral, e.g. gold or copper.

Noble metal Also called precious metal, a metal that is highly resistant to corrosion and oxidation. Technically the electrode potential is greater than zero. Elements that fulfill these properties are gold, silver, platinum, palladium, rhodium, iridium, osmium and ruthenium.

Outcrop The area over which a particular rock unit occurs at the surface.

Ore A mineral containing metal in quantities that make its extraction profitable.

Orogenic A mountain-building event.

Oz Troy ounce (Feinunze) = 31.1 grammes. Generally used for trade and reporting of noble metals like gold, silver, platinum etc.

Pegmatite A very coarse-grained igneous rock, usually with granitic composition.

PGM Abbreviation for platinum group metals.

Photovoltaics The conversion of light into electricity using semiconductors.

Pig iron An intermediate stage in iron and steel production, when iron ore has been smelted with a high-carbon fuel.

Placer A deposit formed by gravity separation in water, causing dense minerals to be concentrated.

Platinum group metals (PGM) platinum, ruthenium, rhodium, palladium, osmium and iridium.

Porphyry An igneous rock containing relatively large crystals set in a finer-grained groundmass.

REE Rare Earth Elements are divided into two categories on the basis of atomic structure. Light group rare earth elements (LREE) – La, Ce, Pr, Nd, Pm, Sm, Eu and Gd. Heavy group rare earth elements (HREE) – Y, Tb, Dy, Ho, Er, Tm, Yb and Lu.

Reserves-to-production ratio (R/P) the remaining amount of a non-renewable resource, expressed in years.

Room and pillar mining One of the oldest mining methods used in horizontal or near-horizontal deposits, where mineral is extracted from 'rooms' leaving 'pillars' for roof support.

Run-of-mine Unprocessed material coming directly from a mine.

Sacrificial anode A mass of metal attached to any submerged or buried metallic structure, e.g. boats, pipelines, etc., which corrodes preferentially as a result of electrochemical action, so protecting the structure.

Scarce metal A term that was introduced by B J Skinner in 1976 to determine geochemically scarce elements within the earth's crust, i.e. these elements that contribute less than 0.1% of weight to the earth's crust.

Smelting A process of extracting metals from ores by heating in the presence of a reducing agent.

Spodumene A lithium-aluminium-silicate mineral.

Stearate A salt or ester of stearic acid.

Stockworks A large-scale set of mineral-filled fissures.

Stoping A mining method for steeply dipping orebodies that requires horizontal roadways to be driven along the body and the ore extracted into the roadway.

Subduction A process that takes place at the boundaries of tectonic plates, where one plate is driven or sinks under another.

Tailings pond A storage site for waste materials resulting from mineral processing.

Ultrabasic rocks Igneous rocks that are deficient in silica and are essentially composed of iron and magnesium minerals.

Unconformities A term to describe the relationship between two rock units where there has been a gap in deposition.

USGS Abbreviation for United States Geological Survey.

Key references

In order to keep this handbook easy to read, a scientific citation style has been avoided. This does not, of course, neglect the efforts and insights of scientists, analysts and companies around the world. This list shows the major sources for information used in developing this handbook. A lot of data has also been drawn from the knowledge base of the University of Augsburg, derived through many years of research in an interdisciplinary approach at the Chair of Resource Strategy. All internet links have been checked at January 2014.

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Materials regarded as critical in other key studies

Materials included			US DOE	EU Critical Raw Materials	EU JRC	BGS Risk list 2012	Resnick Institute	APS Physics	UKERC	This handbook
He	Helium	2						blue	blue	
Li	Lithium	3	green				blue	blue	blue	purple
Be	Beryllium	4		blue		blue				
B	Boron	5								
C	Carbon	6				blue				
Mg	Magnesium	12		blue						
P	Phosphorus	15								purple
K	Potassium	19								purple
Sc	Scandium	21						blue	blue	*
V	Vanadium	23			blue					purple
Cr	Chromium	24								purple
Mn	Manganese	25	green							
Co	Cobalt	27	green	blue			blue	blue	blue	purple
Ni	Nickel	28	green		blue					purple
Cu	Copper	29								blue
Ga	Gallium	31	green	blue	purple		blue	blue	blue	purple
Ge	Germanium	32		blue		blue	blue	blue	blue	purple
Se	Selenium	34			blue		blue	blue	blue	
Sr	Strontium	38				blue				
Y	Yttrium	39	purple				blue	blue	blue	*
Nb	Niobium	41		blue	blue					purple
Mo	Molybdenum	42			blue	blue				purple
Ru	Ruthenium	44		blue			blue	blue	blue	
Rh	Rhodium	45		blue			blue	blue	blue	purple
Pd	Palladium	46		blue			blue	blue	blue	blue
Ag	Silver	47			blue		blue	blue	blue	blue
Cd	Cadmium	48			blue		blue			purple
In	Indium	49	blue	blue	purple		blue	blue	blue	purple
Sn	Tin	50			blue					
Sb	Antimony	51				blue				
Te	Tellurium	52	blue		purple		blue	blue	blue	purple
Ba	Barium	56				blue				
La	Lanthanum	57	blue	blue		blue	blue	blue	blue	*
Ce	Cerium	58	blue	blue		blue	blue	blue	blue	*
Pr	Praseodymium	59	green	blue		blue	blue	blue	blue	*
Nd	Neodymium	60	purple	blue	purple	blue	blue	blue	blue	*
Pm	Promethium	61		blue		blue				*
Sm	Samarium	62	green	blue		blue		blue	blue	*
Eu	Europium	63	purple	blue		blue	blue	blue	blue	*
Gd	Gadolinium	64		blue		blue		blue	blue	*
Tb	Terbium	65	purple	blue		blue	blue	blue	blue	*
Dy	Dysprosium	66	purple	blue	purple	blue	blue	blue	blue	*
Ho	Holmium	67		blue		blue				*
Er	Erbium	68		blue		blue				*
Tm	Thulium	69		blue		blue				*
Yb	Ytterbium	70		blue		blue		blue	blue	*
Lu	Lutetium	71		blue		blue		blue	blue	*
Hf	Hafnium	72			blue					
Ta	Tantalum	73		blue						
W	Tungsten	74		blue		blue				purple
Re	Rhenium	75						blue	blue	purple
Os	Osmium	76		blue			blue	blue	blue	
Ir	Iridium	77		blue			blue	blue	blue	
Pt	Platinum	78		blue			blue	blue	blue	purple
Hg	Mercury	80				blue				
Bi	Bismuth	83				blue				
U	Uranium	92								purple
	REEs									purple

N.B. A range of criteria are used to assess criticality across the studies, which do not necessarily correspond with the criteria used in this handbook. This makes accurate comparisons of criticality impossible.
The table uses purple, blue and green to indicate high, medium and low criticality.
* In this handbook, criticality of REEs is considered collectively.

Elements and their uses

Atomic number	Element		Major uses
1	**Hydrogen**	H	■ Ammonia synthesis ■ Oil refining ■ Fuel cells ■ Rocket fuels ■ Secondary energy source
2	**Helium**	He	■ Cooling agent ■ Required for some superconductor appliances ■ Altitude research/ meteorological balloons
3	**Lithium**	Li	■ Nuclear technology as shielding and cooling material ■ Batteries ■ Alloying agent for high-performance aircraft parts
4	**Beryllium**	Be	■ Alloying agent of beryllium-copper, which is a good electrical and thermal conductor ■ X-ray detection diagnostic
5	**Boron**	B	■ Pyrotechnical mixtures and rocket propellant (amorphic B) ■ Addition to increase strength of W- or C-fibre (airplanes, space, sports) ■ Isotope in control rods in nuclear reactors (good neutron absorber)
6	**Carbon**	C	■ Base element for coal, diamond and graphite allotropes ■ Diamond - industrial ■ Graphite - lubricant, pencil 'leads', dry-cell and arc-light electrodes
7	**Nitrogen**	N	■ Inert gas in electronics and metals industries ■ Fertilizer from ammonia ■ Refrigerant
8	**Oxygen**	O	■ Melting, refining and manufacture of metals ■ Manufacture of chemicals by controlled oxidation ■ Rocket propulsion ■ Medical life support ■ Mining, production and manufacture of stone and glass products
9	**Fluorine**	F	■ Production of uranium hexafluoride used for isotope-separation of nuclear propellants ■ Cooling agent and plastics production ■ Plasma etching in semiconductor manufacturing, flat-panel display production and MEMs (micro-electro-mechanics) fabrication
10	**Neon**	Ne	■ Lighting ■ High-voltage indicators ■ Cryogenic refrigerant

Atomic number	Element		Major uses
11	**Sodium**	Na	■ Manufacture of organic compounds ■ Sodium chloride – common salt ■ To improve structure of certain alloys, e.g. in sodium vapour lamps ■ Cooling agent (breeder nuclear plants)
12	**Magnesium**	Mg	■ Alloys mainly with Al for weight reduction ■ Reducing agent for production of pure metals ■ Desulfurization and reduction agent in the iron and steel industry
13	**Aluminium**	Al	■ Light metal in automobiles and aerospace industries ■ Electricity grid ■ Packaging ■ Mirrors
14	**Silicon**	Si	■ Deoxidizer ■ Alloy integrals to provide resistance to Al, Mg and Cu ■ Electronics industry (integrated circuits, PV, semiconductors) ■ Ceramics
15	**Phosphorus**	P	■ Fertilizers ■ Explosives ■ Steel production
16	**Sulfur**	S	■ Production of sulphuric acid - an industrial raw material ■ Fertilizer manufacture ■ Explosives ■ Electrode in NaS-cells (type of battery)
17	**Chlorine**	Cl	■ Chemical laboratory reagents ■ Water purification ■ Cleaning products (bleach/disinfectants) ■ Manufacture of consumer products, including paper, dyestuffs, food, paints, plastics and medicines
18	**Argon**	Ar	■ Inert gas in lightbulbs ■ Shield gas for welding
19	**Potassium**	K	■ Fertilizer ■ Compounds (carbonates and hydroxides) used in glass and liquid soaps
20	**Calcium**	Ca	■ Deoxidizer for metal manufacture ■ Decarbonizer for steel products ■ Desulphurization of petroleum

Atomic number	Element		Major uses
21	**Scandium**	Sc	■ Alloying agent for Al-, Ti-, Ni-, and Ta-alloys ■ Host for Eu and Tb dotted phosphors ■ Oil-well tracers
22	**Titanium**	Ti	■ Ti-alloys - for high-tensile strength and low-weight applications (jet engines, aircraft, submarines, missiles) ■ Medical uses, e.g. hip and knee replacements, pacemakers ■ Titanium dioxide is a white pigment used in outdoor paint
23	**Vanadium**	V	■ Steel additive - alloys used in crankshafts, axles and gears ■ Alloys with titanium used in jet engines and others in nuclear reactors ■ Vanadium oxide is a chemical catalyst
24	**Chromium**	Cr	■ Steel alloys ■ Chrome plating ■ Metal ceramics ■ Reduction agent ■ Cosmetics
25	**Manganese**	Mn	■ Deoxidation and desulphurization ■ Steel and aluminium alloys
26	**Iron**	Fe	■ Most used metal - 95% of metal tonnage produced worldwide ■ Main constituent of steel ■ Catalyst ■ Magnets
27	**Cobalt**	Co	■ High performance metal alloys ■ Magnets ■ Catalysts for petroleum and chemical industries ■ Pigment
28	**Nickel**	Ni	■ Steel refining ■ Nickel alloy, e.g. in super alloys ■ Catalyst in oil refining and chemical industries ■ Ceramics ■ NiCd batteries
29	**Copper**	Cu	■ Electrical equipment ■ Construction ■ Industrial machinery, e.g. heat exchangers ■ Alloys including bronze, brass and copper-tin-zinc
30	**Zinc**	Zn	■ Galvanizing, zinc coating (corrosion resistance) ■ Construction work ■ Batteries ■ Medical
31	**Gallium**	Ga	■ GaAs compound in semiconductors ■ Analogue integrated circuits ■ GaN phosphors ■ Magnetic materials ■ Weaponry: Pu+Ga in nuclear weapons ■ High-temperature thermometers
32	**Germanium**	Ge	■ Semiconductor used in transistors and integrated circuits ■ Photodetectors ■ Basis for GaAsP in LEDs and solar cells
33	**Arsenic**	As	■ Glass industry and zinc production ■ GaAs and InAs in semiconducting technology ■ Pesticides, herbicides, wood treatment ■ Arsine gas is dopant gas in microchip industry ■ Organic compounds as chemical weapons
34	**Selenium**	Se	■ Solar cells CIS, CIGS ■ Photodiodes, photocopiers ■ Production of glass, pigments, alloys, steel, oxidation stopper for lubricants, vulcanization of rubber
35	**Bromine**	Br	■ Organobromo compounds are used as insecticides, in fire extinguishers and in pharmaceutical manufacture ■ Fumigants, dyes, medicinals, photography agent, lachrymator (tear gas)
36	**Krypton**	Kr	■ Electric lamp bulb gas ■ Photographic projection lamps and high-powered arc lights ■ Inert gas for radiation counter
37	**Rubidium**	Rb	■ Photocell manufacture ■ Getter (remover of trace gases) in vacuum tubes ■ Isotope in positron-emission-tomography
38	**Strontium**	Sr	■ Pyrotechnics in fireworks and flares ■ Carbonate used in special glass for television screens ■ Getter (residual gas remover) in vacuum tubes
39	**Yttrium**	Y	■ Phosphors ■ YAG (yttrium aluminium garnet) laser ■ Automotive appliances (spark plugs, lambda sensors) ■ Super alloys with Al and Mg
40	**Zirconium**	Zr	■ Construction material (corrosion resistance) ■ Vacuum tubes (electrical engineering) ■ Pyrotechnical use ■ Cladding material ■ Catalyst (as Zr organic compound)
41	**Niobium**	Nb	■ Construction steels, high temperature steels ■ High-strength, low-alloy steels for offshore platforms, pylons ■ Nuclear reactor construction, coating of nuclear fuel rods ■ Superconducting magnet wires (tin/titanium alloys)

Atomic number	Element		Major uses
42	**Molybdenum**	Mo	■ Steel alloying agent for high-temperature strength ■ Chemical catalyst ■ Electrodes
43	**Technetium**	Tc	■ Nuclear medicine ■ Catalyst ■ High-temperature thermo-elements (utilizing thermoelectric effect) with superconducting features
44	**Ruthenium**	Ru	■ Electronic industry – chip resistors ■ Chemical industry – anodes for Cl production in electochemical cells ■ Hardener for Pd and Pt ■ Catalyst in PGM alloys, autocatalysts
45	**Rhodium**	Rh	■ Autocatalysts ■ Pt and Ir alloys - furnace windings, pen nibs, electrical contacts and thermocouple and resistance wires ■ Pt/Pd-thermoelements
46	**Palladium**	Pd	■ Jewellery ■ Electronics ■ Electrodes in fuel cells ■ Catalyst (fluid catalytic cracking, automotive)
47	**Silver**	Ag	■ Chemistry, catalyst, anodes for galvanizing, electrodes ■ Jewellery, cutlery, coins ■ Batteries, capacitors ■ Photography
48	**Cadmium**	Cd	■ NiCd batteries ■ Neutron moderator in control rods in nuclear plants ■ PV (one of several possible technologies) ■ Pigments, coatings and plating
49	**Indium**	In	■ Anti-corrosion coating ■ Semiconductor, neutron absorber, transistors ■ Electronics
50	**Tin**	Sn	■ Tin plate ■ Soft solder ■ Tin oxide used in ceramics and gas sensors ■ Chemicals (fungicides, disinfectant)
51	**Antimony**	Sb	■ Alloy with lead and tin (lettermetal) ■ Batteries ■ Diodes and infrared detectors
52	**Tellurium**	Te	■ Vulcanization of rubber (caoutchouc) ■ Production of glass, ceramics, alloys and enamel pigments ■ CdTe solar panels
53	**Iodine**	I	■ Medical ■ Manufacture of printing inks and dyes ■ Water purification tablets ■ Added to table salt
54	**Xenon**	Xe	■ Lighting ■ Lasers ■ General anaesthetic

Atomic number	Element		Major uses
55	**Caesium**	Cs	■ Atomic clocks ■ Catalyst promoter ■ Glass strengthener (salts) ■ Removes oxygen traces from vacuum tubes and light bulbs
56	**Barium**	Ba	■ Removal of trace gases in electron beam ■ Fluorescent lamps ■ Compounds used to make drilling mud ■ Medicinal imaging
57	**Lanthanum**	La	■ Catalyst (fluidized catalytic cracking) ■ Batteries (NiMH) ■ Optics ■ Phosphors ■ Glass
58	**Cerium**	Ce	■ Catalyst (fluidized catalytic cracking, automotive) ■ Glass (UV protection, polishing) ■ Phosphors ■ Alloying agent
59	**Praseodymium**	Pr	■ Electrodes ■ Steel alloying ■ Partial substitute for neodymium in permanent magnets ■ Glass colouring ■ Fluorescent lamps
60	**Neodymium**	Nd	■ Permanent magnets ■ Lasers ■ Steel alloys ■ Fluorescent lamps
61	**Promethium**	Pm	■ Nuclear batteries
62	**Samarium**	Sm	■ Permanent magnets (SmCo) ■ Catalyst (ethanol) ■ Infrared-absorbing glass
63	**Europium**	Eu	■ Phosphor ■ Control rods in nuclear reactors (high neutron absorption)
64	**Gadolinium**	Gd	■ Control rods in nuclear reactors (high neutron absorption) ■ Contrast agent in MRT/ MRI (magnetic resonance tomography/imaging)
65	**Terbium**	Tb	■ Laser ■ Phosphors ■ Addition to permanent magnets to increase temperature resistance ■ Stabilizer in fuel cells
66	**Dysprosium**	Dy	■ Control rods in nuclear reactors (high neutron absorption) ■ Improved temperature resistance in PM (permanent magnets) ■ High-performance halogen lamps

Atomic number	Element		Major uses
67	**Holmium**	Ho	■ Glass colouring ■ Pole shoe (magnetic flux concentrator) for high-performance magnets ■ Control rods for nuclear reactors (breeder reactor) ■ Medical laser
68	**Erbium**	Er	■ Signal amplifier in glass fibre cables ■ Glass-colouring agent ■ Medical laser
69	**Thulium**	Tm	■ Materials tester in nuclear reactors ■ Laser
70	**Ytterbium**	Yb	■ Used in some steels ■ Laser ■ Military use in IR decoys ■ Substitute for Cs in atomic clocks
71	**Lutetium**	Lu	■ Magnetic bubble memory ■ Beta-emitter ■ Medical use in cancer therapy
72	**Hafnium**	Hf	■ Control rods in nuclear reactors ■ Neutron absorber in nuclear fuel reprocessing ■ High-temperature alloys and ceramics
73	**Tantalum**	Ta	■ Capacitor ■ Medical ■ High-temperature resistant metal alloys ■ Handling corrosive chemicals
74	**Tungsten**	W	■ Lighting ■ Superalloys, high-speed steels ■ Hard metals ■ Coating of nuclear fuels ■ Microchip technology and LCDs
75	**Rhenium**	Re	■ Thermoelements ■ Space applications ■ Catalyst ■ Superalloys - engine turbine blades ■ Filaments in ovens/lamps
76	**Osmium**	Os	■ Catalyst (as alloy ingredient) ■ Hard metal material
77	**Iridium**	Ir	■ Electrode material ■ Alloying agent ■ Catalyst
78	**Platinum**	Pt	■ Catalyst ■ Jewellery ■ Fuel cells
79	**Gold**	Au	■ Coins, jewellery ■ Electronics (gold-plated connectors) ■ Catalyst (theoretical, expensive)
80	**Mercury**	Hg	■ Barometers, thermometers ■ Medical ■ Batteries ■ Gold processing

Atomic number	Element		Major uses
81	**Thallium**	Tl	■ Potential for high-temperature superconductor ■ Low-temperature thermometers ■ Glass for reflective lenses
82	**Lead**	Pb	■ Batteries ■ Radiation shielding ■ Electrodes
83	**Bismuth**	Bi	■ Alloying agent ■ Solders ■ Medical use (antiseptic)
84	**Polonium**	Po	■ Portable neutron source ■ Radiation chemistry and radiobiology
85	**Astatine**	At	■ Nuclear uses (rare)
86	**Radon**	Rn	■ Therapeutical use ■ Hydrologic and geologic research
87	**Francium**	Fr	■ None
88	**Radium**	Ra	■ Used to produce Ac (in nuclear reactors) ■ Luminous paint ■ Produces radon gas for cancer treatment
89	**Actinium**	Ac	■ Generation of neutrons
90	**Thorium**	Th	■ Fuel for high-temperature reactors ■ Neutron source ■ Lighting ■ High-temperature alloys for jet engines
91	**Protactinium**	Pa	■ Scientific research
92	**Uranium**	U	■ Nuclear fuel ■ Atomic weapons
93	**Neptunium**	Np	■ Neutron detectors
94	**Plutonium**	Pu	■ Nuclear weapons ■ Nuclear fuel for breeder reactors
95	**Americium**	Am	■ Smoke detectors ■ Portable gamma ray source
96	**Curium**	Cm	■ Space use for power generation
97	**Berkelium**	Bk	■ No common use
98	**Californium**	Cf	■ Neutron source ■ Cancer therapy
99	**Einsteinium**	Es	■ No common use
100	**Fermium**	Fm	■ Potential medical use
101	**Mendelevium**	Md	■ No common use
102	**Nobelium**	No	■ No common use
103	**Lawrencium**	Lr	■ No common use
104	**Rutherfordium**	Rf	■ No common use
105	**Dubnium**	Db	■ No common use
106	**Seaborgium**	Sg	■ No common use
107	**Bohrium**	Bh	■ No common use
108	**Hassium**	Hs	■ No common use
109	**Meitnerium**	Mt	■ No common use
110	**Darmstadtium**	Ds	■ No common use

Group / Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H Hydrogen																	2 He Helium
2	3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
3	11 Na Sodium	12 Mg Magnesium											13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulphur	17 Cl Chlorine	18 Ar Argon
4	19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
5	37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
6	55 Cs Caesium	56 Ba Barium	Elements 57–71	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
7	87 Fr Francium	88 Ra Radium	Elements 89–103	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium							

57 La Lanthanum	58 Ce Cerium	59 Pr Praseo-dymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

- Alkali metals
- Alkaline earth metals
- Transition metals
- Other metals
- Other non-metals
- Halogens
- Inert gases
- Lanthanides
- Actinides
- Trans-actinides
  Man-made atoms that exist for less than a second

Solid line: Materials referenced in handbook

Dashed line: Rare earth elements (REEs)

Materials critical to the energy industry
An introduction

SECOND EDITION

Materials critical to the energy industry – An introduction is a study that highlights the reliance of the energy industry on a range of naturally occurring materials and explains what factors affect their supply. The book is based on data gathered by the Resource Strategy Department at Augsburg University.

This book explains how materials move along energy pathways from production to final uses, outlines how the range of materials involved in energy pathways has grown through time and how that range has changed as energy pathways developed. The routes taken from minerals in the ground to useable materials are described along with the factors that can influence the sustainable supply of materials. The book emphasizes that although in the earth's crust there is a wealth of all materials necessary in energy pathways, political, economic and environmental factors can all interrupt supply. The contributions of recycling and substitution to overcome supply constraints are examined, as is the role and influence of the markets in controlling supply.

Twenty-three materials are described in detail with explanations of their uses in energy and other sectors, their physical properties and origins, reserves, trading position, ecological impact, the processing required to bring them to market and their recyclability and substitutability. Sustainability indicators are assigned to allow an understanding of the degree to which a material is necessary to an energy pathway.

The handbook offers a valuable guide for policy makers, businesses and academics on the materials required to maintain energy pathways and the actions needed to ensure sustainable supplies.

Materials critical to the energy industry – An introduction shows:

- What are the materials critical to the energy industry, and why.
- How innovation is driving demand for more and new materials.
- How, where and with what ecological impact materials are produced, and what factors influence their price.
- The extent to which material recycling and substitution can contribute to meeting demand.
- How market effectiveness and politics are often more important than actual availability in ensuring materials supply.

Supported by BP, as part of the multi-partner Energy Sustainability Challenge, which explores the implications for the energy industry of competing demands for water, land and minerals.

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