Magnesite & Magnesia

a critical raw material?

By

Dipl.-Ing. Dr.mont. Eva Gerold
Univ.-Prof. Dr.mont. Helmut Antrekowitsch

Brussels, October 2024

Chair of Nonferrous Metallurgy

Magnesia/magnesite – a critical raw material?

Dipl.-Ing. Dr.mont. Eva Gerold
Univ.-Prof. Dr.mont. Helmut Antrekowitsch

October 2024

Content

1 Basics of the Critical Raw Materials Act

The European Union's Critical Raw Materials Act (CRM Act) aims to improve the security of supply of critical raw materials and strengthen the EU's strategic autonomy. The Act promotes the diversification of supply sources, supports domestic production and introduces the category "Strategic Raw Materials" for particularly important raw materials that are required for key technologies such as batteries and renewable energies. It also places great emphasis on sustainability by demanding high environmental and social standards in the extraction of raw materials and promoting innovations in recycling and the circular economy. Through these measures, the CRM Act aims to make the EU industry more resilient to global supply chain risks and contribute to the green and digital transformation. The main drivers and goals within the CRM are displayed in Figure 1. [1–3]

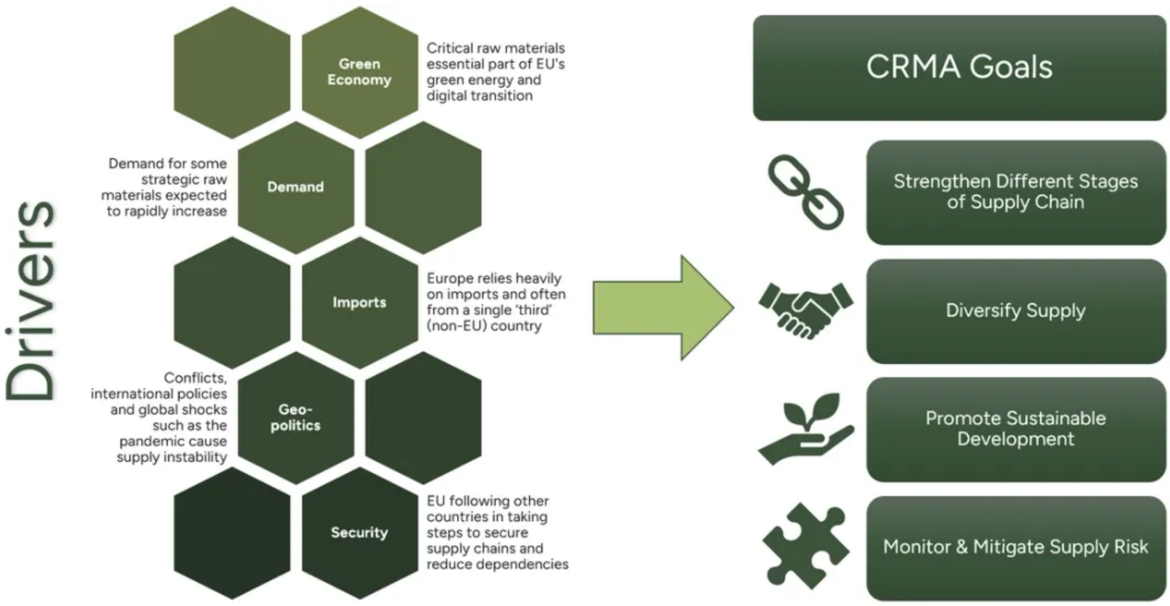


Figure 1: Drivers and goals of the critical raw materials act of the European Union [3]

It has ambitions goals to reduce dependence on dominant suppliers of strategic raw materials and to commit EU Member States to rapidly increase efforts to secure stable, long-term supplies of raw materials for strategic purposes from within the EU and partner countries. The main objectives of the CRMA for 2030 are as follows: [1]

- **>10% Mining:** Mining in EU countries must account for >10% of the EU's annual consumption of strategic raw materials (SRMs).
- **>40% Processing:** Processing of raw materials in EU countries must account for >40% of the EU's annual consumption of SRMs.

- **>25% Recycling:** Recycling in EU countries must account for >25% of the EU's annual consumption of SRMs.
- **<65% Single source:** No more than 65% of the annual EU consumption of an individual SRM can come from a single third country.

1.1 Magnesia/magnesite as critical raw material

Magnesite was first included in the European Union's list of critical raw materials in 2014. This inclusion took place in the course of the second publication of the EU list of critical raw materials. The classification as critical was based on factors such as economic importance and supply risk, with magnesite being considered potentially critical for European industry during this period. [4]

The main reason for categorising magnesia/magnesite as a critical raw material in 2014 was that there are hardly any substitution options for this material. The country production figures show a higher degree of concentration than in the calculations of the previous report in 2010, with China's share increasing and Brazil's decreasing. There is a slight decrease in economic importance due to changes in use patterns and megasector values. There is no recycling for the main applications and few substitution options for the main uses. [4]

1.1.1 Loss of criticality for magnesia/magnesite

In 2017, the European Union carried out its next evaluation (after 2014) of the criticality of raw materials. As a result of this activity, magnesite lost its status as a critical raw material.

The economic importance (EI) for magnesite (4.0) meets the minimum EI threshold, but the supply risk (SR) result (SR=0.7) does not. The economic importance of magnesite/magnesia decreased between 2014 and 2017, due to the change in methodology of the evaluation and a better representativeness of the end-use applications covered by refractories. In the study of 2014, refractory applications accounted for 83% of magnesia applications, with the remainder split between caustic calcined applications. In the study, the project team was able to allocate between specific end-use applications, thanks to feedback from various stakeholders. The supply risk indicator is lower than in previous years, due to the methodological change, i.e. the inclusion of EU and global supply in the calculation of the supply risk. [5]

1.1.2 Definition of terms

Essentially, the terms magnesia, magnesite and magnesium play an important role in this study. These three terms are defined as follows in order to clearly differentiate them.

Magnesite ($MgCO_3$): [6]

- Chemical Composition: Magnesite is a naturally occurring mineral, composed of magnesium carbonate ($MgCO_3$).
- Formation: It forms through the alteration of magnesium-rich rocks or through the precipitation from magnesium-rich waters.
- Industrial Use: Magnesite is used primarily as a source for producing magnesia and in refractory materials, due to its resistance to high temperatures. It is also used in the production of fertilizers and as a raw material in the manufacture of magnesium compounds.
- Appearance: Typically white, grey, or yellowish in color, magnesite can be found in crystalline or massive form.

Magnesia (MgO): [6]

- Chemical Composition: Magnesia, also known as magnesium oxide (MgO), is the product of calcining magnesite at high temperatures, a process that removes carbon dioxide (CO_2) and leaves behind MgO.
- Properties: Magnesia is a white powder with a high melting point and excellent thermal and electrical insulation properties.
- Industrial Use: Magnesia is extensively used in refractory materials, particularly in steelmaking, as it can withstand extreme temperatures. It also finds use in ceramics, cement, and as a food additive (e.g., in supplements or as an antacid). Furthermore, high-purity magnesia is used in advanced ceramics and electronics.

The key difference between magnesite and magnesia lies in the fact that magnesite is a naturally occurring mineral, whereas magnesia is the product of processing magnesite (see Figure 2).

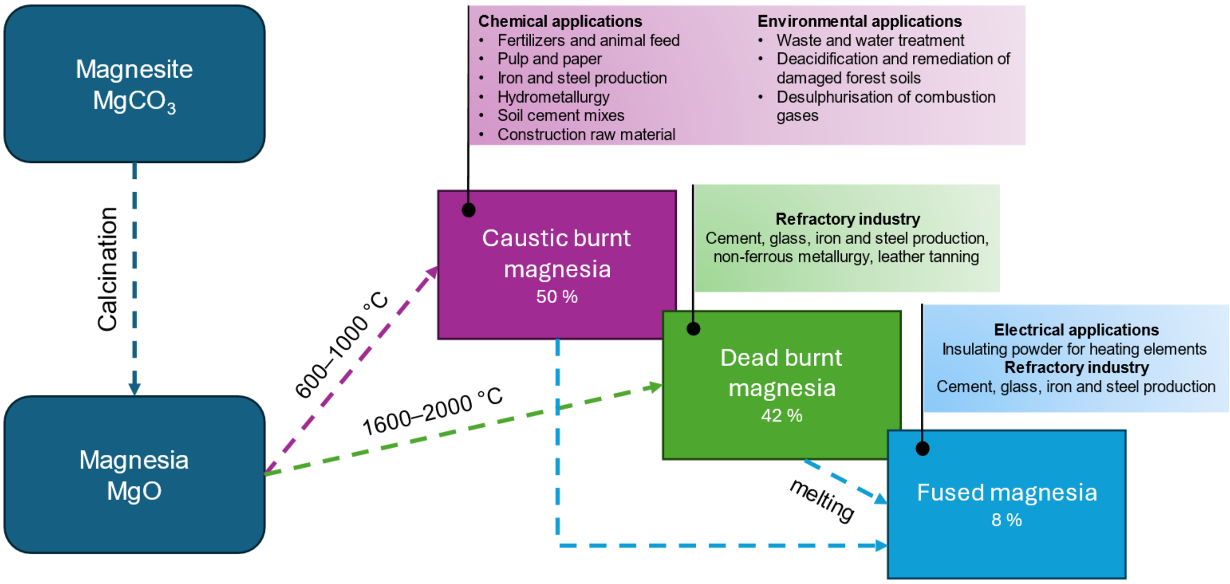


Figure 2: Production of magnesia and illustration of commercial qualities (% shares of global magnesia production in 2018) after [7]

Magnesium (Mg): [6]

- Chemical Composition: Magnesium is a metallic element with the symbol Mg and atomic number 12. It is a light, silvery-white metal in its pure form.
- Properties: Magnesium is known for being one of the lightest structural metals, with excellent strength-to-weight ratio, good thermal conductivity, and strong corrosion resistance when alloyed.
- Industrial Use: Magnesium is used in alloys (e.g., with aluminum) in the automotive and aerospace industries for lightweight, high-strength components. It is also essential in the production of electronics, tools, and consumer products like laptops and cameras. Additionally, magnesium is used in the production of chemicals and as a reducing agent in the refining of titanium.

1.2 Introduction of the category “strategic raw materials”

The first list of strategic raw materials was also published with the European Union's CRM Report 2023. The Commission has carried out a criticality assessment to identify those raw materials that are critical for the EU based on their economic importance and supply risk. The Act proposes that certain measures, including those on monitoring, circularity and sustainability, should apply to all critical raw materials. However, the Commission recognises the need to pay particular attention to those raw materials that are used in strategic sectors such as renewable energy, digital, space and defence technologies, and for which the projected growth in demand compared to the current level of supply, combined with the

difficulties in scaling up production, are likely to create supply risks in the near future. On the basis of this assessment, a list of strategic raw materials has been drawn up and will be reviewed at least every four years. [1]
This list of strategic raw materials is based on the following definition and criteria: [1]

- Definition: Strategic raw materials are a sub-category of critical raw materials that are of particular importance to the EU's economic and technological sovereignty. These raw materials are considered essential for the production of key technologies needed for the green transition, digital transformation and defence.
- Criteria: Selection is based on economic importance, supply risk and substitution potential. Raw materials that play a key role in technologies such as batteries, renewable energies, electromobility and semiconductor production are prioritised.
- Examples of strategic raw materials: Strategic raw materials include materials such as lithium, cobalt, nickel, rare earths and gallium. These are required for the production of energy storage systems, permanent magnets for wind turbines and electric vehicles as well as for electronic components.

As a result, the CRM act proposes specific measures to address strategic commodities, namely through measures to increase domestic capacity, diversification and risk preparedness. In addition, measures relating to strategic stocks and joint purchasing apply to strategic commodities. [1]
The introduction of the "Strategic Raw Materials" category under the CRM Act emphasises the EU's strategic focus on a sustainable and independent supply of raw materials. This category will help to secure the competitiveness of European industry in key areas and at the same time improve environmental and social standards. The current list of strategic raw materials is shown in the Figure 3. [1,3]

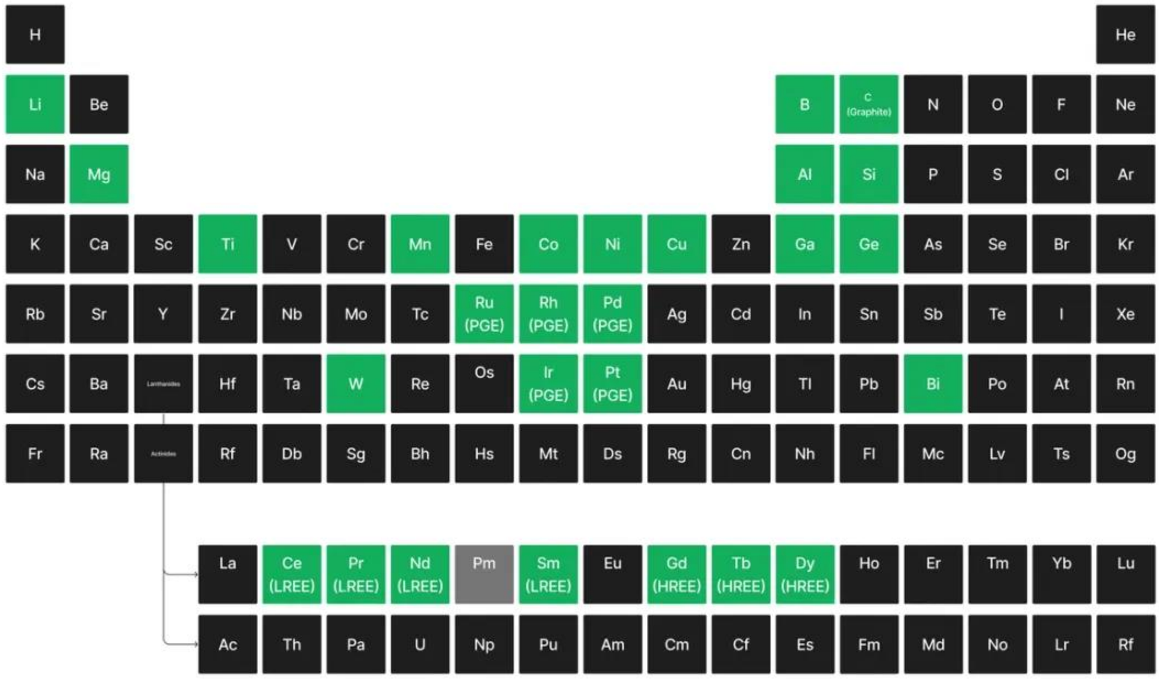


Figure 3: Strategic raw materials based on the CRM Act 2023 [3]

2 Areas of application for magnesite, magnesia and magnesium

In Europe, more than 98% of magnesite is used for magnesia processing and refined into three commercial product types: caustic calcined magnesia (CCM), dead burned magnesia (DBM) and fused magnesia (FM). DBM and FM are mainly used in the refractory industry for cement, glass, iron and steel production (see Figure 4) , but it is also an important raw material in some advanced electrical applications, leather tanning and other similar applications. CCM is mainly used in chemical-based applications such as fertilisers and animal feed, pulp and paper, rubber and plastics, pharmaceuticals, hydrometallurgy and waste or water treatment. [8]

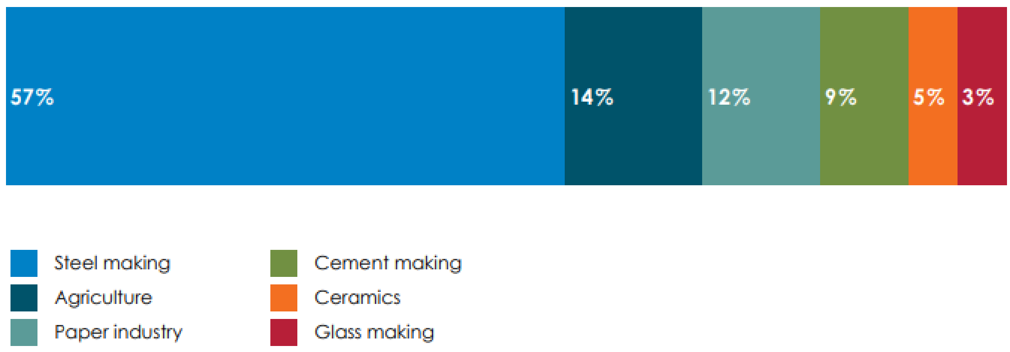


Figure 4: Main application for magnesia over the period of 2012–2016 [8]

The following chapters will discuss the main areas of application in detail, with a particular focus on those sectors in which the substitution of magnesite or magnesia is hardly possible or not feasible at present.

At a global level, the data from Statista shows that magnesite production is heavily dependent on China (see Figure 5). Europe is strongly dependent on magnesite imports as its own production is limited, which poses a risk to security of supply. This dependence makes the EU vulnerable to geopolitical and market fluctuations, particularly as China controls a large proportion of global magnesite production. [9]

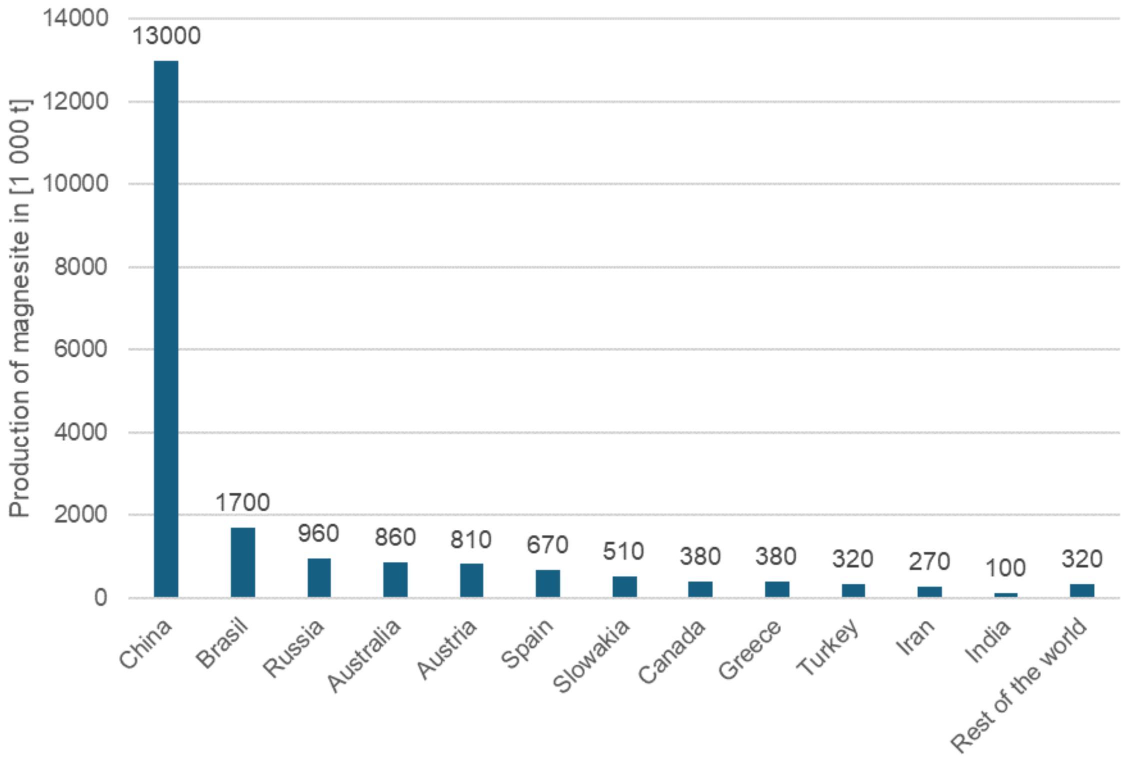


Figure 5: Mining production of magnesite by the most important countries in 2023 [9]

2.1 The role of magnesia in the production and processing of critical metals

The following subsections will illustrate the critical role of magnesia, predominantly in the form of refractory products, in relation to the production of critical and strategic raw materials in the European Union. The multitude of examples illustrates the pivotal role of magnesia in the fulfilment of the CRM Act, as the sufficient availability of magnesia is a prerequisite for the European production of numerous other critical raw materials. Conversely, the scarcity or disruption of magnesia supply can result in difficulties in the provision of other critical raw materials to the European Union. To provide further insight into the potential applications, the production routes of selected metals are outlined in the following sections.

2.1.1 Antimony

Antimony is employed in a number of industrial sectors, notably in metallurgy, where it is utilised in the production of lead-antimony alloys for use in batteries, which are widely deployed in the automotive industry. Additionally, antimony is employed in the production of flame retardants for plastics, textiles and electronic devices. The element is also utilised in the production of semiconductors and alloys, where it serves to enhance the hardness and mechanical properties of metals. [10]

Antimony is a critical element for the European Union, given that it is mainly imported and that there is a high demand for it (supply risk: 1.8; economic importance: 5.4), particularly for strategic industrial applications. The dependence on a limited number of supplier countries, in particular China (share of 56%), and the restricted availability of antimony increase the risk of supply shortages, thus classifying antimony as a critical raw material for the EU. [11]

2.1.1.1 Extraction of antimony

Antimony occurs in a wide variety of mineral compounds. The pyrometallurgy of antimony is based on the low melting point of Sb_2S_3 at 546 °C and the eutectic with Sb_2O_3. This property provides the possibilities for pyrometallurgical processing (see Figure 6). [12]
In the first step, sulphide ores are enriched by segregation. The concentrated material is then oxidised in a roasting process, which usually takes place in a rotary kiln. To obtain metallic antimony, reduction takes place in a hearth furnace or short drum furnace using iron as reducing agent. The most important reactions for this are (see Equation (1) and (2)): [12]

$$2Sb_2O_3 + Sb_2S_3 \leftrightarrow 6Sb + 3SO_2 \quad (1)$$

$$Sb_2S_3 + 3Fe \leftrightarrow 2Sb + 3FeS \quad (2)$$

Sodium salts, which form a thin, slightly melting slag, serve as slag formers. Antimony is purified using vacuum sublimation. Manganese and aluminium are added to produce low-volatility compounds. The product contains 99.99% antimony. The extraction of pure antimony (99.9999%) is possible using a zone melting process under inert gas. [12]

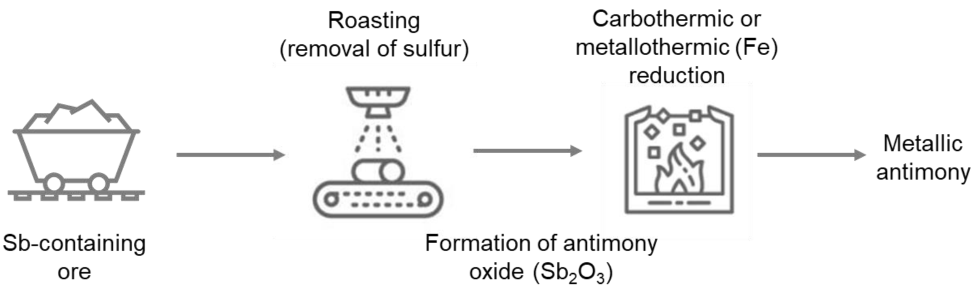


Figure 6: Primary production route of antimony

2.1.1.2 Use of magnesia in the production of antimony

The slag formers used (e.g. sodium salts), which exhibit basic behaviour, require correspondingly basic refractory material (magnesia bricks) in order to prevent a reaction between the slag and the furnace lining. Aggregates used in vacuum sublimation and zone melting processes require inert and high-temperature resistant refractory materials.

2.1.2 Aluminium

Aluminium is used in many industries because of its light weight, corrosion resistance and good conductivity. It plays a key role in the transport sector, particularly in the automotive and aerospace industries, where it is used to reduce weight and improve energy efficiency. It is also used in the construction industry for facades, window frames and structural components. In the packaging industry, aluminium is widely employed for its barrier properties in beverage cans and films, and as a conductor and heat sink in electronics and energy technology. Aluminium is a critical element for the European Union as its production is very energy intensive and the EU is highly dependent on imports of both aluminium and bauxite, the raw material for aluminium production (supply risk: 1.2; economic importance: 5.8). This makes the EU vulnerable to supply shortages and price fluctuations on the world market. [6,12]

2.1.2.1 Extraction of aluminium

The production of aluminium involves two major steps (Bayer proces and electrolysis), which are shown in Figure 7.

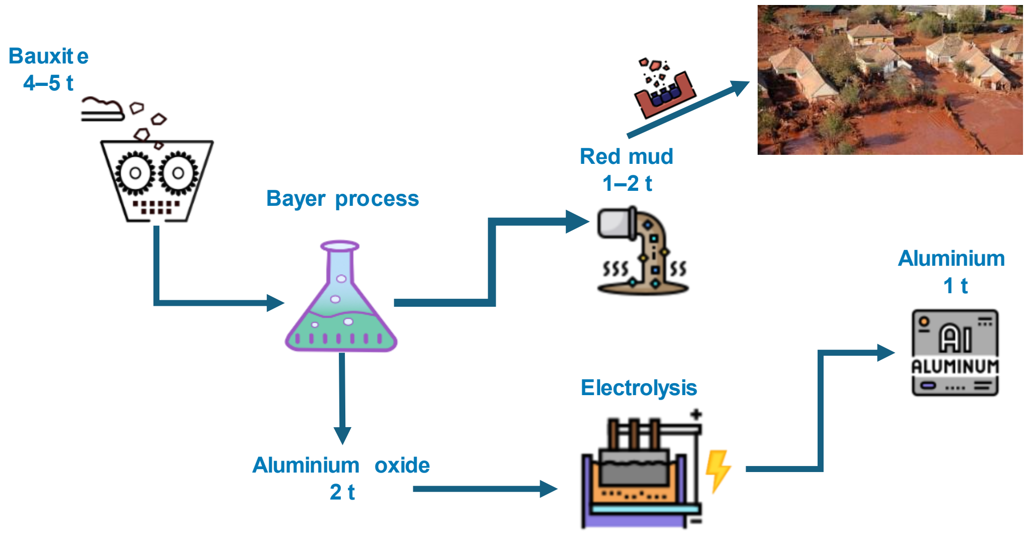


Figure 7: Primary production route of aluminium

The starting raw material for the production of aluminium is bauxite. The Bayer process, which comprises the first step in Al production, is a process for digesting bauxite with aqueous caustic soda at high temperatures and usually takes place in a tubular reactor at increased pressure. The end product is an aluminium hydroxide, which is precipitated from the sodium hydroxide solution by seeding with solid $Al(OH)_3$. This hydroxide is calcined to Al_2O_3 in a rotary kiln.

In the second step (fused-salt electrolysis) aluminium metal is produced. To achieve this, the previously obtained Al_2O_3 is dissolved in cryolite and decomposed into aluminium and oxygen using direct current. [6,13]

2.1.2.2 Use of magnesia in the production of aluminium

The use of MgO is irreplaceable, especially in the production of aluminium. The process parameters in aluminium production are selected to dissolve or melt aluminium. The use of a high quality of refractory material is therefore necessary. The simultaneous high temperatures and chemically aggressive conditions that prevail in fused-salt electrolysis require chemically resistant refractory materials.

2.1.3 Bismuth

Bismuth is used in a wide range of industries due to its unique properties. It serves as an efficacious non-toxic replacement for lead in applications such as pharmaceuticals, cosmetics and ammunition, thus rendering it a valuable component in environmentally friendly products. It is also used in alloys for fire detection systems and low melting point solders, as well as in the manufacture of metallurgical additives and catalysts.

For the European Union, bismuth is considered a critical element because it is mainly obtained as a by-product of the extraction of other metals, making its supply dependent on the production of those metals. In addition, the EU has limited domestic production and relies heavily on imports, particularly from non-EU countries (China: 70%), which increases supply risks and contributes to its critical status in meeting EU industrial needs (supply risk: 1.9; economic importance: 5.7). [11,14]

2.1.3.1 Extraction of bismuth

Bismuth is only found in small quantities in the earth's crust. Typical ores are bismuth lustre (Bi_2S_3) or bismuth coker (Bi_2O_3). A large proportion of bismuth originates from the copper and lead industry. Due to the process management, bismuth is usually concentrated in sludge from lead and copper electrolysis and in the slag from the Kroll Betterton process. Processing is time-consuming due to the complex composition of the starting materials and requires many process steps to remove the impurities. The latter can be carried out by means of zone melting or vacuum distillation. [6]

Bismuth is primarily produced from bismuth-containing ores, such as bismuthinite (Bi_2S_3), through a process that begins with roasting (see Figure 8). During roasting, the ore is heated in the presence of oxygen to remove sulfur, resulting in the formation of bismuth oxide (Bi_2O_3). This oxide is then subjected to carbothermic reduction, where it is heated with carbon (typically coke or coal) at high temperatures. The carbon acts as a reducing agent, converting the bismuth oxide into metallic bismuth by releasing carbon dioxide (CO_2). The final product is purified through additional refining processes, depending on the required purity level. [6]

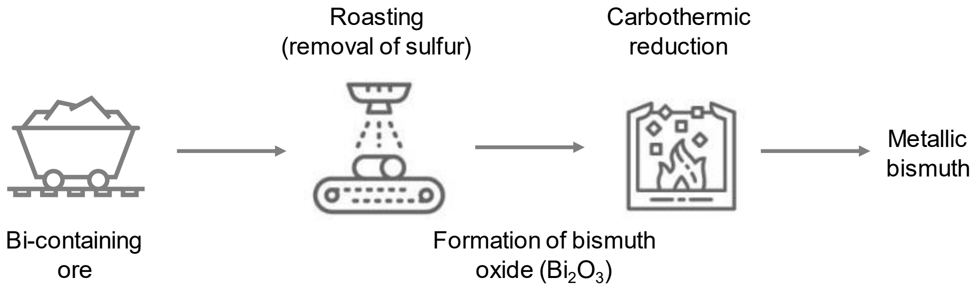


Figure 8: Primary production route of bismuth

2.1.3.2 Use of magnesia in the production of bismuth

The process sequences show that the production of bismuth involves a large number of different aggregates (especially for high-purity bismuth). The conditions in some of these are critical for the refractory material and therefore require careful selection. Aggregates within a alkaline environment are essential for the extraction of bismuth. Due to this, MgO is required as the refractory material in these aggregates.

2.1.4 Copper

Copper is an indispensable metal in many technological and industrial applications, particularly in electronics and electrical engineering. Because of its excellent conductivity, copper is used in power cables, electrical wires, transformers and motors. It also plays a key role in the construction industry, in heat exchangers and in the manufacture of pipes and fittings. With increasing electrification, for example through the development of renewable energies and electromobility, the demand for copper is rising steadily. [15]
Copper is a strategic raw material for the European Union, as Europe is highly dependent on imports and the main producing countries, such as Chile and Peru, are exposed to geopolitical and environmental challenges. Copper's strategic importance lies in particular in its key role in energy infrastructure, digitalisation and decarbonisation, which makes a secure and sustainable supply essential for Europe (supply risk: 0.1; economic importance: 4.0). [11]

2.1.4.1 Extraction of copper

The production of copper comprises two major areas. Firstly, the pyrometallurgical route for sulphidic ores and secondly a hydrometallurgical route for oxidic ores. The process sequence can be seen in Figure 9. [6,12]
The pyrometallurgical extraction of copper initiates with the crushing and grinding of the sulphide ore, with the objective of separating the copper-bearing minerals from the gangue. Subsequently, the ore is subjected to a roasting process, whereby sulphur is separated. In the smelting process, impurities (slag) are removed and a copper matte is produced. In a

subsequent converter process, the copper is further purified by oxdidation of any remaining impurities. Finally, the copper is electrolytically cleaned in a refining process to obtain high-purity copper. [6,12]

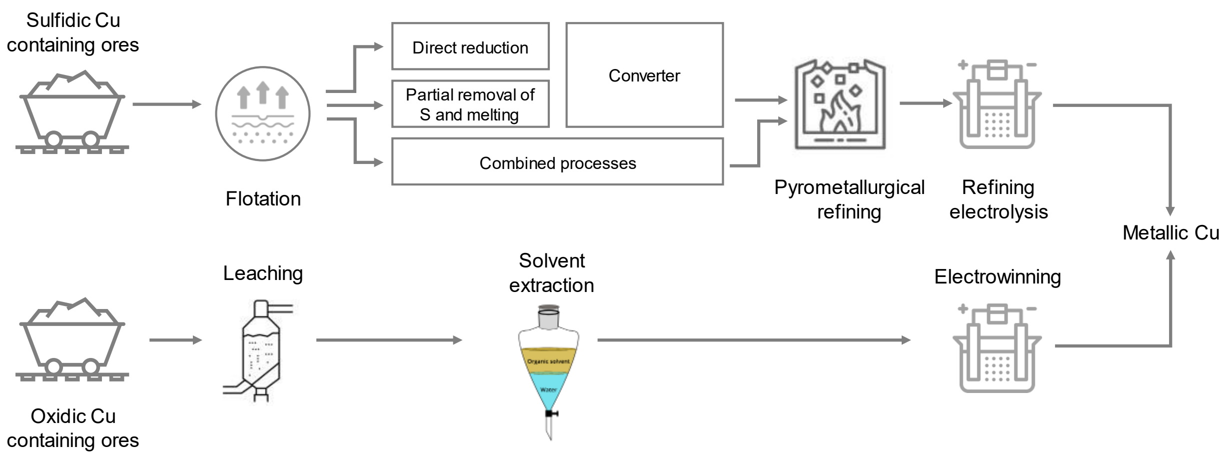


Figure 9: Primary production route of copper for oxidic and sulfidic ores

2.1.4.2 Use of magnesia in the production of copper

Magnesia is primarily used in the pyrometallurgical route. The reason for this is the high process temperatures that are required in the primary pyrometallurgical route, as well as in the recycling of copper scrap. Another point is the alkalinity of the slag. In the presence of basic slags as found in the converter, the use of basic refractory material is common.

2.1.5 Cobalt

Cobalt is an essential metal for many industrial applications, particularly in the manufacture of lithium-ion batteries used in electric vehicles, portable electronic devices and stationary energy storage systems. It is also widely used in high temperature resistant superalloys for aerospace and gas turbines. In the chemical industry, cobalt is used as a catalyst and in magnetic alloys. [16]

Cobalt is a critical raw material for the European Union as it is highly dependent on imports and the main sources of supply are located in politically unstable regions such as the Democratic Republic of Congo (63%). These geopolitical risks, combined with the central role of cobalt in the energy transition and technological development, make a secure supply strategically vital for Europe (supply risk: 2.8; economic importance: 6.8). [11]

2.1.5.1 Extraction of cobalt

Cobalt ores can be divided into three groups: sulphide, oxide and arsenide. Cobalt is extracted via a hydrometallurgical process. However, pyrometallurgical pretreatment is carried out first to concentrate the ore and facilitate the leaching process (see Figure 10). [6,12]
Sulphide ores usually contain high levels of copper and are therefore considered copper ores. Flotation can be used to concentrate these and oxidic ores. The sulphide ores are then roasted. The concentrated oxidic components obtained in this way can now be acid leached and then separated electrolytically. [6,12]

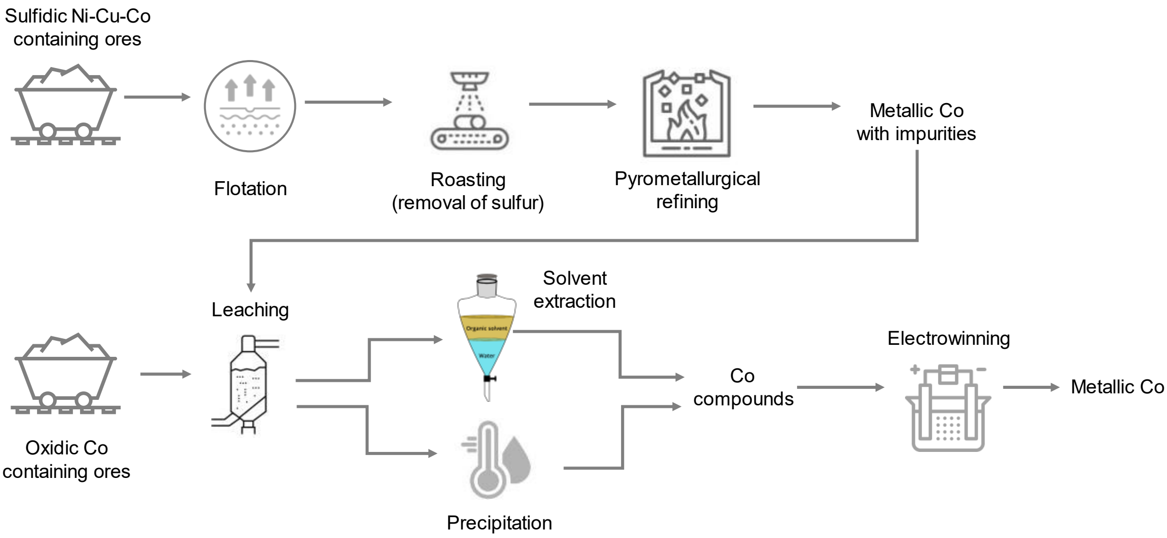


Figure 10: Primary production route of cobalt for oxidic and sulfidic ores

2.1.5.2 Use of magnesia in the produciton of cobalt

Magnesia bricks are a significant input in the co-processing of cobalt via the copper extraction route (see chapter 2.4.2) and are also required for the pyrometallurgical pre-treatment of sulphide cobalt ores..

2.1.6 Manganese

Manganese is an essential metal that is primarily used in the steel industry, where it is employed as an alloying element to enhance the strength, resilience and wear resistance of steel. Additionally, manganese is employed in the manufacture of high-strength aluminium and in the production of batteries, particularly lithium-ion batteries. In smaller quantities, manganese is employed in the chemical industry as a catalyst. [17]
Manganese is regarded as a critical raw material for the European Union, given the EU's significant reliance on imports, particularly from countries such as South Africa (41%), Gabon (39%) and Brazil (8%). As manganese is indispensable for the steel sector and battery

technology, ensuring a secure supply and stable trade relations is of paramount importance for European industry and the energy transition (supply risk: 1.2; economic importance: 6.9). [11]

2.1.6.1 Extraction of mangenese

Manganese occurs naturally only as rich oxidic ore. Enrichment is therefore not always required, but often flotation or gravity separation is performed. Extraction is carried out either pyrometallurgically or hydrometallurgically. Pyrometallurgical extraction is done either by carbothermic reduction or by silicothermic/aluminothermic processes (see Figure 11). [6,12]
Hydrometallurgy is also used for the extraction of high-purity manganese. In this process, the manganese ore is leached with sulphuric acid or another alkaline solution, causing the manganese to dissolve. Subsequently, the manganese is electrolytically separated in order to obtain a high-purity metallic manganese product. [6,12]

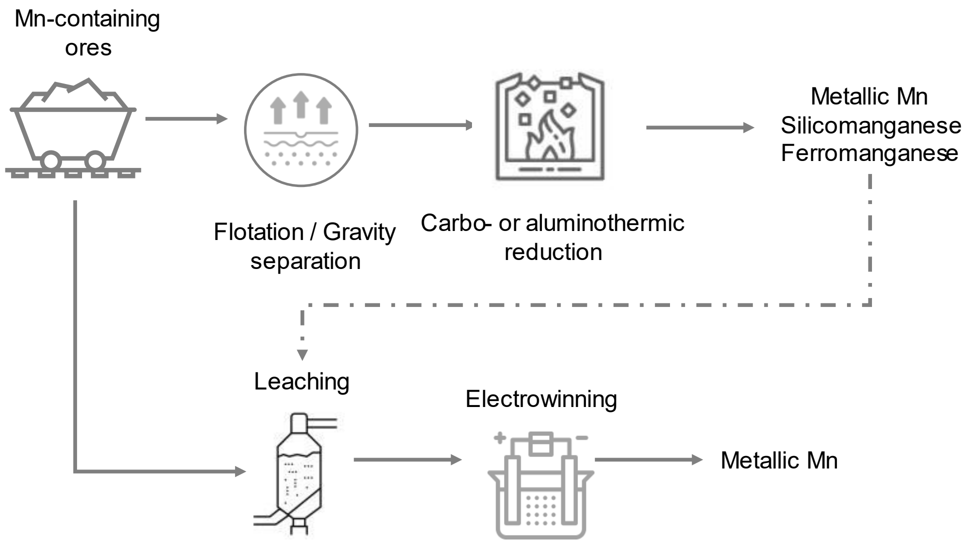


Figure 11: Primary production route of manganese

2.1.6.2 Use of magnesia in the production of manganese

The production of manganese (in particular, ferromanganese) from manganese-bearing ores, such as pyrolusite (MnO_2), necessitates the utilisation of elevated temperatures to facilitate the reduction and melting of the metal. The production of basic slags necessitates the use of magnesia-based refractory materials, given the latter's high resistance to basic slags and high temperatures.

2.1.7 Nickel

Nickel is an essential metal with a wide range of applications, particularly in the production of stainless steel and high-performance superalloys used in the aerospace, chemical and energy sectors. Furthermore, nickel is a vital component in the production of batteries, particularly in

lithium-ion batteries for electric vehicles and stationary energy storage systems. This makes it a important element in the process of electrification and the transition to a more sustainable energy source. [18]
The European Union is heavily reliant on imports of nickel from geopolitically sensitive regions, including Russia (29%), Indonesia and the Philippines. This dependency makes nickel a critical raw material for the EU, as it is not only of central importance for the steel and alloy industry, but also for the strategic further development of sustainable technologies, which requires a stable and diversified supply to be secured (supply risk: 0.5; economic importance: 5.7). [11]

2.1.7.1 Extraction of nickel

The majority of nickel is extracted from iron ores containing nickel and copper. To make it economically viable, the nickel content must first be increased to approx. 5% by flotation. The ore is then roasted in a similar way to copper production. In this step, the ore is first pre-roasted to convert some of the iron sulphide to iron oxide. Silicates and coke are then added to slag the iron oxide as iron silicate. At the same time, a copper-nickel phase is formed, consisting of nickel, copper and iron sulphide. As this is specifically heavier than the iron silicate slag, the two phases can be tapped separately. [6,12]
The sulfidic phase is transferred to a converter where silicon dioxide is added. By oxidation, the remaining iron sulphide is removed. The result is copper-nickel phase, which contains about 80% copper and nickel and about 20% sulphur. [6,12]
In order to remove nickel from the copper, the material is melted with sodium sulphide. Two easily separable phases of copper-sodium double sulphide (liquid) and nickel sulphide are formed. After separation, the nickel sulphide is roasted to nickel oxide and then reduced to nickel with coke. Nickel with a purity of 99.9% can now be achieved using electrolysis.
There are also a number of hydrometallurgical processes for processing nickel-bearing intermediates and low-nickel concentrates. One example is direct leaching (Sherritt-Gordon process), which involves two-stage leaching with NH_3. [6,12]
Given the multitude of process routes for the production of nickel, which are contingent upon the ore composition and the technical capabilities and equipment of the producer, a process diagram is not provided here.

2.1.7.2 Use of magnesia in the production of nickel

Roasting takes place at temperatures between 1100°C and 1230°C in a fluidised bed furnace. This requires refractory materials with good mechanical properties to minimise abrasion and wear. Due to the aggressive environment, the melting units also require the use of magnesia bricks for refractory lining.

2.1.8 Tantalum and Niobium

Tantalum and niobium are metals of significant strategic importance, with a diverse range of industrial applications. Tantalum is primarily employed in the electronics industry for the manufacture of tantalum electrolytic capacitors, which are indispensable components in mobile phones, computers and other sophisticated electronic devices. Tantalum's excellent corrosion resistance also renders it suitable for use in the chemical industry and in medical implants. Niobium is employed primarily in the steel industry, where it is utilized as an alloying agent to enhance the strength and heat resistance of specialized steels utilized in construction, gas and steam turbines, and the aerospace industry, among other applications. [19,20]
Both tantalum (supply risk: 1.3; economic importance: 4.8) and niobium (supply risk: 4.4, economic importance: 6.5) are considered critical raw materials for the European Union, given that the EU is almost entirely dependent on imports from a few countries, including Brazil (92% for Nb) and Rwanda. The significance of these metals for pivotal sectors such as electronics, energy infrastructure and high technology underscores the necessity for a reliable and multifaceted supply chain, particularly in view of the evolving global demand patterns and the inherent geopolitical risks. [11]

2.1.8.1 Extraction of tantalum and niobium

The extraction or enrichment of niobium and tantalum is conducted concurrently and represents the preliminary stage of a slightly different subsequent processing phase (see Figure 12). [6]
Digestion can be carried out pyrometallurgically by melting with alkalis, by chlorination or hydrometallurgically by dissolving in acids. Dissolution is the most frequently used method. The further reduction to metallic niobium can be realised by means of an aluminothermic reaction. An additional option is fused-salt electrolysis or direct hydrogen reduction. Tantalum metal is produced by fused-salt electrolysis using sodium salts. [6]

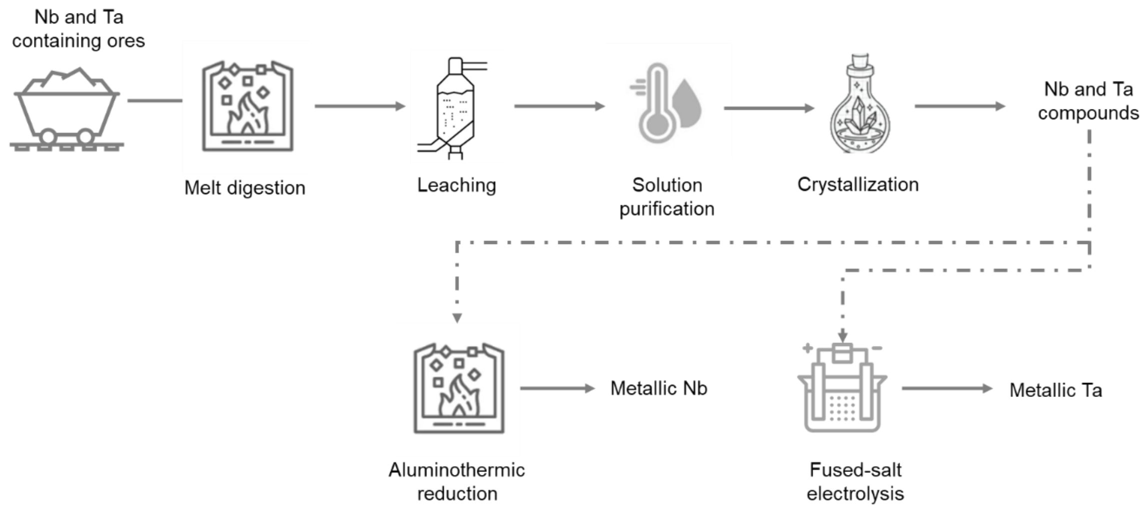


Figure 12: Primary production route of niobium and tantalum

2.1.8.2 Use of magnesia in the production of tantalum and niobium

Digestion and further processing involve very aggressive chemicals and highly reactive compounds. The pyrometallurgical route requires temperatures in excess of 2000°C in some cases. This can only be achieved using special refractory materials (e.g. magnesia bricks).

2.1.9 Titanium

Titanium is a high-performance metal that is utilised in a number of industries, including the aerospace, automotive and chemical sector. Due to its combination of high strength, low weight and excellent corrosion resistance, titanium is an indispensable material for the production of structural components in aircraft, engines and space systems. Additionally, titanium is employed in the field of medical technology, where it is utilised in the fabrication of implants and prostheses. Furthermore, it is utilised in the energy industry, where it is incorporated into heat exchangers and offshore applications. [21]
From the perspective of the European Union, titanium is a critical raw material, given the EU's substantial reliance on imports of titanium ore and titanium metal, particularly from countries such as Russia and Kazakhstan. The strategic importance of titanium for European industry, particularly in security-related areas such as the defence and aerospace industries, and the concentration of global production in just a few countries make a stable and diversified supply essential for the EU (supply risk: 1.6; economic importance: 6.3; both for titanium metal). [11]

2.1.9.1 Extraction of titanium

Ilmenite, an iron-titanium oxide, is the most important ore in the production of metallic titanium. As illustrated in Figure 13, the initial reduction of the compound occurs in a fluidised bed furnace, in which chlorine is injected. This produces highly volatile chlorides from the titanium and other accompanying elements from the ore. Due to the different boiling points of the impurities, a distillation step is carried out to separate the titanium chloride. This is followed by a reduction using liquid magnesium (Kroll process) through which the titanium chloride is passed. [6]

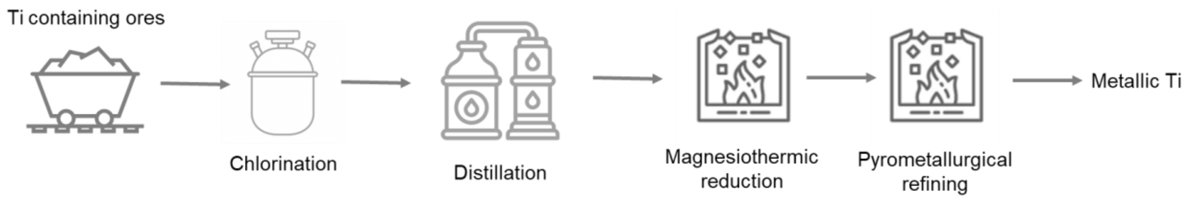


Figure 13: Primary production route of titanium

2.1.9.2 Use of magnesia in the production of titanum

The Kroll process involves process temperatures in excess of 900 °C, which, combined with aggressive chemical reactions, require a refractory material that can withstand them. Another critical factor is the chemical inertness between titanium compounds and MgO.

2.1.10 Vanadium

Vanadium is an indispensable alloying element, predominantly utilised in the steel industry to enhance the strength, resilience and corrosion resistance of steels. Vanadium alloys, particularly ferrovanadium, are employed in the production of high-strength steels for utilisation in construction, pipelines and the automotive industry. Furthermore, vanadium is integral to the production of vanadium redox flow batteries (VRFBs), which are regarded as a promising energy storage technology for renewable energies. [22]

Vanadium is a critical raw material for the European Union, given the EU's substantial reliance on imports, particularly from countries such as Russia, China and South Africa. The strategic importance of vanadium for steel production and its emerging importance in energy storage make the maintenance of a stable and diversified supply essential to support technological advances and the energy transition in the EU (supply risk: 2.3; economic importance: 3.9). [11]

2.1.10.1 Extraction of vanadium

In addition to vanadium ores themselves, vanadium-bearing iron ores are among the most important raw materials for the production of V_2O_5. Vanadium is reduced with the iron ore in the blast furnace and ends up in the pig iron. Vanadium is oxidised in the LD converter and can then be found in the slag. A magnetic separator is used to concentrate the vanadium compounds. These are pelletised with sodium sulphate and sodium chloride and heated in a rotary kiln. This produces water-soluble $NaVO_3$, which can be leached. After basic precipitation and drying, V_2O_5 is produced. This is then metallothermally reduced. A calciothermic reduction using Ca and CaCl in a high vacuum produces 99.9% vanadium as the final product (see Figure 14). [6]

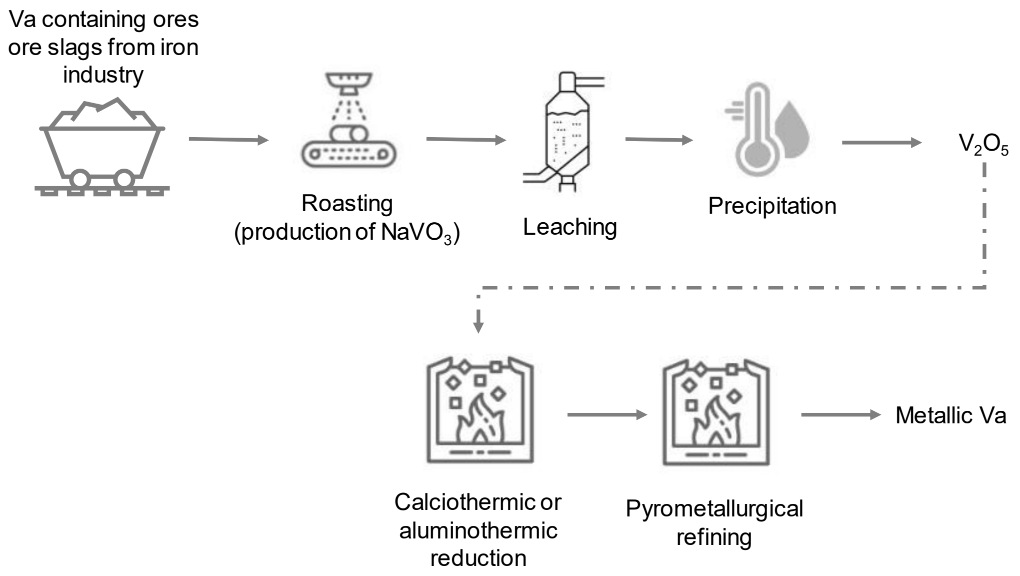


Figure 14: Primary production route of vanadium

2.1.10.2 Use of magnesia in the production of vanadium

Alkaline process conditions, such as those found in slag or during calciothermic reduction, require basic refractory materials.

2.1.11 Silicon

Silicon is a pivotal material in the electronics and solar industries, as well as in the production of aluminium alloys. High-purity silicon is employed in the semiconductor industry for the manufacture of microprocessors, memory chips and other electronic components. Furthermore, silicon plays a important role in photovoltaics, where it serves as the primary material for solar cells. In the field of metallurgy, silicon is employed as an alloying agent in aluminium and steel alloys, enhancing their strength and corrosion resistance. [23]

Silicon is a critical raw material for the European Union, as the EU is dependent on imports of silicon metal, particularly from China. The high level of dependence on a limited number of supplier countries, coupled with the pivotal role of silicon in emerging technologies such as renewable energy and electronics, underscores the necessity for a secure and diversified supply chain to ensure the continued technological and industrial competitiveness of the EU (supply risk: 1.3; economic importance: 4.9). [11]

2.1.11.1 Extraction of silicon

The production of silicon commences with the reduction of quartz sand to metallurgical silicon in an electric arc furnace (see Figure 15). The melting of quartz sand occurs at temperatures of approximately 2,000 °C in an electric arc furnace, accompanied by the presence of coke, which serves as a reducing agent. In this reaction, silicon dioxide is reduced to metallic silicon. For applications in the electronics and solar industry, this silicon is subjected to further purification by chemical processes in order to obtain high-purity polysilicon. This polysilicon can then be processed further into monocrystalline form, which is employed in the production of semiconductors and photovoltaics. [6,24]

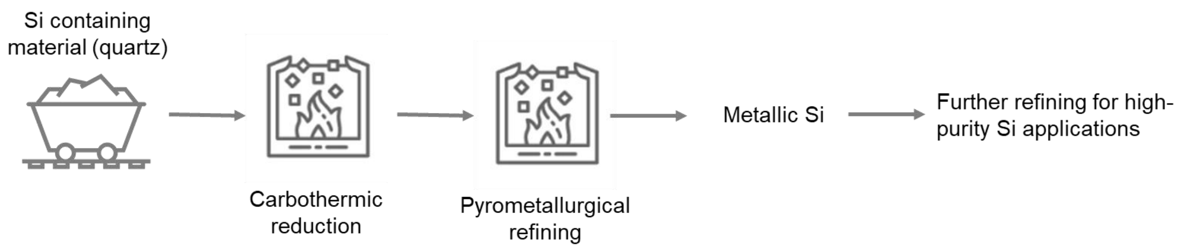


Figure 15: Primary production route of silicon

2.1.11.2 Use of magnesia in the production of silicon

Magnesia plays a pivotal role in the production of silicon, particularly in the manufacture of refractory products that are essential for high-temperature processes. Due to its high melting point and excellent thermal stability, magnesia is employed as a refractory lining material in electric arc furnaces in which silicon is extracted from quartz sand at temperatures exceeding 2,000 °C.

2.2 Production of magnesium

In addition to the use of magnesite by calcination as magnesia in refractory bricks, the production of magnesium is another application in the field of critical raw materials. This approach is discussed in the following sections.

2.2.1 Concentration and preparation for reduction

Various processes have been developed for obtaining the (anhydrous) magnesium chloride required for fused-salt electrolysis, which can be categorised as follows:

- Processing of carnallite
- Dehydration of magnesium chloride hydrates
- Chlorination of oxidic or carbonatic magnesium compounds

The extraction takes place in three stages:

- Production of mainly anhydrous $MgCl_2$
- Fused-salt electrolysis
- Refining (must also be carried out in the silicothermic magnesium production)

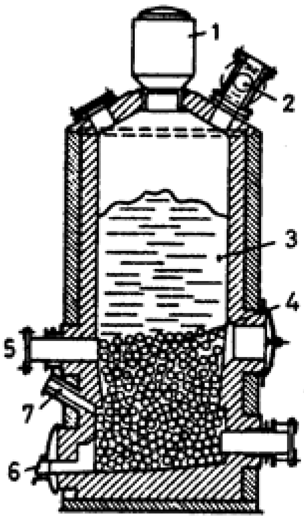
Fused-salt electrolysis with dissolved MgO in a MgF_2 melt fails because of the low solubility of the MgO. Additives to increase the solubility and lower the melting point are only possible to a very limited extent, since the Mg formed decomposes the additives magnesiothermically and is itself contaminated in the process. Therefore, only the fused-salt electrolysis of $MgCl_2$ is carried out. [6,12]
The $MgCl_2$ for the fused-salt electrolysis is produced via the

- Final leaching liquors from the potash industry,
- production from seawater,
- production from magnesite.

For some electrolysis processes anhydrous $MgCl_2$ is necessary, so at the end of the fluidised bed $MgCl_2$ extraction processes are realized via three or more stages. In particular, the removal of H_2O and sulphates is necessary, as they reduce the current yield due to side reactions and contribute to sludge formation. [6,12]
Magnesite is calcinated at a low temperature to prevent grain enlargement and the associated reduction in reactivity. The calcinated magnesite is mixed with coal and magnesium chloride liquor to form a paste, extruded and cut into small briquettes. In a shaft furnace (see Figure 16), the lower part is filled with coke that serves as a resistor for the electric heating, the briquettes are fed in at the top and chlorine gas is introduced. At 900–1,000 °C, the formation of $MgCl_2$ takes place according to the equation: [6,12]

$$MgO + C + Cl_2 \Leftrightarrow MgCl_2 + CO$$

The impurities of the magnesite such as Si, Al, Fe are discharged as highly volatile chlorides with CO and excess Cl_2, and liquid $MgCl_2$ is withdrawn at the bottom. The operation is continuous. [6,12]
For the silicothermic reduction of magnesium oxide (MgO), 70–85% FeSi as reducing agent and calcinated dolomite as Mg source have proven successful. Additional preparation of feedstock is not necessary for this production route. [6,12]



1…Input, 2…Off-gas, 3…Briquettes, 4….Resistive carbon, 5… Electrode, 6… Tapping, 7… Chlorine gas

Figure 16: Chlorination furnace for the production of magnesium chloride [12]

2.2.2 Extraction processes A: Fused-salt electrolysis

In the fused-salt electrolysis of magnesium chloride with the addition of other alkali chlorides, the following are produced at 700–800 °C after the reaction

$$MgCl_2 \leftrightarrow Mg + Cl_2$$

magnesium and chlorine gas are produced.

One of the basic conditions of fused-salt electrolysis is a minimum difference in the densities of metal and electrolyte, so that there is sufficient separation and no formation of metallic mist. In practice, various salt mixtures have a higher density than the liquid Mg, so that the deposited liquid metal floats on top. Table 1 lists some electrolyte compositions including physical data. [6,12]

Table 1: Electrolyte composition and physico-chemical data [6,12]

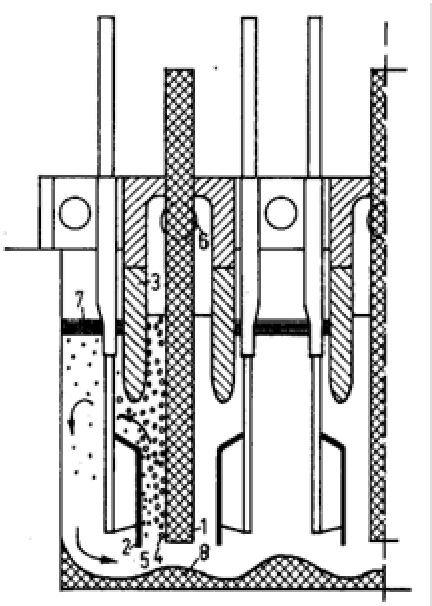
Electrolyte type	Composition in %	Solidification	Density	Temperature: 700 °C		
				El. Conductivity	Viscosity	Surface tension
		[°C]	[kg·m^{-3}]	[S . m^{-1}]	[mPa·s]	[mN·m^{-1}]
Potassium	5-12 $MgCl_2$, 70-78 KCl, 12-16 NaCl	650	1600	183	1.35	104
Sodium/Potassium	10 $MgCl_2$, 50 NaCl, 40 KCl	625	1625	200	1.58	108
Sodium/Calcium	8-16 $MgCl_2$, 30-40 $CaCl_2$, 35-45 NaCl, 0-10 KCl	575	1780	200	2.22	110
Lithium/Potassium	10 $MgCl_2$, 70 LiCl, 20 KCl	550	1500	420	1.20	-
Lithium/Sodium	10 $MgCl_2$, 70 LiCl, 20 NaCl	560	1521	488	-	-
Natrium/Barium	10 $MgCl_2$, 20 $BaCl_2$, 50 NaCl, 20 KCl	686	1800	217	1.70	110
Magnesium		649	1580			

General technical data of the industrial electrolysis plants are:
Current density: 2,000–8,000 A/m²
Electrode distance: 3–12 cm
Energy consumption: 10–20 kWh/kg
Current efficiency: 75–95%

IG cell

This cell, developed more than 50 years ago, is still in use today, except for a few improvements. Figure 17 shows the section of such a cell. The graphite anodes are connected to a chlorine bonnet, iron cathodes are placed in the lower part quite close to the anode to force a small bath voltage and a good bath circulation. About 10% of sludge is produced per ton of Mg, which consists of NaCl, CaCl2 and MgO and has to be removed periodically. The following operating data are available: [6,12]

Cell voltage: 5.5–6.0 V (50% decomposition voltage)
Temperature: 700–750 °C
Current efficiency: 80–90%
Total current: 150 kA
Energy consumption: 15–18 kWh/kg Mg

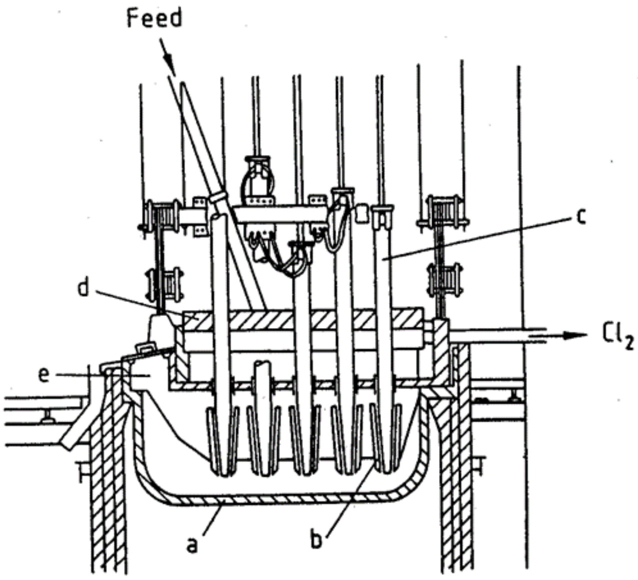


1…Anode, 2…Cathode, 3…Separation wall, 4…Chlorine bubbles, 5…Magnesium drops, 6…Chlorine off gas, 7…Magnesium layer, 8…Sludge

Figure 17: Section of an IG cell (electrolyte flow and product separation) [12]

DOW cell

Hydrous $MgCl_2$ is introduced to this cell. While the IG cell is heated by the cell current, the DOW cell hast to be heated also from the outside, as Figure 18 shows. The iron cathodes are attached to the container, the graphite anodes are consumed by reaction with water and must be replenished. The anode gas consists not only of chlorine, but also contains HCl, CO and CO_2. It is burnt with hydrogen to form hydrochloric acid gas and is used to dissolve the precipitated $Mg(OH)_2$. The cells are operated at 90 kA and have a relatively poor current efficiency of less than 80%. Therefore, despite saving the heating current, the energy consumption is about the same as for the IG cell. [12]



a…Steel container, b…Steel cathode, c…Graphite anode, d…Ceramic lid, e…Metal container

Figure 18: Schematic illustration of the DOW cell [6,12]

There are other types of fused-salt electrolysis, but the basic principle is the same for all of them. The individual cells (IG-Norsk-Hydro, VAMI, Alcan, Ishizuka and DOW cells) differ in the feed (anhydrous or hydrous $MgCl_2$), the structure of the electrolysis cell and the materials used. [12]

2.2.3 Extraction process B: Silicothermic magnesium production

The extraction is based on the following equation:

$$2\,(CaO \cdot MgO) + Si(Fe) \Leftrightarrow 2\,Mg_{(g)} + 2\,CaO + SiO_2 + (Fe)$$

The corresponding G°-T curves for different negative pressures are given in Figure 19. Furthermore, the working ranges of the individual processes used in practice are drawn. In fact, the reaction proceeds via several intermediate stages, the most important of which is the formation of Ca_2Si, which forms a ternary eutectic melting below 1000 °C with the ferrosilicon present. The liquid phase contributes significantly to the acceleration of the solid reaction. [1,4]

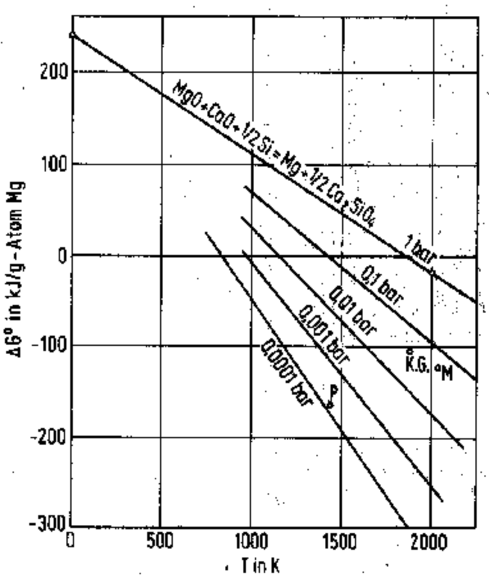
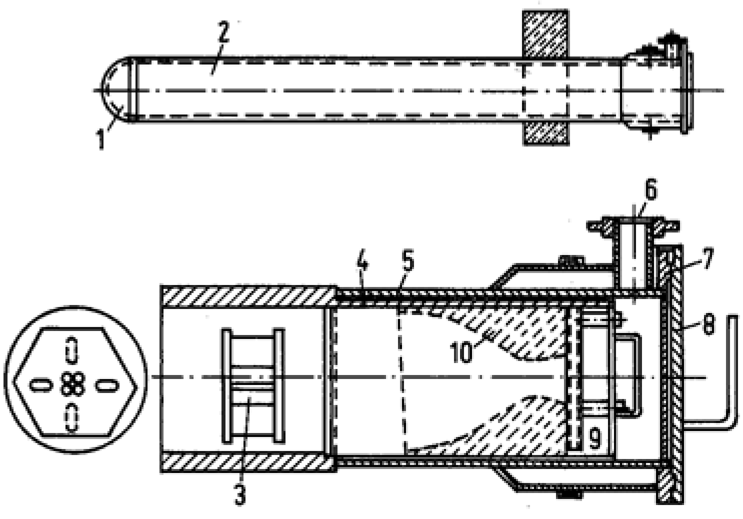


Figure 19: Free enthalpy of reaction in Mg extraction as a function of pressure and temperature (P...Pidgeon process, K.G....Knapsack-Griesheim and M...Magnetherm process) [6,12]

<u>Pidgeon process</u>

The oldest process still in operation bears the name of its inventor, Pidgeon. China produces all of the Mg with this technology. Calcinated dolomite and ferrosilicon with 75% Si are finely ground, briquetted and heated to 1170 °C in horizontal retorts made of Cr-Ni steel at a negative pressure of 0.13 mbar. The Mg vapour formed is condensed at the cold end of the retort (see Figure 20), where a radiation shield facilitates condensation. Up to 40 retorts with a diameter of 0.3 m and a length of 3 m are housed in an electrically heated furnace. Approximately 100 kg of briquettes are heated for about 10 hours, yielding 14 kg of Mg. [6,12]

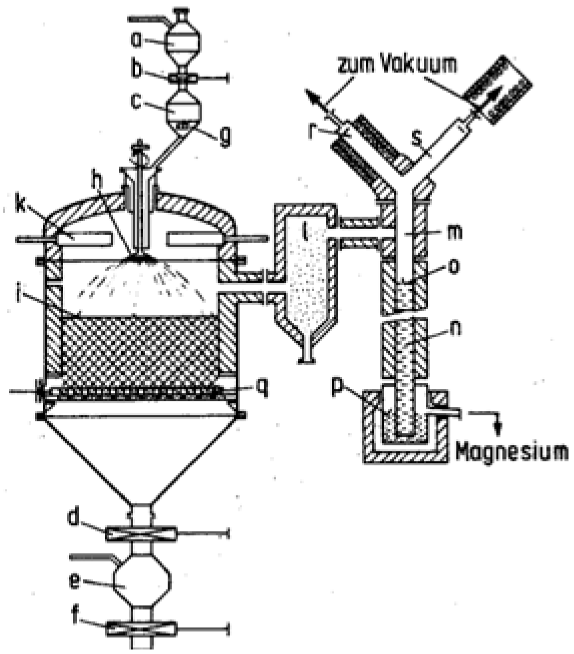


1, 2... Retort made of Cr-Ni steel, 3... Radiation shield, 4, 5...Conical bushing, 6...to vacuum pump, 7, 8....End cap, 9...Alkali collector, 10...Condensed Mg

Figure 20: Schematic drawing of a retort (Pidgeon) [12]

Knapsack-Griesheim process

A conversion to a continuously operated process was carried out by Knapsack-Griesheim AG (see Figure 21). The solid materials are fed in and discharged via a system of vacuum locks. The briquettes are heated to 1,600 °C by radiation using graphite resistance elements. The metal vapour is condensed after flowing through a dust chamber and collected in a liquid column so that the discharge of the liquid Mg can take place continuously at normal pressure. At the high reaction temperature of 1,600 °C, a moderate vacuum of approx. 40 to 45 mbar is sufficient. However, this process is not currently used industrially. [6,12]

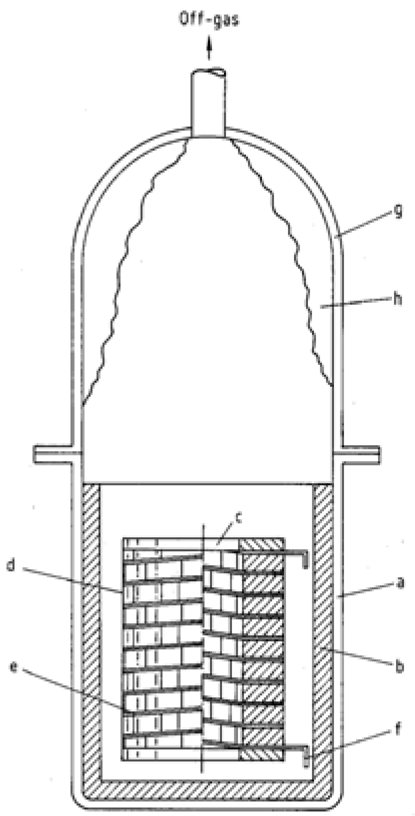


f...Vacuum locks, g...Dosing device, h...Distributor, i...Surface of the residue, k...Radiation source, l...Dust chamber, m...Condenser, n...Liquid metal column, o, p...Liquid level of the columns, q...Cooled grate, r, s...Condensers connected in parallel

Figure 21: Schematic drawing of the continuous process of Knapsack-Griesheim AG [4]

Bolzano process

In this process, a refractory-lined reactor (see Figure 22), which is heated from the inside, is used. The briquettes of dolomite and FeSi are loaded onto a charging system. The internal electrical heating is connected to the charge via the charging system. The process operates at approx. 1,300 °C and < 4 mbar. The Mg vapour condenses in the water-cooled condenser at 400 to 500 °C. The reactor has a capacity of about 2 t per day. Per t of Mg, about 5 t of slag are produced, which can be sold. The difficulties in this process are the discontinuous charging and the removal of the slag. However, this process is not currently used industrially. [6,12]

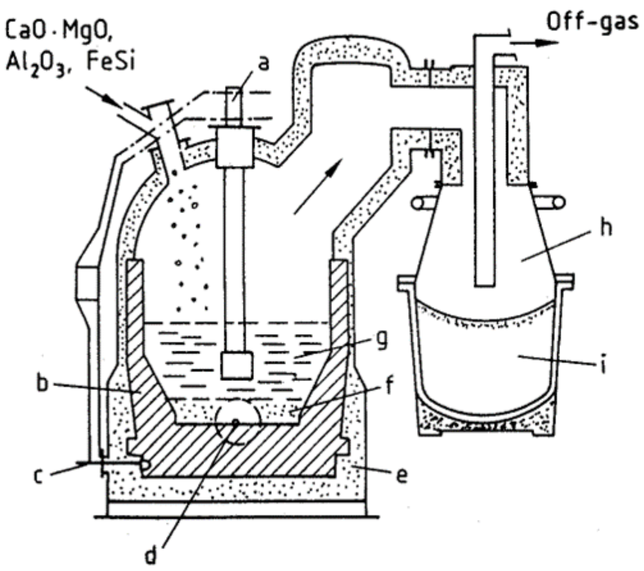


a...Steel shell, b...Brick lining, c...Exchangeable charging vessel d...Charged briquettes, e...Charging device, f...Electrical contact for heating, g...Exchangeable condenser, e...Condensed Mg

Figure 22: Schematic drawing of the Bolzano reactor [4,5].

Magnetherm process

The final step in the development was the Magnetherm process, where a liquid slag is used. The slag composition is determined by the melting point, which is lowered to 1,380 °C by adding Al_2O_3 to $CaO{\cdot}SiO_2$ (melting point 2,130 °C). This process requires less than 9 kWh/kg Mg. The FeSi is not completely converted, a magnesium-containing 20% FeSi alloy remains, which is sold in the steel and cast iron industries. The slag can be used in the cement industry. Figure 23 shows the scheme of a reduction furnace. In a shaft-like vessel there is a slag container, which is kept liquid by resistance heating. The current is fed from the top through a water-cooled electrode, the other pole being the graphite-lined bottom. The material is added continuously and consists of a mixture of calcinated dolomite, bauxite and 75% FeSi. The distilled Mg is condensed to solid metal in a crucible. The slag is periodically tapped off under normal pressure. The crucible with solid Mg is changed every 12 hours and re-melted in an associated foundry, refined with a molten salt and cast into ingots. This process was also used for the recycling of hazardous waste, however, it is not currently used industrially [1,5]



a...Copper electrode, b...Graphite lining, c...Bottom electrode, d...Tapping hole, e...Refractory lining, f...FeSi, g...Slag, h...Condenser, i...Crucible in the condenser

Figure 23: Schematic drawing of a Magnetherm reactor [6,12]

2.3 Magnesia as a refractory material

In the following section, the role of magnesia as a refractory material is discussed in detail.

2.3.1 Basics of refractory materials

The basic materials for the production of refractories are generally carbon (C) and the following six oxides: [25]

- SiO_2: Silica
- Al_2O_3: alumina
- Cr_2O_3: Chromium(III) oxide
- MgO: Magnesia
- CaO: calcium
- ZrO_2: Zirconia

For the production of products with grain sizes up to 6 mm, in special cases up to 25 mm, the so-called coarse ceramic production is used. [25]
The production process is divided into the following steps: [25]

- Preparation
- Mixing
- Moulding
- Drying and heat treatment up to 800 °C

- Calcination

During calcination, the characteristic structure of the refractory material is created by transformations, reactions in the solid state, recrystallisation, melt phase formation as well as by dissolution and precipitation processes. This refers to the type, quantity, size, shape, orientation and arrangement of the phases that make up the material. [25]
The three main structural components of fired refractory materials are: [25]

- The grain, which is usually not significantly changed during calcination.
- The binding matrix, which is only formed during calcination and is usually more porous than the grain.
- The pores, which basically determine many properties.

With increasing calcination temperature and time, the porosity usually decreases and the cold and hot strength, the pressure softening, the average pore size and thus the gas permeability as well as the crystallite size increase. The firing temperatures are limited upwards by a strong shrinkage or by deformations, as a result of which the required shape and dimensional accuracy of the bricks is lost. [25]

2.3.2 Magnesia bricks

The main component of magnesia bricks is magnesium oxide (MgO). Iron and aluminum silicates are added in small quantities to modify specific properties such as thermal expansion and chemical resistance. Additives such as chromium oxide (Cr_2O_3) or carbon (C) are added for specific applications. [7]
In general, four different types of magnesia bricks can be distinguished: [7]

- Calcined magnesia bricks: These are manufactured by calcination of magnesite ($MgCO_3$) or other magnesium-containing materials at high temperatures (approx. 1400–2000 °C).
- Electro-fused magnesia bricks: These are produced by melting magnesite or magnesium oxide in an electric arc furnace and offer higher purity and density.
- Magnesia-chrome bricks: These consist of a mixture of magnesium oxide and chromium oxide and are mainly used for special requirements with higher chemical resistance.
- Magnesia-carbon bricks: These contain a mixture of magnesium oxide and carbon (often in the form of graphite), which is used in high-temperature resistant applications such as steel casting ladles and electric arc furnaces.

Alternative manufacturing processes for dead burned magnesia

The process of solution mining involves extracting magnesium salts, particularly from minerals like bischofite and carnallite, which are located underground, typically at depths of around 1,500 meters. Water is injected into subterranean caverns, where it dissolves the magnesium salts. This magnesium-rich brine is then pumped to the surface for further refinement and processing. This method allows for efficient extraction, as the magnesium salts dissolve preferentially over sodium chloride. [26]

Nedmag operates this process at their facility, utilizing these techniques to extract and process magnesium chloride from the Zechstein salt deposit, ensuring a consistent and high-quality supply of raw materials for their various product lines. [26]

Key Process Steps: [26]

1. **Solution Mining**: Magnesium salts are dissolved by introducing water into caverns and pumped upwards. The salts dissolve preferentially over sodium chloride, making the extraction efficient.
2. **Purification**: Raw magnesium chloride is purified through filtration and oxidation for specific applications.
3. **Flaking**: The magnesium chloride is converted into a solid form by heating and flaking on cooled drums.
4. **Boron Removal and Magnesium Hydroxide Precipitation**: Boron and sulfate are removed to improve the chemical purity for producing high-quality magnesium oxide.
5. **Calcination and Briquetting**: Magnesium hydroxide is dried and calcined to produce magnesium-rich briquettes, which are sintered to create dead burned magnesia (DBM).

The Nedmag process offers several key advantages. Firstly, it is characterized by the high purity of the extracted magnesium chloride brine, containing less than 1% impurities. This is a critical factor for the quality of the final products, such as dead burned magnesia (DBM), magnesium chloride, and calcium chloride. Secondly, Nedmag employs an innovative solution mining method where the selective dissolution of magnesium salts, in preference to sodium chloride, enables efficient extraction of raw materials. This method, combined with the "squeeze mining" technique, where salts are naturally pressed into the caverns, enhances the efficiency and sustainability of the process. [26]

Another significant advantage is the versatility of the production. Nedmag produces a wide range of products, including DBM, CCM, magnesium chloride, and calcium chloride, which are used in various industries, from steelmaking to environmental applications such as dust suppression and de-icing. [26]

Areas of application

Because of their excellent thermal stability, chemical resistance and mechanical strength, magnesia bricks are used in various industries. The most important areas of application include the steel industry (e.g. electric arc furnaces, converters, ladles), the cement industry (e.g. rotary kilns), the glass industry (e.g. glass melting furnaces), non-ferrous metallurgy (e.g. melting furnaces for copper and nickel production) and the ceramics industry (e.g. kilns). The wide range of applications demonstrates the versatility and robustness of magnesia bricks under demanding conditions. [6,7]

2.4 Magnesium in the chemical industry

The importance of magnesium in the chemical industry is considerable, as it plays an indispensable role in many processes and products. Its use as a reducing agent in metallurgy, as a desoxidation agent in the steel industry and as an alloying element in light metal alloys are just a few examples that illustrate the strategic relevance of magnesium. Due to the importance and complexity of the first two applications for European industry, they are discussed in separate chapters. In addition, magnesium offers important advantages for industrial processes and products thanks to its versatility and wide range of applications in chemical synthesis, materials technology and energy storage. [27–30]

The main areas of application for magnesium in the chemical industry include: [27–30]

- Production of light metal alloys: Magnesium is an essential alloying element, especially in the aluminium industry. Aluminium-magnesium alloys are used in many areas due to their low weight, high strength and good corrosion resistance, e.g. in the automotive, aviation and packaging industries.
- Production of magnesium compounds: Magnesium serves as a starting material for the production of various magnesium compounds such as magnesium oxide (MgO), magnesium chloride ($MgCl_2$) and magnesium hydroxide ($Mg(OH)_2$). These compounds are widely used, e.g. in refractory materials, water treatment and as pharmaceutical excipients.
- Anode material in batteries: Magnesium is being investigated and developed as an anode material in batteries, particularly magnesium-ion batteries. These batteries have the potential to be safer and cheaper than conventional lithium-ion batteries, which makes them interesting for future applications in energy supply.
- Chemical synthesis and reactions: Magnesium is widely used as a reagent in organic chemistry, particularly in the Grignard reaction where it is used as a catalyst to form carbon-carbon bonds. These reactions are fundamental to the synthesis of a variety of

organic compounds that are important in the pharmaceutical, polymer and fine chemicals industries.

The two most important magnesium compounds (with the exception of magnesia itself as refractory material) in industry are magnesium hydroxide and magnesium chloride. [27]
Magnesium hydroxide is mainly produced from seawater and brines, from the mineral brucite (which is naturally rich in magnesium hydroxide) or from caustic calcined magnesia (CCM). The world's largest producers and consumers of magnesium hydroxide are China and Japan. In Japan, a significant proportion of magnesium hydroxide is obtained as a slurry from seawater, which is then used directly in flue gas treatment. The demand for magnesium hydroxide, particularly in the form of magnesium dihydrate (MDH) flame retardants, has been growing rapidly due to its excellent smoke suppression properties and ability to withstand processing temperatures in excess of 300°C. [27]
Magnesium chloride is widely used in the manufacture of Sorel cement and in applications such as dust binding, de-icing and thawing, as well as in the food and pharmaceutical industries. Synthetic or recrystallised magnesium sulphate is usually produced by the reaction of caustic calcined magnesia with sulphuric acid or by the recrystallisation of natural kieserite. The most commonly produced form is the heptahydrate salt, known as Epsom salt. More than three-quarters of the magnesium sulphate produced is used in fertilisers and animal feed, underlining its important role in agriculture. [27]
As magnesium oxide is often a starting material for the production of other magnesium compounds or products, the global supply situation for MgO is discussed here. China continues to dominate the market as the largest producer and consumer of magnesium oxide (see Figure 24), as well as the world's largest exporter. In 2023, more than half of mainland China's magnesium oxide exports were refractory magnesia for use in steel and cement production. The remainder was caustic calcined magnesia destined for environmental, construction and agricultural markets. Global consumption of magnesia is expected to grow by an average of 1.2% per year over the period 2023–2028. [27,29]

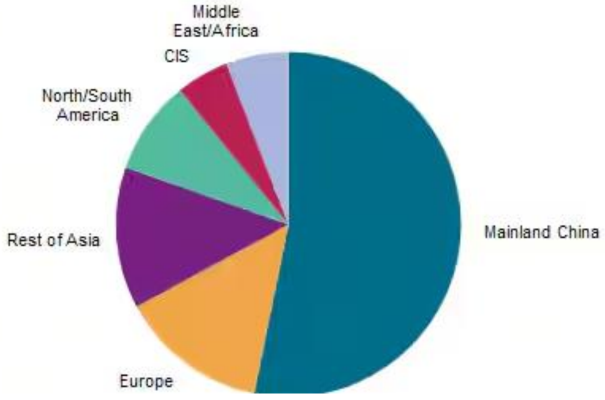


Figure 24: World consumption of magnesium oxide in 2023 [27]

2.5 Magnesium in the steel industry

Magnesium is not only used in the chemical industry, but also in the iron and steel industry in particular. In this industrial sector, magnesia is not only required as a refractory lining in furnaces, but also in form of magnesium for iron and steel desulphurisation. [31]

2.5.1 Sources of sulphur in the iron and steel industry

The majority (over 90%) of the sulphur is introduced via the fuels (coke, blast coal and oil) and the remainder via the burden. The fuels contain organic sulphur, but the ash contains sulphates and sulphides: in the ore and aggregates there are sulphates such as $CaSO_4$, $BaSO_4$ and sulphides such as FeS, FeS_2 and CaS (in the sinter). Sulphur inputs range from 2 to 14 kg per tonne of pig iron. Most of the sulphur (over 90%) leaves the blast furnace with the slag, between 2 and 5% with the blast furnace gas as SO_2 and H_2S. [31]

2.5.2 Pig iron desulphurisation

One option for desulphurising pig iron is precipitation desulphurisation. By adding or injecting elements with an affinity for sulphur, a metal sulphide is formed which is separated (precipitated) from the pig iron (see Equation (1)). [31]

$$Me + [S] \leftrightarrow (MeS) \qquad \text{Equation (1)}$$

Magnesium (Mg) is often used for Me (see Equation (2)). [31]

$$Mg + [S] \leftrightarrow (MgS) \qquad \text{Equation (2)}$$

2.5.3 Steel desulphurisation

Sulphur is generally an undesirable element in steel because it has predominantly negative effects (e.g. embrittlement, segregation). Exceptions are free-cutting soft steels, where sulphur improves machinability. [31]
During refining, there is virtually no oxidation of sulphur in the molten iron, as sulphur is more noble than iron. The most effective desulphurisation takes place at the interface between the molten metal and the basic slag after Equation (3): [31]

$$[FeS] + (MeO) \leftrightarrow (MeS) + (FeO) \qquad \text{Equation (3)}$$

Calcium carbide (CaC_2), CaSi, CaAl, magnesium (Mg) and lime (CaO) can be used as desulphurisation agents. When magnesium is added to molten steel, it reacts with sulfur to

form magnesium sulfide (MgS), a compound with a high melting point that can be easily separated from the steel during slag formation. Magnesium-based desulfurization is particularly effective and is often employed in combination with other agents like calcium carbide or lime to optimize the desulfurization process. [31]
In terms of market dynamics, the use of magnesium for steel desulfurization accounts for a significant portion of magnesium consumption in the metallurgical sector. According to industry analyses, about 14% of primary magnesium metal consumption is directed towards desulfurization in iron and steel production. [32]

2.6 Magnesia in the recycling industry

Magnesia-based refractories are of significant importance within the European recycling industry, particularly in high-temperature applications that are indispensable for the reprocessing of metals, glass and other raw materials. The recycling processes that are currently being implemented in the EU are characterised by a strong focus on circularity and the reduction of the consumption of primary raw materials. In order to withstand the thermal and chemical stresses that are inherent to such processes, it is necessary to utilise specialised equipment. Refractories composed of magnesium oxide (MgO) are distinguished by a high corrosion resistanceand thermal stability, rendering them optimal for safeguarding equipment in harsh recycling environments. [7,33,34]

2.6.1 Steel recycling

The steel recycling industry, which represents one of the largest recycling sectors in Europe, is heavily reliant on the use of electric arc furnaces (EAF). In these furnaces, steel scrap and other metal waste are melted down at temperatures in excess of 3,000 degrees Celsius. Magnesia-based refractory products are employed as a lining material for the inner walls of the furnaces, with the objective of protecting them from corrosion by slag and molten metal. Given the elevated temperatures attained in these procedures, the exceptional thermal characteristics of magnesia are indispensable. In the absence of these refractory materials, the operational availability of the plant would be considerably diminished, resulting in elevated maintenance and furnace lining replacement costs. Magnesia's inherent stability enables the extended and more efficient operation of furnaces, thereby reducing recycling costs and enhancing the sustainability of the process. [33,34]

2.6.2 Recycling of non-ferrous metals

In addition to the steel industry, the recycling of non-ferrous metals, including copper and aluminium, represents a significant component of the European recycling industry. The recycling of copper frequently occurs in smelting facilities, where elevated temperatures are necessary to separate the metal from impurities. Magnesia-based refractory materials are employed in order to safeguard the smelting units from the erosive impact of the liquid metals and slag. In the recycling of aluminium, which occurs at lower temperatures, magnesia is employed to stabilise the walls of the smelting furnaces against the reactive aluminium slag. In this context, magnesia plays a pivotal role in enhancing the durability of the furnaces and preventing metallic contamination. [33,34]

2.6.3 Glass recycling

Additionally, magnesia-based refractory linings are utilised in the glass recycling industry to safeguard furnaces from the corrosive effects of molten glass. The melting point of glass is in excess of 1,500 degrees Celsius, and the highly corrosive molten glass can rapidly attack furnace linings. Magnesia offers the requisite protection due to its chemical resistance and thermal stability, thereby ensuring the efficient and continuous production of recycled glass. By utilising magnesia, the high temperatures and corrosive effects of the molten glass can be controlled over extended periods, minimising downtime and maintenance costs. [33,34]

2.6.4 Cement recycling

Additionally, magnesia refractory products are utilised in the production of cement and the recycling of building materials. In rotary kilns employed in cement production, recycled construction waste is incinerated and transformed at elevated temperatures. Magnesia-based linings provide the requisite protection against the abrasive and chemically aggressive conditions that prevail in these furnaces. [33,34]

2.6.5 Significance of magnesia refractories in the the recycling industry

The significance of magnesia refractories for the European recycling industry is substantial. They not only prolong the operational lifespan of high-temperature facilities but also enhance their efficiency and dependability. In light of the European Union's ongoing efforts to reduce CO_2 emissions and advance the circular economy, a robust recycling infrastructure is of paramount importance. The recycling industry depends on the continued operation of high-temperature plants that are both durable and efficient in order to reduce the need for primary raw materials and minimise energy consumption. The utilisation of magnesia-based refractories plays a pivotal role in the attainment of these objectives, as they facilitate the stabilisation of processes, the safeguarding of equipment and the reduction of operational costs.

In conclusion, magnesia in the form of refractories is an indispensable component for the European recycling industry. The utilisation of magnesia-based linings in high-temperature processes, such as those employed in the recycling of metals, glass and other materials, enables European companies to operate in a more efficient manner, extending the lifespan of their equipment while enhancing the sustainability and profitability of their recycling processes. This renders magnesia a strategically important material for the circular economy in the European Union. [8,11,33–35]

3 Importance of metals in European industry

The European Green Deal's target of carbon neutrality by 2050 will be based on its industrial leadership in the production of green technologies such as electric vehicles, batteries, computers, solar panels and wind turbines. In this context, the European non-ferrous metals sector is clear that Europe needs robust systems to ensure the supply of responsibly produced minerals and metals. A level playing field is essential to support this clean energy transition.

China accounts for more than half of world production of processed minerals and metals and is the EU's main supplier of several critical raw materials (see Table 2 for the year 2020). For example, China's share of refining is around 40% for copper, 35% for nickel, 55% for lithium, 60% for aluminium and almost 90% for rare earths elements (REEs). Chinese dominance in key strategic areas is already leading to supply crises in European sectors and creating further risks over the next decade. [36]

Table 2: Main EU and global supplier of critical raw materials in 2020 [36]

CRM in 2020	Main EU supplier	Share	Main global supplier	Share
Light Rare Earth Elements (REEE)	China	99 %	China	86 %
Heavy Rare Earth Elements (HREE)	China	98 %	China	86 %
Magnesium	China	93 %	China	89 %
Bismuth	China	49 %	China	80 %
Natural graphite	China	47 %	China	69 %
Baryte	China	38 %	China	38 %
Tungsten	China	26 %	China	69 %
Silicon metal	Norway	33 %	China	66 %
Germanium	Finland	51 %	China	80 %
Gallium	Germany	35 %	China	80 %
Antimony	Turkey	62 %	China	74 %
Phosphorous	Kazakhstan	71 %	China	74 %
Scandium	n/a	n/a	China	66 %
Fluorspar	Mexico	25 %	China	65 %
Coking coal	Australia	24 %	China	55 %
Phosphate rock	Morocco	24 %	China	48 %
Indium	France	28 %	China	48 %
Titanium	n/a	n/a	China	45 %
Vanadium	n/a	n/a	China	39 %
Niobium	Brazil	85 %	Brazil	92 %

Beryllium	n/a	n/a	USA	88 %
Platium-group metals	n/a	n/a	South Africa (iridium, platinum, rhodium); Russion Federation (palladium)	75 %; 40 %
Cobalt	DRC	68 %	DRC	59 %
Hafnium	France	84 %	France	49 %
Lithium	Chile	78 %	Chile	44 %
Borate	Turkey	98 %	Turkey	42 %
Natural rubber	Indonesia	31 %	Thailand	33 %
Tantalum	DRC	36 %	DRC	33 %
Strontium	Spain	100 %	Spain	31 %

On the basis of current data, it is possible to identify four critical metals or groups of metals for which the European Union's dependence could become significant, particularly in the near future: [36]

- Magnesium: China has an almost total monopoly on world magnesium production (89%) and, since Europe was forced to close its last magnesium plant in 2001 due to dumped Chinese imports, it now supplies approx. 93% of the EU's needs.
- Critical metals for wind, solar and electric vehicles: With the expansion of a clean energy value chains for wind, solar and electric vehicles, it will be vulnerable to new supply disruptions for the metals that would be needed in higher volumes but where China is dominant, including REEs for wind turbines and electric vehicles, and gallium, germanium and indium for solar panels.
- Battery metals: Prolonged EU vulnerability could also give China a huge long-term advantage in the supply of many of the metals needed for batteries, for which it has already built up an 80% share of global refining and is a major investor in global mining supply. Experts predict shortages of lithium and some other battery metals in the next decade as supply sources struggle to keep up with demand (and Europe is also already dependent on China for 90% of its manganese supply).
- Export of scrap metals: Chinese companies export copper scrap from the EU market to China, while EU companies are not allowed to buy Chinese copper scrap from the Chinese market. This questions the future outcome of the EU Green Deal and Europe's supply of recycled metals.

4 Future development required in the European Union to secure the supply of raw materials

The supply of critical raw materials plays a decisive role in Europe's economic and technological development. Critical raw materials, such as rare earths, lithium, cobalt and other strategically important metals, are essential for the production of high technology, renewable energies and the mobility transition, as illustrated in Figure 25. However, Europe is heavily dependent on imports, particularly from China, which plays a dominant role in the global supply chain for these raw materials. This dependence harbours considerable risks for the security of supply and the competitiveness of the European economy. [37,38]

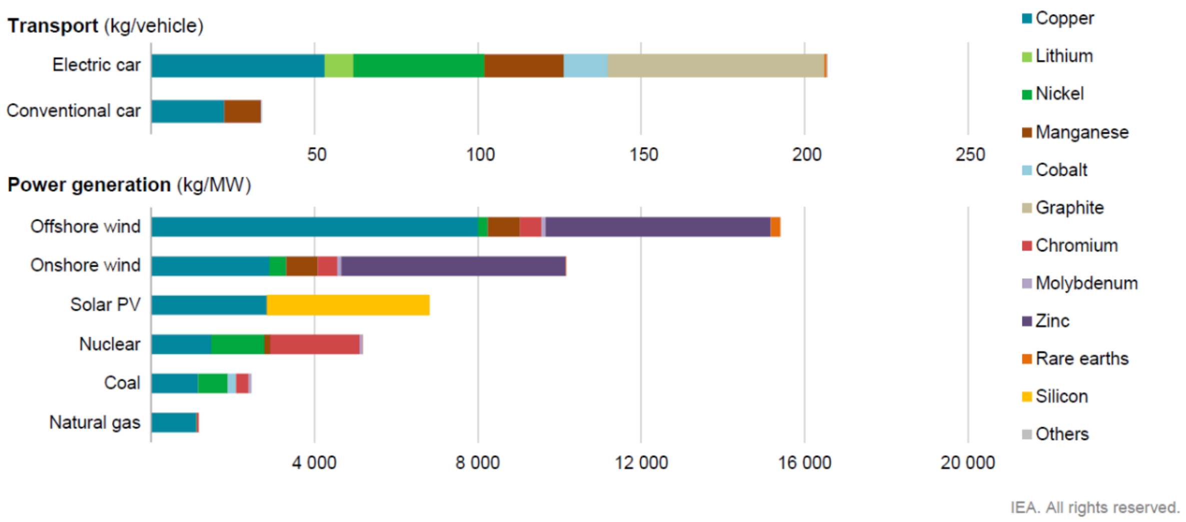


Figure 25: Minerals and metals used in selected clean energy technologies [37]

4.1 Significance of independency of the EU from China

China controls much of the world's production and processing of critical raw materials. In the case of rare earths, for example, China has built up an almost monopolistic production system in recent decades, as shown in Figure 26. This dependence on China represents a significant risk for the EU, as geopolitical tensions or trade restrictions could lead to significant supply shortages. [39]

Europe's technological and economic development, especially in key industries such as electromobility, renewable energies and semiconductor technology, depends to a large extent on the availability of these raw materials. Without access to these resources, innovation processes could be slowed down and economic competitiveness significantly weakened. [39]

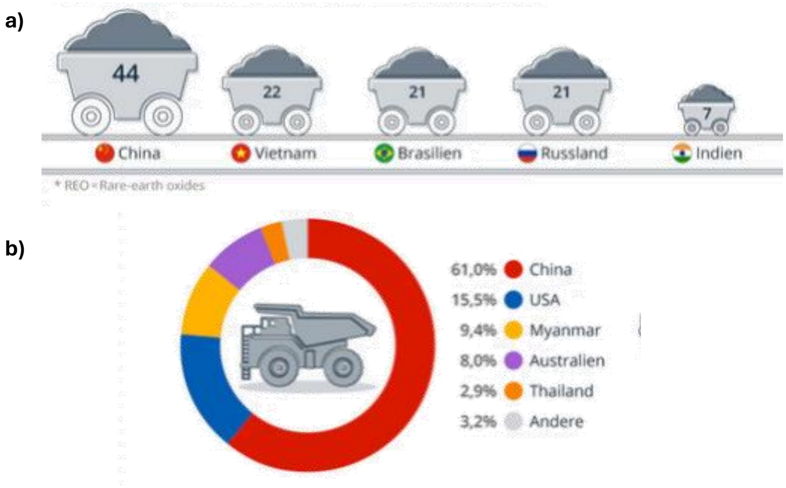


Figure 26: a) Global reserves (in million tonnes) and b) production of rare earths in 2021 [39]

4.2 Challenges for Europe

Based on the findings of this report, there are a number of areas where the European Union can take action to address future challenges, particularly in relation to raw material dependency. Import dependence affects the European economy in several ways:

- Security of supply: unforeseen supply disruptions or political tensions could threaten the supply of critical raw materials, leading to production stoppages in key industries.
- Competitiveness: European companies could be at a disadvantage if they face higher production costs than their global competitors due to raw material shortages or price increases.
- Innovation: Without a secure supply of raw materials, Europe risks falling behind in the development of new technologies and products, which could weaken its economic and technological position in the long term.
- Sustainability: The lack of regional sources of raw materials could hamper the transition to a circular economy needed to meet Europe's climate change targets.

4.3 Developments and strategies needed

Several strategic approaches are needed to reduce dependence and secure supply of critical raw materials:

- Diversifying supply chains: Europe needs to diversify its sources of raw materials in order not to be dependent on a single supplier. This could be done by developing partnerships with other resource-rich countries, especially in Africa and Latin America.
- Strengthen European raw material production: The extraction and processing of critical raw materials within Europe should be encouraged. This includes exploring new

deposits in Europe and supporting projects to develop environmentally friendly and efficient extraction technologies.

- Promoting the circular economy: A key approach to securing the supply of raw materials is to improve recycling capacities. The development of efficient recovery technologies for strategic materials from e-waste and other waste sources should be strongly encouraged.
- Research and innovation: Investment in research and development is needed to find alternatives for critical raw materials and to develop new technologies that can reduce or replace material consumption.

4.4 Importance of the refractories industry for Austria as a business location

Even securing important resources over several decades is not enough to ensure the independence of individual sectors. 90% of the industrial focal points in Austria listed in Table 3 are dependent on refractories. This means that even if sufficient resources are available for production, this is not yet fully secured. A closed-loop economy in the refractories industry is not foreseeable in the coming years due to the constantly growing demand and the strong increase in consumption. This means that a large part of Austrian industry is based on and dependent on the refractories industry. [40]

Table 3: Economic focus in Austrian federal states [40]

Upper Austria	Iron, steel, chemical and mechanical engineering industry
Salzburg	Electrical, wood and paper industry, supra-regional services in the retail and transport industry
Vorarlberg	Textiles, clothing
Carinthia	Wood and paper industry
Styria	Motor vehicles, iron and steel industry, processing industry
Tyrol	Glass, wood
Vienna	Financial services

5 Summary

In summary, magnesia and magnesite play a central role in a wide range of industrial applications due to their unique properties such as high temperature resistance, chemical resistance and mechanical stability as refractory material. In particular, magnesia-based refractories are indispensable in steel, cement, glass and non-ferrous metallurgy, providing reliable protection under extreme conditions. These materials are also increasingly used in Europe's recycling industry, where their stability and resilience contribute to the efficiency and sustainability of recycling processes.

The EU Raw Materials Act underlines the strategic importance of these materials and aims to diversify sources of supply and strengthen Europe's own production to reduce dependence on imports. Magnesia and magnesite are essential for the production and processing of many other critical raw materials important for future technologies such as renewable energy, batteries and electric mobility. Their limited availability and dependence on imports, particularly from China, make them an important part of Europe's raw materials strategy.

Overall, the study highlights the versatility and importance of magnesia in high-temperature industrial processes and the need for a secure and sustainable supply to ensure the competitiveness of European industry and support the transition to a low-carbon circular economy.

6 Literatur

[1] Regulation (EU) 2024/1252, 11.4.2024. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=OJ:L_202401252 (letzter Zugriff am 8.8.2024).

[2] European Commission (2024). The European Green Deal. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/story-von-der-leyen-commission/european-green-deal_en?prefLang=de (letzter Zugriff am 8.8.2024).

[3] Lepley, B. (2024). Understanding the European Commission's new Critical Raw Materials Act (CRMA). https://www.slrconsulting.com/eur/insights/understanding-the-european-commission-s-critical-raw-materials-act-crma/ (letzter Zugriff am 8.8.2024).

[4] European Commission (2014). Report on critical raw materials for the EU.

[5] European Commission (2017). Study on the review of the list of Critical Raw Materials. Criticality Asessments.

[6] VCH Verlagsgesellschaft mbH (Hrsg.) (1996). Ullmann's Encyclopedia of Industrial Chemistry, 5. Aufl. Weinheim, Germany.

[7] GeoSphere Austria (2023). Magnesit - vielseitiger Rohstoff aus Österreich.

[8] European Association of Mining Industries (2020). The European Magensite / Magnesia Industry. enabler in the transition to a low-carbon economy. https://www.euromines.org/files/euromines_magnesite-decarbonisation_297x210mm_fin.pdf (letzter Zugriff am 8.8.2024).

[9] US Geological Survey (2024). USGS - Mineral Commodity Summaries 2024, Virginia, USA.

[10] Butterman, W. C., Carlin, J. F. (2004). Antimony: Mineral Commodity Profiles. U.S. Geological Survey.

[11] Grohol, M., Veeh, C. (2023). Study on the Critical Raw Materials for the EU 2023, Brussels, Beglium.

[12] Pawlek, F. (1983). Metallhüttenkunde. DE GRUYTER, Berlin, Germany.

[13] Krammer, C. (2002). Aluminium-Taschenbuch, 16. Aufl. Aluminium Verlag Düsseldorf.

[14] Tolcin, A. (2024). Bismuth: Mineral Commodity Profiles. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024-bismuth.pdf (letzter Zugriff am 1.10.2024).

[15] Kamran, M., Raugei, M., Hutchinson, A. (2023). Critical elements for a successful energy transition: A systematic review. Renewable and Sustainable Energy Transition **4**, 100068.

[16] Alves Dias, P., Blagoeva, D., Pavel, C., Arvanitidis, N. (2018). Cobalt: demand-supply balances in the transition to electric mobility, Brussels, Beglium.

[17] Schnebele, E. K. (2022). Mineral Commodity Summaries: Manganese.

[18] McRae, M. E. (2022). Mineral Commodity Summaries: Nickel.

[19] Friedline, C. A. (2024). Mineral Commodity Summaries: Niobium.

[20] Friedline, C. A. (2024). Mineral Commodity Summaries: Tantalum.

[21] Grand view reserach (2023). Titanium Market Size and Trends. https://www.grandviewresearch.com/industry-analysis/titanium-market-report (letzter Zugriff am 1.10.2024).

[22] Polyak, D. E. (2024). Mineral Commodity Summaries: Vanadium.

[23] Schnebele, E. K. (2024). Mineral Commodity Summaries: Silicon.

[24] Xakalashe, B. S., Tangstad, M. (2011). Silicon processing: from quartz to crystalline silicon solar cells, Johannesburh.

[25] Kepllinger, W. L. (2017). Werkstoffe in der Verfahrenstechnik - Feuerfeste und korrosionsbeständige Werkstoffe. Skriptum.

[26] Nedmag B.V. (2004). A Dutch solution for magnesia, AE Veendam, Netherlands.

[27] S&P Global (2023). Magnesium Oxide and Other Magnesium Chemicals. Chemical Economics Handbook. https://www.spglobal.com/commodityinsights/en/ci/products/magnesium-oxide-chemical-economics-handbook.html (letzter Zugriff am 14.8.2024).

[28] Jarosinski, A., Radomski, P., Lelek, L., Kulczycka, J. (2020). New Production Route of Magnesium Hydroxide and Related Environmental Impact. Sustainability **12**/21, 8822.

[29] Guo, T., Geng, Y., Song, X., Rui, X., Ge, Z. (2023). Tracing magnesium flows in China: A dynamic material flow analysis. Resources Policy **83**, 103627.

[30] US Geological Survey (2024). Magnesium Compounds. Mineral Commodity Summaries.

[31] Babich, A. e. a. (2008). Ironmaking Textbook. RWTH Aachen University, Department of Ferrous Metallurgy, Aachen, Germany.

[32] US Geological Survey (2023). Magnesium Metal. Mineral Commodity Summaries.

[33] Harbison-Walker Refractories Company (2005). Handbook of Refractory Practice. Harbison-Walker Refractories Co., Moon Township.

[34] Charles, A. S., Schacht, C. (2017). Refractory Linings. CRC Press.

[35] Schorcht, F., Kourti, I., Scalet, B. M., Roudier, S., Sancho, L. D. (2013). Best Available Techniques (BAT) Reference Document for the Production of Cement, Lime and Magnesium Oxide.

[36] Eurometaux (2021). Overcoming EU metals strategic dependencies is a key solution for EU's Green Deal success. Eurometaux Policy Paper.

[37] International Energy Agency (2021). The Role of Critical Minerals in Clean Energy Transitions, Paris.

[38] International Energy Agency (2021). World Energy Outlook, Paris, France.

[39] Bocksch, R. (2022). China dominiert den Markt für Seltene Erden. https://de.statista.com/infografik/27806/weltweite-reserven-und-minenproduktion-von-seltenen-erden/ (letzter Zugriff am 1.10.2024).

[40] Österreichisches AußenwirtschaftsCenter Zagreb (2024). Wichtige Sektoren. https://www.advantageaustria.org/hr/zentral/business-guide/zahlen-und-fakten/wirtschaft/wichtige-sektoren/wichtige-sektoren.de.html (letzter Zugriff am 2.9.2024).