SCRREEN2

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

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SCRREEN

Solutions for CRitical Raw materials - a European Expert Network

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

MAGNESIUM

AUTHOR(S):

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MAGNESIUM

OVERVIEW

Magnesium (Mg) is the eighth most abundant element in the Earth's crust (2.1% in weight) and the third most abundant element in solution in seawater. Magnesium is a metal which does not occur in its elemental form in nature, but is found in different forms in minerals (dolomite, magnesite, carnallite) as well as in seawater and brines. Although seawater was a major source of magnesium during the second half of the twentieth century, closure of seawater magnesium plants and increase in output from China led to a magnesium supply now dominated by mineral sources. Magnesium is the lightest of all commonly used structural materials.

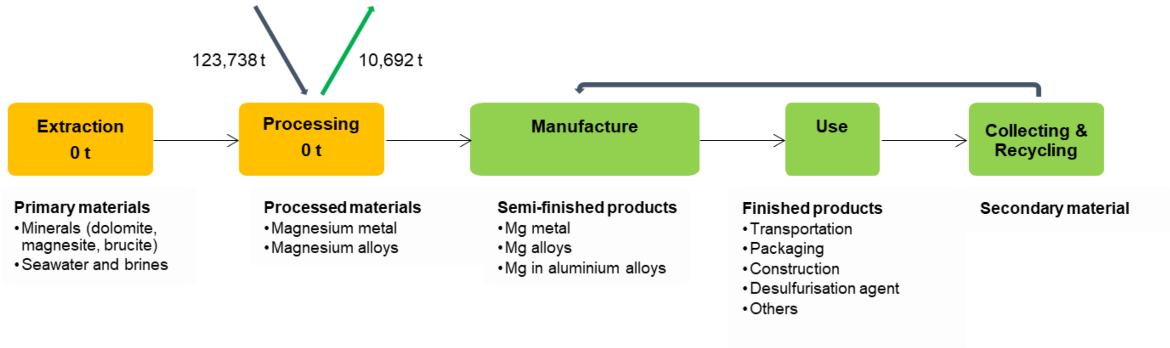

Figure 1. Simplified value chain for magnesium in the EU[1]

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
982,712	China 91% USA 3% Israel 2% Brazil 2% Russia 1%	120,520	12%	China 97% Israel 1% UK 1%%	100%

Prices: Prices for magnesium metal are primarily cost driven, reflecting supply overcapacity (particularly in China). In 2008, magnesium plants were shut down for environmental concerns during Beijing Olympics game, which led to a price hike on the global market since China is the major supplier of magnesium worldwide (IMA, 2016). Since 2008, magnesium prices remained more stable up till 2016.

Primary supply: First stages of the value chain of magnesium (extraction, processing) take place outside of the EU, although there are reserves of magnesium in the EU. There are no imports of magnesium ores in Europe and all primary magnesium is processed outside the EU (except from very small volumes of magnesium alloys).

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

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China's dominance of global magnesium production increased in the reported period, whereas there was little or no growth in other producing countries, despite some capacity expansion (e.g. Brazil) and new primary production units (e.g. in Malaysia, South Korea and Turkey).

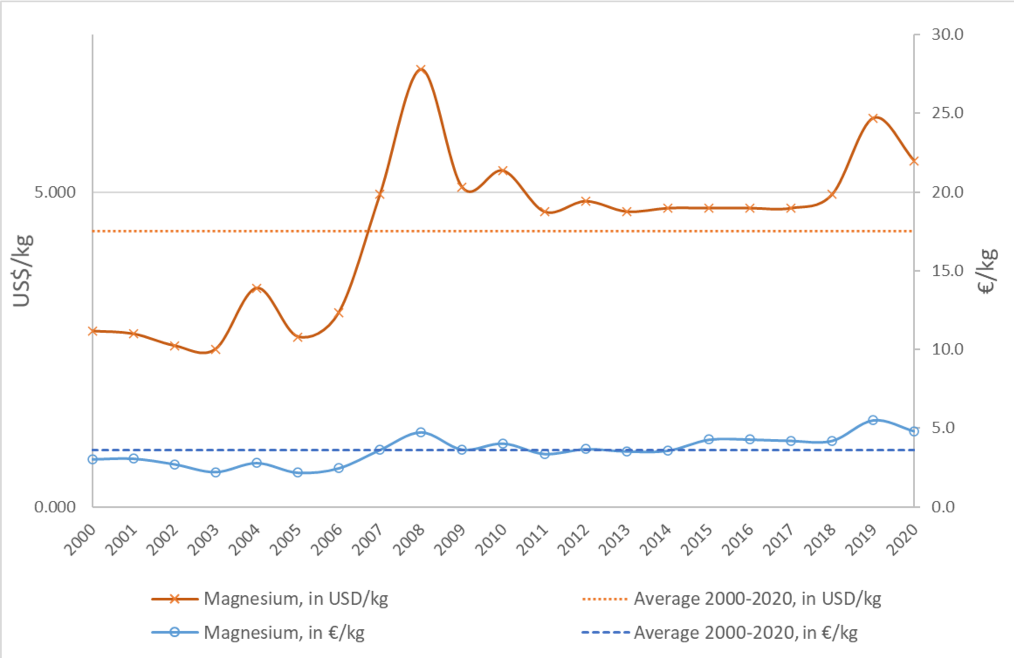

Figure 2. Annual average price of magnesium between 2000 and 2020 (USGS, 2021)[2].

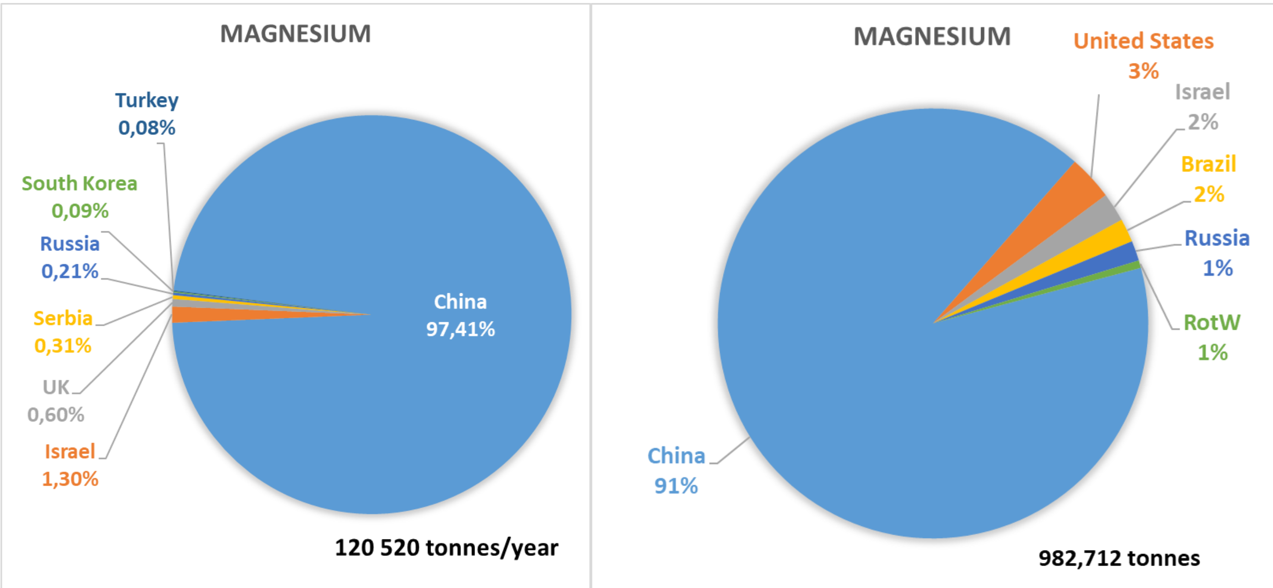

Figure 3. EU sourcing of magnesium (left, CN 81041100 and 81041900, Mg content, Eurostat 2022) and global mine production (right, USGS 2022)

[2] Values in €/kg are converted from original data in US$/kg by using the annual average Euro foreign exchange reference rates from the European Central Bank (https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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Secondary supply: Secondary magnesium is an important component in global magnesium supply, with production estimated to be in the range of 200-250 ktonnes/y, 125 tonnes/y of which is in the USA (International Mining, 2016). The amount of secondary material used in the magnesium industry depends on various factors, among others: amount of material lost in the melting cycle, quantity of different cast components, quality of process scrap, or recycling operation efficiency (IMA, 2016). At the EU level, the magnesium recycling capacity is about 75,000 tonnes/y (mostly for new scrap).

Uses: The major end-uses of magnesium are in the transportation sector, with most (and increasing) usage in automotive applications. Magnesium in aluminium alloys is also used in packaging, construction and non-structural applications such as a desulphurisation agent (European Commission, 2014b; IMA, 2019; SCRREEN workshops, 2019 & 2022, EC Data 2025-30).

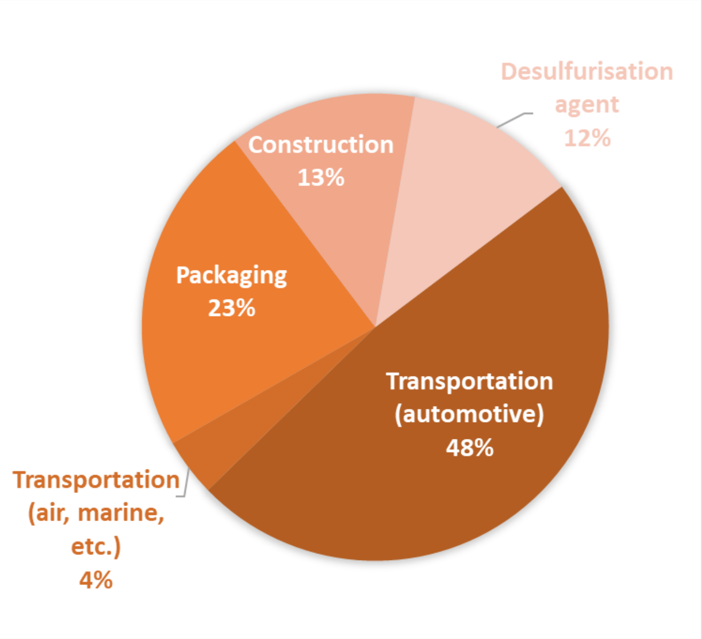

Figure 4: EU uses of magnesium

Substitution: Magnesium in casting alloys as well as in aluminium alloys may be partially substituted, e.g. to lower the need for magnesium.

Table 2. Uses and possible substitutes

Use	Share*	Substitutes	Sub share	Cost	Performance
Transportation (automotive)	48%	Aluminium	30%	Similar or lower costs	Reduced
Transportation (automotive)	48%	Steel (AHSS)	5%	Similar or lower costs	Reduced
Transportation (automotive)	48%	Composite materials	5%	Slightly higher costs (up to 2 times)	Similar
Transportation (automotive)	48%	Titanium	0%	Slightly higher costs (up to 2 times)	Reduced
Transportation (air, marine, etc.)	4%	Aluminium	12.5%	Similar or lower costs	Reduced
Transportation (air, marine, etc.)	4%	Steel (AHSS)	12.5%	Similar or lower costs	Reduced
Transportation (air, marine, etc.)	4%	Composite materials	12.5%	Slightly higher costs (up to 2 times)	Similar
Transportation (air, marine, etc.)	4%	Titanium	12.5%	Slightly higher costs (up to 2 times)	Reduced

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Packaging	23%	Steel	0%	Similar or lower costs	Similar
Packaging	23%	Glass	8%	Similar or lower costs	Similar
Packaging	23%	Plastic	8%	Similar or lower costs	Similar
Desulfurisation agent	12%	Calcium carbide	25%	Similar or lower costs	Reduced
Desulfurisation agent	12%	Calcium oxide	25%	Similar or lower costs	Reduced
Construction	13%	No substitute	100%		

*EU ens use shares 2016-2020 (IMA-Euope, 2022)

Other issues: Primary magnesium (Mg) is classically not produced from artisanal mining nor associated with Acid Mine Drainage. It is extracted from deposits with a limited association with other heavy metals and radioactive substances (German Environment Agency, 2020). The use/ban of Magnesium is not restricted under REACH Regulation (EC) No 1907/2006 Annex XVII (Deutsche Forschungsgemeinschaft and Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area, 2002).

Magnesium production requires relatively large amounts of process materials, in particular dolomite (10.5 kg per kg Mg in a modern Pidgeon process as average consumption according to Ehrenberger, 2013) and ferrosilicon (1.05 kg of FeSi per kg Mg; Ehrenberger, 2013). Moreover, total average direct electricity consumption required by the Pidgeon process is estimated to amount to 1,232 kWh/tonne Mg (Ehrenberger, 2013). In addition, indirect requirements in electricity for the production of input materials (in particular FeSi) add to the total energy balance of Mg production (Ehrenberger, 2013). Finally, relatively high water factors have been reported for the Pidgeon process as well as for other processes (e.g. Magnetherm; Cherubini et al., 2008).

Globally the beryllium economy is a very small (about 0.009% of the total world trade market). The importance of this market is also anecdotic for the main producing country (China 0.04%, New Zealand 0.02%, Israel 0.11%, Germany 0.004%, USA 0.006%, Turkey 0.03% and Canada 0.007% of their total export trade value…). (COMTRADE, 2020).

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3 Magnesium supply and demand (processing), in metric tonnes Mg content, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
982,712	China 91% USA 3% Israel 2% Brazil 2% Russia 1%	120,520	12%	China 97% Israel 1% UK 1%%	100%

Over the last decades, there has been a massive restructuring of global magnesium production / supply: In the beginning of the 1990s, China had a marginal share in global magnesium production; the USA was the main producer of magnesium; global magnesium production was, country-wise, relatively diversified, e.g., Russia, Canada and Norway being significant producers of magnesium on the global scale; the dominant production route of magnesium was the electrolytic one (cf. European Commission, 2020; USGS, 1996). Since then, global magnesium production grew at high rates (5% to 7.5% per year on average) driven by China's continuous magnesium production expansion (cf. Schmitz et al., 2019). In the present, the major actor on the supply side is China, which contributes by far the greatest part to global supply and applies the thermic-reduction route (see Table 1; European Commission, 2020). Chinese magnesium production takes place in the provinces Anhui, Inner Mongolia, Ningxia, Shaanxi, Shanxi and Xinjiang (CM, 2021); most of them are in North and Northwest China. Key firm-level actors at the magnesium market in China include the following companies: Chaohu Yunhai, Jintaiyang, Jinwantong, Shanxi New Energy, Taida, Wanyuan, Wulong, Wutai Yunhai, Xintian, Yunsheng, Zhenxin and Zhongxin (CM, 2021).

On the *demand* side, China is the major actor as well, being the largest global magnesium consumer (CM, 2022). The magnesium (metal) market can be viewed as split into thirds, where each of the following applications has a market share of ca. one third (CM, 2022; Schmitz et al., 2019; Tauber, 2019): aluminium alloys (which are used in packaging, automotive and construction industries for the greatest part), die casting (mainly used for applications in automotive industry and communication technologies) and other applications (e.g., as desulfurization agent).

There is 'free-market' trade for magnesium in form of, e.g., powder and ingots, and corresponding price indices are published. Magnesium (e.g., 99.9% min.) is traded in warehouse Rotterdam, FOB China, in warehouse Russia, FOB US warehouse, etc.

OUTLOOK FOR SUPPLY AND DEMAND

Demand and supply are expected to grow in the long run; battery production may be a significant driver of demand (European Commission, 2020; Schmitz et al., 2019; SCRREEN, 2022). Due to the wide availability of

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magnesium resources (e.g., dolomite and magnesite resources in the EU), raw material-availability will not be the limiting factor in future supply development (SCRREEN, 2022).

EU TRADE

Table 4. Relevant Eurostat CN trade codes for magnesium

Processing/refining	
CN trade code	**title**
28273100	Magnesium chloride
81041100	Unwrought magnesium, containing >= 99,8 % w/w magnesium
81041900	Unwrought magnesium alloy containing 90 % w/w magnesium

Erreur ! Source du renvoi introuvable. and Figure 6 illustrate the import and export trend for magnesium alloys (containing > 90% Mg w/w) and unwrought metallic magnesium at the processing or refining stage between 2002 and 2021..

Figure 7 illustrates the EU import by country for magnesium at the processing or refining stage. China, as expected, is the major supplier to EU since it is the largest producer of refined magnesium products. The quantity of import has rebounded after a fall in 2020 due to COVID.

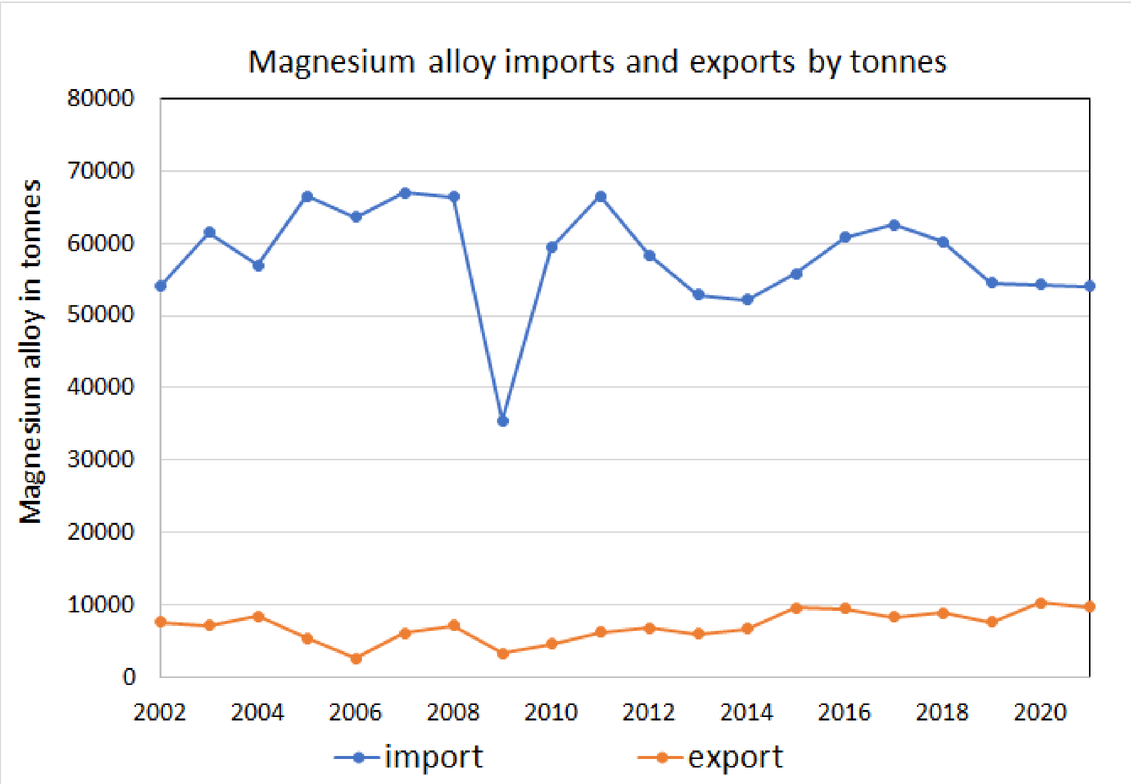

Figure 5. EU trade flows of Unwrought Magnesium alloys (CN 81041900) containing 90% w/w Mg from 2002 to 2021 (Eurostat, 2021)

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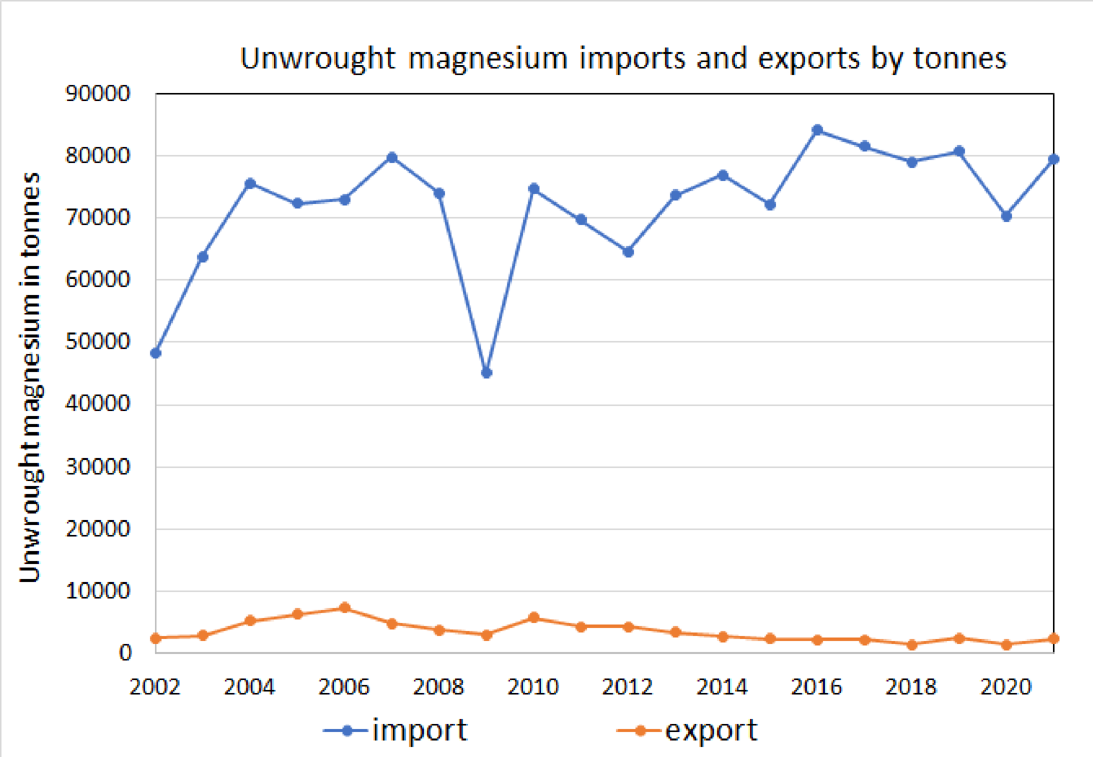

Figure 6. EU trade flows of metallic unwrought metallic magnesium (CN 81041100) from 2002 to 2021 (Eurostat, 2021)

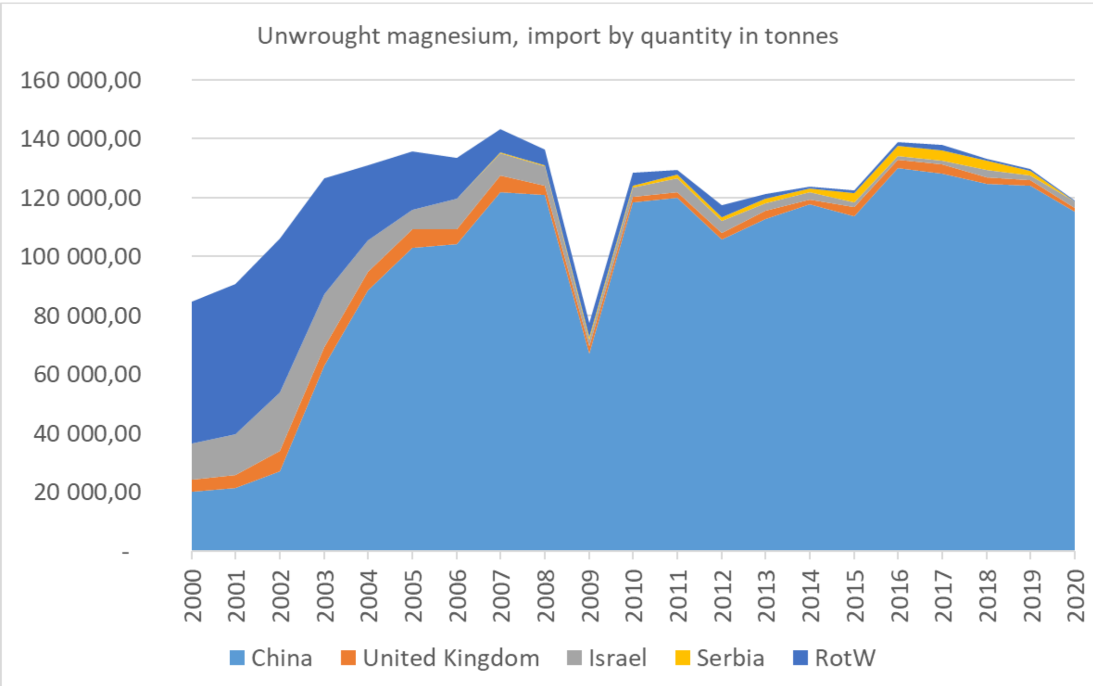

Figure 7. EU imports of Magnesium by country between 2000-2020 (CN 810411000 and 810419000, Mg content, based on Eurostat, 2021)

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PRICE AND PRICE VOLATILITY

Prices for magnesium metal are primarily cost driven, reflecting supply overcapacity (particularly in China). In 2008, magnesium plants were shut down for environmental concerns during Beijing Olympics game, which led to a price hike on the global market since China is the major supplier of magnesium worldwide (IMA, 2016). Since 2008, magnesium prices remained more stable up till 2016.

Magnesium prices gradually decreased down until the first quarter of 2016. As prices moved below this level at the end of 2015, resistance from producers coupled with firming coal prices and better than expected performance in the Chinese economy pushed the price of magnesium up by 11% in April 2016 (International Mining, 2016).

Magnesium prices rose sharply in 2018, but the timing and extent of a retreat depended as much on Beijing's environmental policies as on automotive demand and the wider economic outlook. Tight supply and high prices were believed to reduce the competitiveness of magnesium metal with aluminium and other lightweight alternatives over the longer term, and erode consumer demand. Due to an antidumping-duty in the US for magnesium from China, the price of magnesium metal was higher in the US compared to the EU (Fastmarkets, 2018).

The magnesium market has been under pressure when Covid-19 started. The Covid-19 crisis was slowing down mining production, especially in the most affected countries, and compromising supply. Demand, meanwhile, has quickly returned to pre-crisis levels and stocks of many industrial metals were running low.

China has a near monopoly on the world market, producing 87% of all magnesium. The combination of low stocks, low production, and high demand amounts to a perfect storm for higher prices (Gestion, 2021).

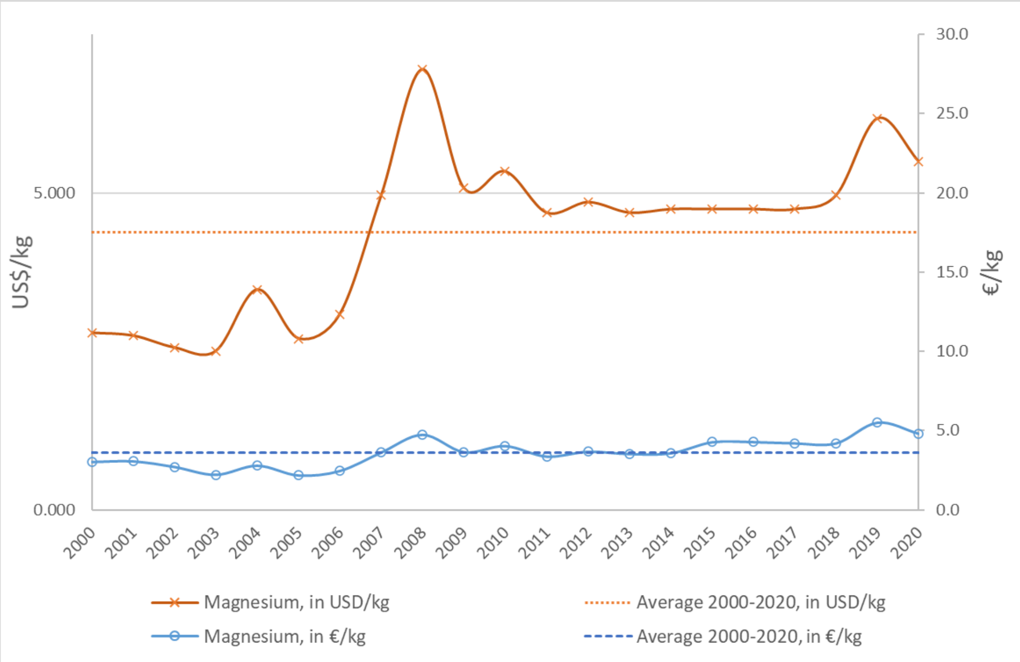

Figure 8. Annual average price of Magnesium between 2000 and 2020 (USGS, 2022)[1].

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DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

The world magnesium consumption was about 1,000 ktonnes in 2020 (Alliance Magnesium, 2022).

The EU apparent average consumption of magnesium is calculated at 145 ktonnes per year for 2019-2020 and 120kt for 2016-2020.

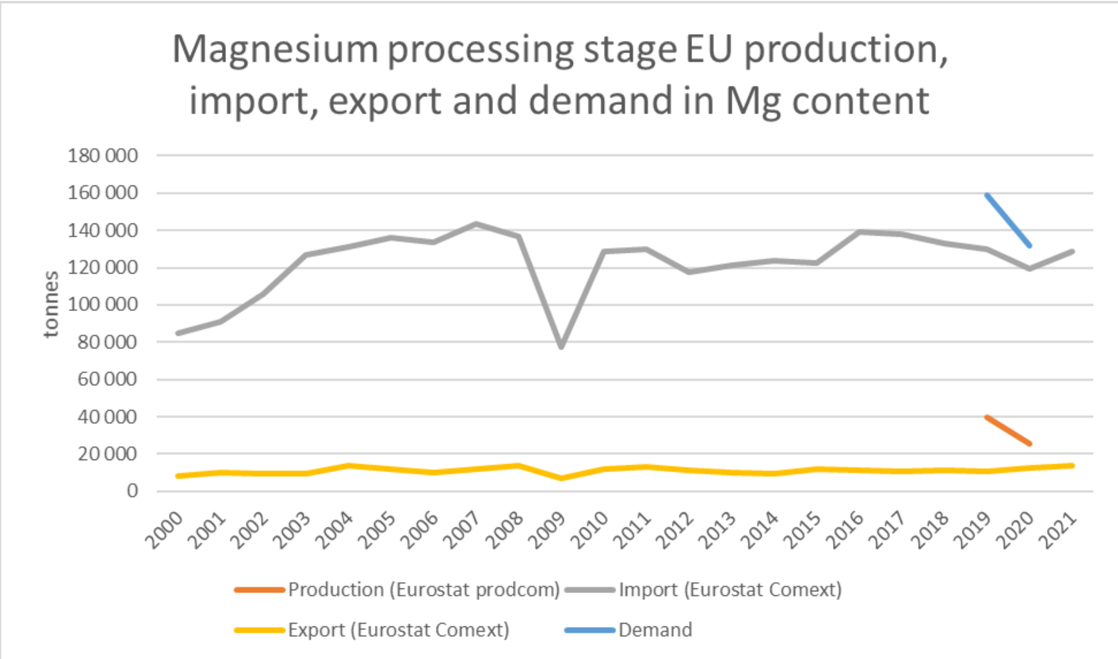

Figure 9. Magnesium (CN 81041100 Unwrought magnesium, containing >= 99,8% by weight of magnesium and 81041900 Unwrought magnesium, containing < 99,8% by weight of magnesium) processing stage apparent EU consumption. Production data is available from Eurostat Prodcom (2022) only for 2019-2020. Consumption is calculated in magnesium content (EU production+import-export).

Almost all of magnesium is imported in the EU as pure magnesium or magnesium alloys; swarf, granules and powders represent gross volumes of about 14 ktonnes (IMA, 2017).

Magnesium processing stage EU consumption is presented by HS codes CN 81041100 Unwrought magnesium, containing >= 99,8% by weight of magnesium and 81041900 Unwrought magnesium, containing < 99,8% by weight of magnesium.

Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 24453024 Unwrought magnesium, containing >= 99,8% by weight of magnesium and PRCCODE 24453026 Unwrought magnesium, containing < 99,8% by weight of magnesium.

Since PRODCOM data are not considered as reliable for the EU production, the average import reliance of magnesium at processing stage is 100% for 2016-2020.

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EU USES AND END-USES

The major end-uses of magnesium are in the transportation sector, with most (and increasing, as per IMA-Europe 2022) usage in automotive applications.

Magnesium in aluminium alloys is also used in packaging, construction and non-structural applications such as a desulphurisation agent (European Commission, 2014b; IMA, 2019; SCRREEN workshops, 2019 & 2022, EC Data 2025-30).

The end-use shares provided in Figure 13 were calculated based on existing studies and stakeholders' feedback (IMA, 2017; IMA, 2019; SCRREEN Expert and Validation Workshop 2022; EC Data 2025-30) and relevant industry sectors are described using the NACE sector codes in **Erreur ! Source du renvoi introuvable.**.

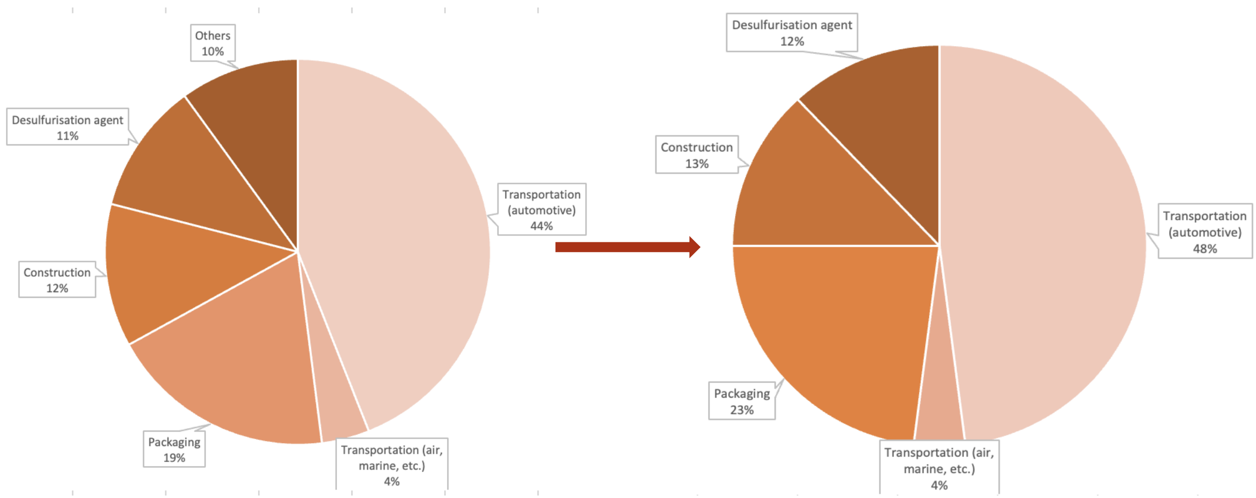

Figure 10. EU end uses of magnesium. Left chart (IMS, 2016, using 2012-2016 average figures). Right chart (IMA-Europe, 2022, using 2016-2020 average figures).

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

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€) - 2019	4-digit CPA
Transportation	C29 - Manufacture of motor vehicles, trailers and semi-trailers C30 - Manufacture of other transport equipment	234,398 49,129*	C2910 - Manufacture of motor vehicles; C2920 - Manufacture of bodies for motor vehicles; C2932 - Other parts for motor vehicles; C3030 - Manufacture of air and spacecraft; C3011 - Building of ships and floating structures; C3020 - Manufacture of railway locomotives and rolling stock; C3092 - Manufacture of bicycles

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Packaging	C25 - Manufacture of fabricated metal products, except machinery and equipment	186,073	C2592 - Manufacture of light metal packaging
Construction	C25 - Manufacture of fabricated metal products, except machinery and equipment	186,073	C2511 - Manufacture of metal structures and parts of structures; C2512 - Manufacture of doors and windows of metal; C2599 - Manufacture of other fabricated metal products n.e.c.
Desulphurisation agent	C24 - Manufacture of basic metals	63,700 *data up to 2014 only	2410 - Manufacture of basic iron and steel and of ferro-alloys

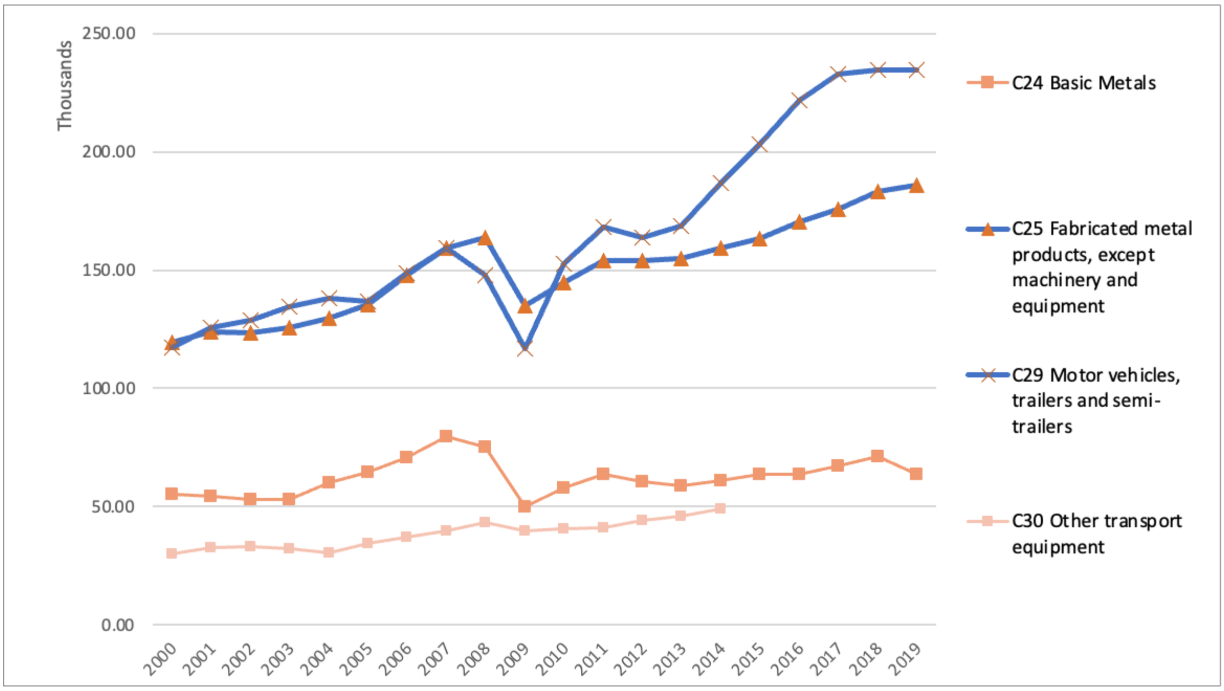

Figure 11. Gross Value Added (€millions) added per 2-digit NACE sector over time (Eurostat, 2022)

APPLICATIONS OF MAGNESIUM IN THE EU:

TRANSPORTATION

Magnesium casting alloys are used in **automotive** applications, i.e., in vehicles to lower the overall weight, for example to replace steel and/or aluminium. The use of magnesium as one single cast piece in vehicles may also increase the strength of the material compared to various steel components.

Magnesium is used in many vehicle parts including:

- Gearboxes
- steering columns
- driver airbag housings
- steering wheels
- seat frames
- fuel tank covers.

Magnesium is also used in **trains and aerospace** applications both civil and military, such as in thrust reversers and in engines and transmission casings of aircrafts and helicopters.

Spacecraft and missiles also contain magnesium as it is capable of withstanding exposure to ozone and impact of high energy particles and matter (IMA, 2016).

PACKAGING

In packaging applications, magnesium improves aluminium strength without removing the material workability, for example in aluminium beverage cans. Magnesium is also used in aluminium alloys in food cans and trays *(see also: CRM Factsheet on aluminium).*

CONSTRUCTION

Magnesium in aluminium alloys is used for doors, windows, cladding, roofing, staircases, air conditioning units, among other components *(see also: CRM Factsheet on aluminium).*

DESULPHURISATION AGENT

Due to its high affinity for sulphur, magnesium is injected in molten iron or steel to reduce the sulphur content. The process prevents sulphur from damaging steel as it causes brittleness in steel; low sulphur facilitates modern production processes (IMA, 2019; International Mining, 2016).

OTHERS

Other applications include:

- Medical and sport applications,
- electrochemical applications - magnesium anodes prevent from galvanic corrosion of steel.
- Use in industrial synthesis such as the Grignard reaction in organic chemistry applications (IMA, 2019).
- Magnesium alloys used in small and portable electronic applications (cameras, cell phones, laptops) for its combination of lightness, strength and durability (e.g. replacing plastics)
- Electronics that require parts or casings with complex shapes.

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SUBSTITUTION

All the identified applications have been considered in the assessments (IMA, 2017; IMA, 2019; IMA 2022, SCRREEN workshops, 2019 and 2022). Consideration has been given to the cost and performance of each potential substitute in each application, relative to that of the material in question, together with the level of production, whether the substitute was previously considered to be 'critical' and whether the potential substitute is produced as a by-, co- or main product.

Table 6. Uses and possible substitutes

Use	Share*	Substitutes	Sub share	Cost	Performance
Transportation (automotive)	48%	Aluminium	30%	Similar or lower costs	Reduced
Transportation (automotive)	48%	Steel (AHSS)	5%	Similar or lower costs	Reduced
Transportation (automotive)	48%	Composite materials	5%	Slightly higher costs (up to 2 times)	Similar
Transportation (automotive)	48%	Titanium	0%	Slightly higher costs (up to 2 times)	Reduced
Transportation (air, marine, etc.)	4%	Aluminium	12.5%	Similar or lower costs	Reduced
Transportation (air, marine, etc.)	4%	Steel (AHSS)	12.5%	Similar or lower costs	Reduced
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Transportation (air, marine, etc.)	4%	Titanium	12.5%	Slightly higher costs (up to 2 times)	Reduced
Packaging	23%	Steel	0%	Similar or lower costs	Similar
Packaging	23%	Glass	8%	Similar or lower costs	Similar
Packaging	23%	Plastic	8%	Similar or lower costs	Similar
Desulfurisation agent	12%	Calcium carbide	25%	Similar or lower costs	Reduced
Desulfurisation agent	12%	Calcium oxide (lime)	25%	Similar or lower costs	Reduced

*EU ens use shares 2016-2020 (IMA-Euope, 2022)

Specific data relating to all these criteria are often difficult to find and several assumptions have had to be made to complete the calculations. Consequently, a significant degree of uncertainty is associated with the results. The level of precision shown for the Substitution Indices does not fully reflect this uncertainty.

Magnesium in casting alloys as well as in aluminium alloys may be partially substituted, e.g. to lower the need for magnesium.

TRANSPORTATION

Reinforced plastics provide similar performance in vehicles and the latest aircraft - but at much higher cost than aluminium alloys containing magnesium.

Steel and titanium are possible substitutes in this sector (only steel has costs are similar to aluminium alloys). However, steel is heavier than aluminium and consequently lesser performing for certain applications.

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PACKAGING

For packaging, steel, glass and plastics are considered as potential substitutes for aluminium alloys, with costs and performance considered to be similar.

CONSTRUCTION

Steel, plastics (such as PVC or vinyl) and wood are possible substitutes.

DESULPHURISATION AGENT

The steel desulphurisation process allows the use of several reagents such as lime (carbon oxide, CaO), calcium carbide (CaC_2) and magnesium (Mg), which remove the sulphur in the hot metal by chemical reaction and convert it to the slag.

SUPPLY

EU SUPPLY CHAIN

The EU supply chain of magnesium can be described by the following key points:

First stages of the value chain of magnesium (extraction, processing) take place outside of the EU, although there are reserves of magnesium in the EU. There are no imports of magnesium ores in Europe and all primary magnesium is processed outside the EU (except from very small volumes of magnesium alloys).

The EU supply of magnesium mainly relies on imports of primary magnesium, processing new scrap and production of secondary magnesium (from post-consumer recycling) although less significantly. The average imports of metallic magnesium in EU (in unwrought form, containing >= 99,8 wt. % according to the product codes CN 81041100 and CN 81041900) was about 132 ktonnes during the period 2016-20220. China is by far the most important trade partner. Over the 95% of the imported magnesium amount originates by China. A minor average annual exported amount around 8 ktonnes to third countries is reported during the same period. United States and United Kingdom are the destination countries.

Magnesium is the lightest structural metal: one quarter the weight of steel, two thirds the weight of aluminium, and has same light weighting potential as carbon fibre. Europe imports primary magnesium in the forms of pure metal or alloys. In addition, the EU relies on imports of intermediate and final products, in particular in the electronics sector.

At the EU level, the magnesium recycling capacity is about 75 ktonnes/y (mostly for new scrap).

The European Union is a net exporter of magnesium scrap, with net gross volumes of 10,370 tonnes in 2018. In 2018 40% of scrap exports are now directed to the US and 21% to Brazil, mainly due to price difference with primary magnesium (increased prices from anti-dumping measures, which were implemented in 2001). For comparison, 76% of scrap was exported to Norway in 2000 (Eurostat, 2019a)

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SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF MAGNESIUM

GEOLOGICAL OCCURRENCE

Magnesium is a relatively common element with a concentration of about 2.1% (21,000 ppm) in the Earth's crust, and of about 46.7 ppm in the uppercrust (Rudnick, 2003). It is found in more than 60 distinct minerals. The most important minerals containing magnesium are rock-forming minerals: the chlorites, the pyroxene and amphibole group minerals, dolomite and magnesium calcite. Magnesium is also present in magnesite, hydrated carbonates (e.g. nesquehonite, lansfordite) and in brucite. In addition, a series of basic magnesium carbonates exist (e.g. hydromagnesite, artinite) (Shand, 2006).

Natural minerals supply the majority of commercialised magnesium (i.e. magnesium oxide): dolomite (85%), MG-brines (15% of commercialised output) (BGR 2019). Brucite is no longer used as a raw material for primary magnesium production (IMA, 2017).

DOLOMITE MINERAL

($CaMg(CO_3)_2$) is found in sedimentary rocks such as dolomite rock and limestones. It can occasionally be found in high-temperature metamorphic rocks and low-temperature hydrothermal veins. Dolomite is the raw material for the majority of the magnesium plants in China; it is also used in Turkey and Brazil (BGS, 2004; Chen et al. 2022).

MAGNESITE MINERAL

($MgCO_3$) exist as cryptocrystalline (amorphous) magnesite or macrocrystalline (bone) magnesite. Four types of magnesite deposits exist: as a sedimentary rock, an alteration of serpentine, as a vein filling or in replacement of limestone and dolomite (Shand, 2006). Magnesite deposits are widespread but high-purity deposits of adequate size are uncommon (BGS, 2004). There are EU efforts to develop new opportunities to get magnesium from low grade sources of magnesite and dolomite based on biotechnology. An example, it is the project Biorecover.

CARNALLITE

($KCl.MgCl2.6H_2O$) is the main source of magnesium in Russia and used to be significant in Chinese production, though not any longer. It is normally delivered as brine produced by the solution-mining of the solid carnallite deposits.

GLOBAL RESOURCES AND RESERVES

No specific information are provided concerning the amount of global magnesite deposits, however they characterized as large (USGS, 2022).

EU RESOURCES AND RESERVES

It is acknowledged that reserves of magnesium are large enough to meet the worldwide consumption needs for the next decades – either from dolomite and other magnesium-bearing evaporate minerals, or from magnesium-bearing brines.

OUTLOOK FOR PRODUCTION

China has long dominated the magnesium market, producing around 85% of the global supply. A shortage of the metal is expected in short term as the Mg supply by China is expected to be influenced by various parameters including (cips.org, 2022; USGS, 2022):

(a) Environmental restrictions concerning the production of ferrosilicon and the Pidgeon process. Given that China is aiming to decarbonise, it is likely that this industry will continue to be exposed to these restrictions.

(b) Power shortages and increase of raw materials necessary for the production magnesium. A coal shortage for the magnesium industry was observed in 2021 due to the strong demand for coal by power plants in the summer months, while the price of ferrosilicon in the same period was increased.

(c) Decreasing of Mg price which at the end of 2021 dropped to 5,400 euros per tonne

(d) Various other parameters, such as constrained shipping, high freight rates, and stockpiling by speculators.

WORLD PRODUCTION OF PROCESSED MAGNESIUM METALS AND ALLOYS

World average refined production of magnesium between 2016 and 2020 totals 1030 ktonnes/y (USGS, since 2000). Production of primary magnesium jumped from 443 ktonnes/y in 2000 to 1005 ktonnes/y in 2020. Primary magnesium is commercialised as pure magnesium (99.8% purity - which may later be used in aluminium alloys) and magnesium alloys (estimated 90% magnesium content in average). Global supply of magnesium is dominated by China with about 88% of the total refined production, equivalent to 903 ktonnes/y (average 2016-2020, USGS data). Russia is the second largeest producer with 48 ktonnes corresponding to the 4.7 % of world production in 2020. Israel and Kazakhstan produced 19 and 16 ktonnes in 2020, respectively corresponding to the 1.8 and 1.5 of the global production (**Erreur ! Source du renvoi introuvable.**). It is thought that production statistics for China may include production figures based on capacity rather than actual production and that some primary magnesium may be double counted when it is sold to local magnesium alloy producers (Roskill, 2013; IMA, 2019).

China's dominance of global magnesium production increased in the reported period, whereas there was little or no growth in other producing countries, despite some capacity expansion (e.g. Brazil) and new primary production units (e.g. in Malaysia, South Korea and Turkey). These capacity increases remained small compared to total global production (Roskill, 2013). According to IMA, Turkey plant produces 8 ktonnes/y, with an installed capacity of 15 ktonnes/y.

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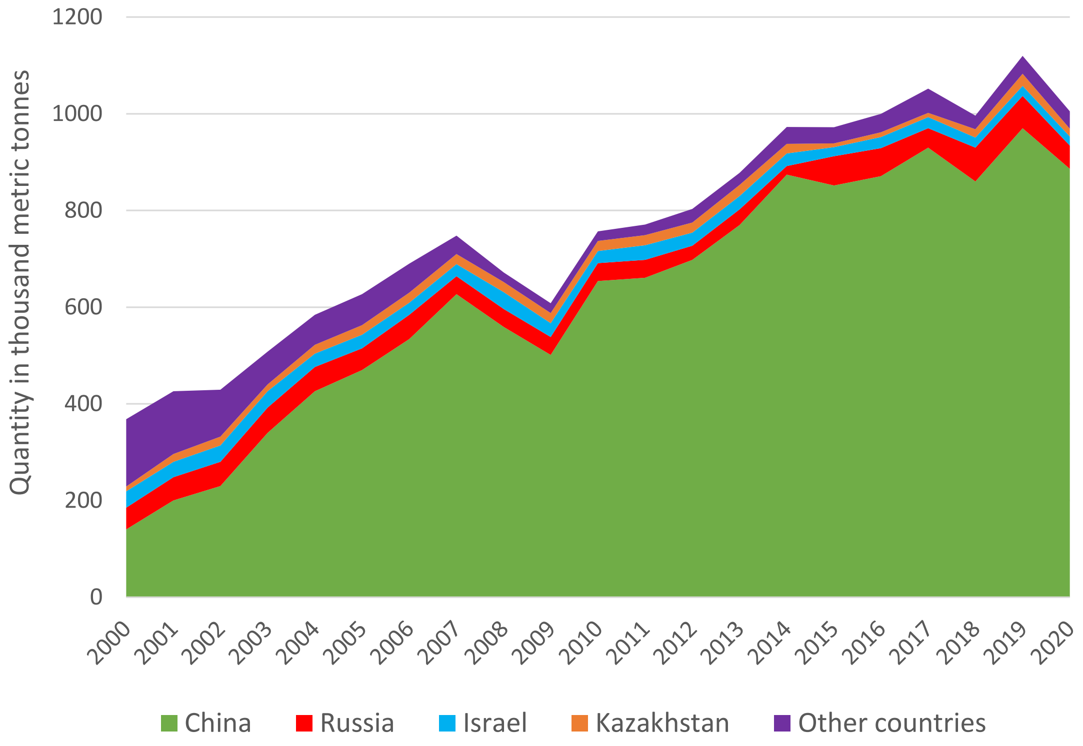

Figure 12. Global production of metallic magnesium since 2000 (USGS, since 2000).

In 2015, there were about 50-80 magnesium smelting operations in China, most of them in the provinces of Shaanxi and Shanxi, which accounted for 61% and 28% of production. On a company basis, the largest productive capacity is held by Shanxi Yinguang Huasheng with 80 ktonnes/y, averaged over 2012-2016, followed by Ningxia Hui-Ye Magnesium with 60 ktonnes/y.

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

POST-CONSUMER RECYCLING (OLD SCRAP)

Secondary magnesium is an important component in global magnesium supply, with production estimated to be in the range of 200-250 ktonnes/y, 125 tonnes/y of which is in the USA (International Mining, 2016). The amount of secondary material used in the magnesium industry depends on various factors, among others: amount of material lost in the melting cycle, quantity of different cast components, quality of process scrap, or recycling operation efficiency (IMA, 2016). At the EU level, the magnesium recycling capacity is about 75,000 tonnes/y (mostly for new scrap). The main European players are in Austria (Non ferrum), Czech Republic (Magnesium Elektron163), Germany (Magontec, Real Alloy Germany GmbH), Hungary (Salgo-Metal), Serbia (Mg Serbien), Romania (Magontec), and in the UK (Magnesium Elektron) (Roskill, 2013, IMA 2019). In the EU, the EoL-RIR for magnesium is estimated at 12-13%, according to three sources: 13% in the MSA study (Bio Intelligence Service 2015), 12.4 % in the Oakdene Hollins report (Bell et al. 2017) and 13.4% in the current criticality assessment, which is in turn based on the MSA of aluminium (Passarini et al. 2018).

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Various recycling methods exist and are currently used to re-melt magnesium scrap: a common process is the remelting and refining of heavy scrap. In order to ensure the same quality criteria (in terms of chemical composition, oxide content) for secondary and primary materials, other recycling methods may be required, in particular for old scrap. For instance, the addition of manganese reduces the levels of iron; distillation or dilution allow for nickel and copper control (IMA, 2016).

In the EU, a large share of magnesium is used as an alloying element in the production of aluminium alloys and derived applications. Therefore, most of end-of-life magnesium scrap is recycled as part of the aluminium value stream. In addition, magnesium alloys are entirely recyclable once they are collected from end-of-life products.

INDUSTRIAL RECYCLING (NEW SCRAP)

Recycling or reuse of new scrap is common in the magnesium industry; the scrap kept within a close loop system reduces the demand of primary magnesium by up to 50%. Die casting foundries recycle scrap internally or externally. Lower grade arising is used as reagents in steel desulfurization or other markets, as replacement to primary magnesium (IMA, 2016). There is no recycling of magnesium from steel desulfurization applications.

PROCESSING

Magnesium-bearing ores are worked by open pit methods, although narrow and deep deposits may be worked by underground drifts and stopes. (United States International Trade Commission, 2012).

Magnesium can be produced through electrolytic methods or thermal-reduction methods such as the Pidgeon process.

The electrolytic method has dominated magnesium production from the 1970s to 1990s – the various processes consist of electrolysis of molten magnesium chloride (produced with different methods), the magnesium produced is liquid (molten). The source of magnesium can be seawater, brine or carnallite, among others (Wulandari et al., 2010). For instance, carnallite is used as raw material for the electrolysis process in Russia (BGR, 2017).

In the thermal-reduction method, calcined dolomite and calcined magnesite are broken down with reducing agents. The mixture is heated in a vacuum chamber forming magnesium vapours which later condense into crystals. The crystals are melted, refined and poured into ingots for further processing (IMA, 2016).

The Pidgeon process (**Erreur ! Source du renvoi introuvable.**) is the most common thermal-reduction method for production of magnesium because its operation is relatively easy, versatile and has low capital cost; however, it is energy intensive and has low productivity. The largest producers of magnesium through the Pidgeon process are China, Brazil and Turkey (IMA, 2016). The process is based on silicothermic reduction of magnesium oxide from calcined dolomite. Dolomite calcination takes place at temperature ranges of 1,000 to 1,300°C. Calcined dolomite and ferrosilicon are mixed; at specific temperatures and pressure, the reduction of calcined dolomite by ferrosilicon produces magnesium vapour. High purity magnesium is obtained from

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condensation of the vapour; the potential impurities (Ca, Fe and Si) are low at these conditions (Wulandari et al., 2010).

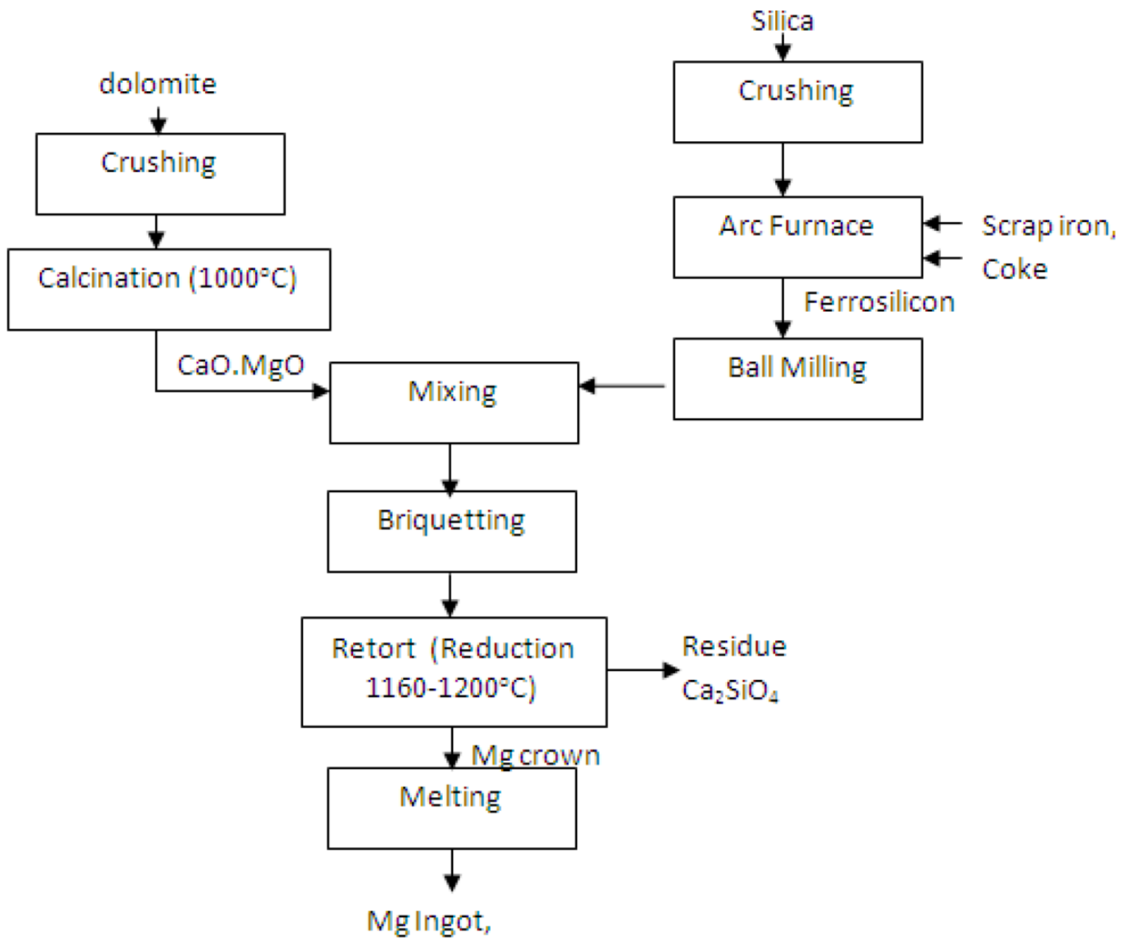

Figure 13. Simplified flowsheet of Pidgeon process for the production metallic Mg (Wulandari et al. 2010)

New processes such as Carbothermic and the Mintek process are high productivity alternatives to the existing technologies that still require further development; they could achieve lower energy usage. There are EU efforts to develop new opportunities to get magnesium from low grade sources of magnesite and dolomite based on biotechnology. An example is the project Biorecover, that has started a few months ago.

COMET project consists of a second non-conventional process aiming to produce metallic magnesium by seawater, while energy is saved in comparison to Pidgeon process. Mg is obtained without the production of magnesium oxide as intermediate product. More specifically: Anhydrous MgCl2 is received through crystallization and ammonization from seawater at ambient conditions, subsequently MgCl2 transformed to an organometallic compound, while it is finally decomposed to metallic magnesium (**Erreur ! Source du renvoi introuvable.**) (Liu et al. 2019).

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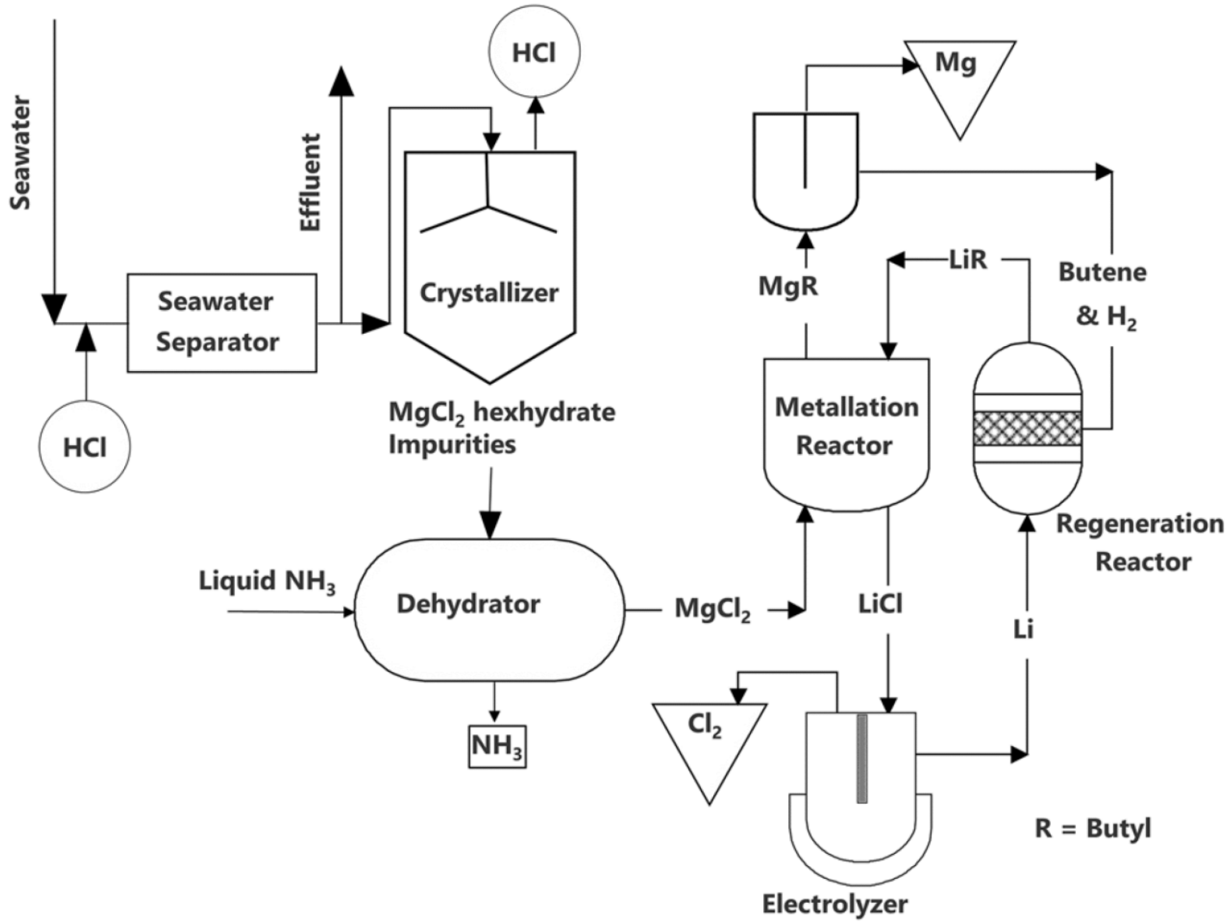

Figure 14. Simplified flowsheet of COMET process to produce metallic magnesium by seawater (Liu et al. 2019).

Magnesium is available in almost all the common forms in which metals are commercially used. Practically pure magnesium, 99.8 %, is supplied as ingot and stick for remelting, and as powder, ribbon, wire, and extruded and rolled strip. Magnesium alloys are produced in various forms including casting, sheet and plate, shapes, forgings, bar, and rod. Due to its low densityof 1.7 g/cm3, Mg and its alloys are used where light weight is an important consideration (e.g., in aircraft components). Mg–Al alloys are the most widely used magnesium alloys. They belong to the wrought Mg alloys with moderate strengths, relatively high plasticities, reasonably high corrosion resistance, and low price. Mg content in Mg-Al alloys is usually around 90% (Pan et al. 2022). Magnox Alloy – AL80 and Elektron are two widely used alloys used in the airspace sector. The first contains Mg and traces of aluminium (0.8%) and beryllium (0.004%). Elektron is a complex alloy containing 0% to 9.5% of the following elements in varying contents: Al (< 9.5%), Y (5.25%), Nd (2.7%), silver (2.5%), Gd (1.3%), Zn (0.9%), Zr (0.6%) and Mn (0.5%) (totalmateria.com; material-properties.org).

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OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES RELATED TO MAGNESIUM OR SPECIFIC/RELEVANT COMPOUNDS AT ANY STAGE OF THE LIFE CYCLE

Primary magnesium (Mg) is classically not produced from artisanal mining nor associated with Acid Mine Drainage. It is extracted from deposits with a limited association with other heavy metals and radioactive substances (German Environment Agency, 2020).

The use/ban of Magnesium is not restricted under REACH Regulation (EC) No 1907/2006 Annex XVII (Deutsche Forschungsgemeinschaft and Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area, 2002).

ENVIRONMENTAL ISSUES

Nowadays, Chinese magnesium is almost exclusively produced through the Pidgeon process (Ehrenberger, 2020) which is mainly under focus in this section. Other production processes regarding some specific, relevant, environmental issues and associated indicators are also considered. In the following, the environmental importance of Mg is evaluated considering a life cycle perspective, and distinguishing: i) firstly, process requirements in energy and materials/reagents; ii) secondly, associated environmental impacts, comparison between Mg production processes and potential for future improvement; and finally, iii) environmental issues beyond the cradle-to-gate production of Mg, considering a broader life-cycle perspective that accounts for the application (and potential environmental benefits) of magnesium-based products in their use phase.

The following analysis mainly builds on two life cycle assessment (LCA) studies on Mg production, as initiated by the International Magnesium Association (IMA) and performed by the Institute of Vehicle Concepts of the German Aerospace Centre (DLR) in 2013 and 2020 (Ehrenberger, 2013; 2020).

Magnesium production requires relatively large amounts of process materials, in particular dolomite (10.5 kg per kg Mg in a modern Pidgeon process as average consumption according to Ehrenberger, 2013) and ferrosilicon (1.05 kg of FeSi per kg Mg; Ehrenberger, 2013). Moreover, total average direct electricity consumption required by the Pidgeon process is estimated to amount to 1,232 kWh/tonne Mg (Ehrenberger, 2013). In addition, indirect requirements in electricity to produce input materials (in particular FeSi) add to the total energy balance of Mg production (Ehrenberger, 2013). Finally, relatively high water factors have been reported for the Pidgeon process as well as for other processes (e.g. Magnetherm; Cherubini et al., 2008).

Secondly, in terms of impacts, according to Ehrenberger (2020), the current Pidgeon process induces 28 kg CO_2-eq when including all upstream processes and reflecting average production for 12 magnesium-producing companies. The use of coke oven and semicoke oven gas (wastes) may be credited to the primary magnesium production, lowering the footprint of Mg production.

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Calcination and reduction are main contributing steps to the greenhouse gas footprint of Mg production (Ehrenberger, 2020), while reduction is also a relatively important contributing step to other impact categories (acidification, eutrophication and resource depletion; Ehrenberger, 2013). Moreover, FeSi production is an important contributor to the environmental impacts of Mg production as well, due to its relatively high energy and material consumption (Ehrenberger, 2013; Gao et al., 2009). Compared to other processes, the Pidgeon process shows the worst performance in terms of atmospheric emissions, material and energy consumption, and subsequently in terms of impacts (Cherubini et al., 2008). Future evolution in production, e.g. the magnesium production site in Qinghai, China (electrolysis plant), may be seen as promising regarding the reduction of impacts from total primary magnesium production (Ehrenberger, 2020); yet to be further analysed in the future.

Finally, undertaking a life cycle perspective is key in the context of Mg. On the one hand, inputs to the Mg production process (e.g. FeSi) and associated upstream environmental impacts (in terms of CO_2-eq) are important contributors to the impacts per kg Mg produced, as already mentioned above. On the other hand, in a context of increasingly stringent regulation of emissions from vehicles and rising petrol costs, making vehicles lighter (e.g. thanks to the use of Mg) is one approach to gain efficiency in terms of fuel consumption. This potentially leads to trade-offs in impacts: potentially more impacts at the stage of raw materials (in that case, Mg) manufacturing, but fewer impacts in the use stage (in that case, less fuel consumption and associated emissions). This is, in particular, true for the aviation industry, for which a benefit in the use of Mg is observed according to Ehrenberger (2020): “the high fuel reduction potential for aircraft leads to extremely fast amortization of emissions from the production stage”.

NORMATIVE REQUIREMENTS RELATED TO THE USE AND PROCESSING OF MAGNESIUM

Technical rules for the use of Fluorspar can be found in the GESTIS Substance database[3].

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF MAGNESIUM FOR EXPORTING COUNTRIES

Globally the beryllium economy is a very small (about 0.009% of the total world trade market). The importance of this market is also anecdotic for the main producing country (China 0.04%, New Zealand 0.02%, Israel 0.11%, Germany 0.004%, USA 0.006%, Turkey 0.03% and Canada 0.007% of their total export trade value…). (COMTRADE, 2020).

SOCIAL AND ETHICAL ASPECTS

No specific issues were identified during data collection and stakeholders’ consultation.

[3] See https://gestis-database.dguv.de/data?name=007120

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At the local scale, one can mention the Alliance Magnesium initiative in Canada. They produce magnesium from asbestos industrial waste and they put in place a sustainable development model with an emphasis on economic and social benefits[4]. Alliance Magnesium provides a unique opportunity to sustainably diversify the economy of the Des Sources RCM in the Eastern Townships, which has gone through its share of difficulties in recent years. The town of Asbestos receives the highest equalization payments in Quebec. Alliance Magnesium is also developing a new industrial sector while maximizing the region's assets, expertise and opportunities. The company is widely supported by socioeconomic stakeholders and the public. Alliance Magnesium operates as an exemplary corporate citizen. Since its founding, the company's guiding principles have reflected its commitment to contributing to the economic development of its host region. To this end, it prioritizes local hiring and acquiring goods and services from nearby businesses. It promotes their integration into the supply chain to create an environment conducive to business development. Between 2019 and 2021, they invested about 150M$ CAN and created more than 100 direct jobs.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

a. R&D trends in terms of emerging LCGT

No data available

b. R&D trends in terms of emerging application of RM in already existing LCGT

- **Magnesium ion batteries**

The green Mg applications in the new batteries are the development of new anodes (Mg-alloys), cathodes (intercalation type: V-Oxides, Mn-Silicates; conversion type: Mo-Sulphide) and electrolytes on MIBs; Mg for both electrodes; Mg-Air on a new kind of batteries (Liu et al.; Huie et al.). As a promising multivalent battery type, rechargeable magnesium batteries (RMBs) have attracted increasing attention because of low reduction potential (−2.37 V vs. SHE), high safety, potentially high energy density (or high theoretical volumetric capacity - 3833 mAh cm^{-3} -) (Li et al.), low-cost thanks to the abundant resource of Mg (Zhao-Karger et al.; Egashira et al.), and the advantage of recyclability (low cost for recycling and melting processes) (Bella et al.; Witte; Ehrenberger et al.). The manufacturing processes for a magnesium-ion battery are less energy-intensive and release less toxins than the equivalent processes for lithium-ion. In rechargeable magnesium ion batteries, the metal utilization as an anode material is impractical mainly because of its high sensitivity to surface reactions, so the choice of the electrolyte becomes extremely difficult, and the ion insertion anodes seem to be necessary to conceive a commercial device (Bella et al.).

Rechargeable metal-S batteries, such as Mg–S batteries, use a cathode based on sulfur, a much cheaper, more abundant, and more sustainable material than the typically Li-, Co-, Mn, and Ni-based cathode materials in LIBs. The technology is still in the stage of basic research (TRL=2). Such systems

[4] https://alliancemagnesium.com/en/sustainable-development/economic-and-social-benefits/

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would be of great interest for more sustainable integration of renewable energies into the grid (Bieker et al.; Salama et al.; Chung et al.; Hong et al.; Durmus et al.). These kinds of batteries have emerged as one of the most promising candidates because of the ideal features of Mg to be used as a metal anode. The key challenges of realising Mg batteries lie in developing efficient electrolytes with high electrochemical stability and identifying suitable cathode materials offering high voltage and high capacity (Zhao-Karger et al.).

Other battery technologies are under development, particularly for larger-scale utility power storage, for instance, in redox flow batteries other than in metal-liquid techs (McPhail et al.).

- **Mg applications in hydrogen production**

Mg alloy hydrolysis is considered a cheap, efficient, environmentally friendly, and sustainable hydrogen production method (Xiaojiang Hou et al., 2022). Mg alloy waste (IMAW) employed in hydrolysis is proposed as a ‘Green hydrogen’ strategy. Fresh melting Mg alloys, such as Mg-Re (Xiaojiang Hou et al., 2020; Xiaojiang Hou et al., 2019), Mg-Cu (SeKwon Oh et al.), and Mg-Sn (SeKwon Oh et al., 2017; Song-Lin Li et al.) systems, have very excellent hydrolysis kinetics and final hydrogen production yields (Xiaojiang Hou et al., 2022).
In addition, Mg-based waste materials can be used in preparing MgH_2, reactive metal hydride composites (RHC) based on Mg and alkali borohydrides (Yuanyuan Shang et al.) to reduce the production cost of hydrogen storage materials.
The solar thermochemical splitting cycle (TSC), as an “indirect” method, is developed by Ontario Tech (Hasan Ozcan et al.; Farid Safari et al.) to produce hydrogen or carbon monoxide plus oxygen as a byproduct from the water molecule or the carbon dioxide molecule. This technology uses the same heat transfer/heat storage fluid in the conventional solar receiver for power generation applications with a four-step Mg-Cl cycle (Hasan Ozcan et al.; Farid Safari et al.) (TRL=4-6).

- **Magnesium utilization in CO_2 capture**

Magnesium-crystalline nanoparticles and bulk-Mg convert CO_2 to methane, methanol and formic acid, using water as the sole hydrogen source (Sushma A. Rawool et al.). One of the most promising materials for carbon mineralization is $Mg(OH)_2$, which is highly reactive and capable of forming stable carbonates under atmospheric or near-atmospheric conditions (Scott et al.; Kelemen et al.; Zarandi et al.). Indirect aqueous carbonation of steel slag using Mg silicates is a promising way for carbon capture, utilisation, and storage (Xiaohui Mei et al.). Reduction by direct carbon capture is already indicated in the previous paragraph (Sushma A. Rawool et al.; Scott et al.; Kelemen et al;. Zarandi et al.) as for the use of wastes (Xiaohui Mei et al.).

OTHER RESEARCH AND DEVELOPMENT TRENDS

- Magnesium and Aluminium Gas Injection Technology for High Pressure Die Casting[5]

The project aims at providing innovative technology which generates hollow metal components with die casting. The automotive industry already uses die casting to produce a variety of solid metal components. Production of hollow components currently requires additional upstream and downstream processes. The

[5] See https://cordis.europa.eu/project/id/950866

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engineers behind the EU-funded MAGIT project have developed a novel gas injection technology for high-pressure die casting of hollow aluminium and magnesium parts. It promises significant savings in time, money and materials. It also accommodates novel shapes such as integrated fluid duct components for the cooling of electronics and electric motors or vehicle batteries.

- Additive Manufacturing of Magnesium Bioresorbable ImplanTs[6]

The project aims to develop Craniomaxillofacial (CMF) implants from bioresorbable materials made from magnesium alloys. These novel implants will have certain advantages over titanium-based counterparts including improved healing, enhanced patient quality of life and reduced healthcare costs as no additional surgeries will be required to remove them.

- Circular Processing of Seawater Brines from Saltworks for Recovery of Valuable Raw Materials[7]

The ancient process of saltworks involves the natural evaporation and fractionated crystallisation of seawater. This process also produces a by-product of brine that is free of calcium and includes some crucial elements at 20 to 40 times more concentrated levels than seawater does. The EU-funded SEArcularMINE project will take the brine to develop and integrate three innovative technologies within a circular procedure that will target magnesium, lithium and other trace elements belonging to the alkaline/alkaline Earth metals or transition/post-transition metals group. These innovative technologies will be based on three different processes: reactive crystallisation, selective membrane separation, and selective sorption/desorption. By adopting a multidisciplinary method, the project will improve knowledge of the processes needed to recover minerals from brines and seawater.

- Unravelling the Metal-Hydride Thermodynamics of Size-Selected Magnesium Nanoalloys.

The project will tap into the potential of electron energy loss spectroscopy to unravel the metal-hydride phase transition of magnesium nanoalloys. Furthermore, it will use four-dimensional scanning transmission electron microscopy to investigate how the interface between magnesium and magnesium hydride and strain affects destabilisation.

REFERENCES

Atrens et al. (2013), Advances in Mg corrosion and research suggestions, Journal of Magnesium and Alloys, Volume 1, Issue 3, 2013, Pages 177-200, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2013.09.003, June 2022

Bell N., Waugh R. and Parker D. (2017), Magnesium Recycling in the EU. Material flow analysis of magnesium (metal) in the EU and a derivation of the recycling rate. A report by Oakdene Hollins for IMA (International Magnesium Association)

Bella et al. (2021), An Overview on Anodes for Magnesium Batteries: Challenges towards a Promising Storage Solution for Renewables, Nanomaterials (Basel), 2021;11(3):810, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8004101/, June 2022

[6] See https://cordis.europa.eu/project/id/101029651

[7] See https://cordis.europa.eu/project/id/869467

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

Bender et al. (2012), A new theory for the negative difference effect in magnesium corrosion, Materials and Corrosion, 63: 707-712, https://doi.org/10.1002/maco.201106225, June 2022

BGR (2019), Communication during the review

Bieker et al. (2021), Intrinsic differences and realistic perspectives of lithium-sulfur and magnesium-sulfur batteries,Commun Mater 2, 37 (2021), https://doi.org/10.1038/s43246-021-00143-0, June 2022

Braun et al. (2021), Time Resolved Measurements of pH in Aqueous Magnesium-Air Batteries during Discharge and Its Impact for Future Applications, ChemElectroChem 2022, 9, e202101191, https://doi.org/10.1002/celc.202101191, June 2022

Chawla N. (2019), Recent advances in air-battery chemistries, Materials Today Chemistry, Volume 12, 2019, Pages 324-331, ISSN 2468-5194, https://doi.org/10.1016/j.mtchem.2019.03.006, June 2022

Chen et al. (2009), Progress in electrical energy storage system: A critical review, Progress in Natural Science, Volume 19, Issue 3, 2009, Pages 291-312, ISSN 1002-0071, https://doi.org/10.1016/j.pnsc.2008.07.014, June 2022

Cherubini, et al. (2008), LCA of magnesium production: Technological overview and worldwide estimation of environmental burdens. Resources, Conservation and Recycling 52, 1093–1100. , https://doi.org/10.1016/j.resconrec.2008.05.001 , February 2022

Chung et al. (2019), Current Status and Future Prospects of Metal–Sulfur Batteries, Adv. Mater. 2019, 31, 1901125, https://doi.org/10.1002/adma.201901125, June 2022

cips.org (2022), available at: https://www.cips.org/supply-management/analysis/2022/february/what-to-do-about-the-magnesium-shortage/

CRM 2020, European Commission (2020), Study on the EU's list of Critical Raw Materials (2020) Critical Raw Materials Factsheets (Final) - CRM Factsheet, https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf, June 2022

Czerwinski F. (2008), Magnesium and Its Alloys. In Magnesium Injection Molding; , Springer: New York, NY, USA, 2008; pp. 1–79, https://link.springer.com/book/10.1007/978-0-387-72528-4, June 2022

Dolega et al. (2021), Green technologies and critical raw materials Strategies for a circular economy - Strategies for a circular economy, Policy Brief, https://www.oeko.de/fileadmin/oekodoc/Green-technologies-and-critical-raw-materials.pdf, June 2022

Dühnen et al. (2020), Toward Green Battery Cells: Perspective on Materials and Technologies, Small Methods 2020, 4, 2000039, https://doi.org/10.1002/smtd.202000039, June 2022

Durmus et al. (2020), Side by Side Battery Technologies with Lithium-Ion Based Batteries,Adv. Energy Mater. 2020, 10, 2000089, https://doi.org/10.1002/aenm.202000089, June 2022

Egashira et al. (2021), Properties of Magnesium Electrode Covered with Magnesium Chloride-Modified Graphene Oxide, Electrochemistry, 2021, Volume 89, Issue 1, Pages 49-53, Released January 05, 2021, https://doi.org/10.5796/electrochemistry.20-00119, June 2022

Ehrenberger et al. (2013), Life-Cycle Assessment of the Recycling of Magnesium Vehicle Components, JOM 65, 1303–1309 (2013), https://doi.org/10.1007/s11837-013-0703-3, June 2022

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

Ehrenberger, S. (2013), Life Cycle Assessment of Magnesium Components in Vehicle Construction, https://elib.dlr.de/87332/1/2013-12_IMA_LCA-Study_Report_Part-I-and-II_incl-summary.pdf , February 2022

Ehrenberger, S. (2020), Carbon Footprint of Magnesium Production and its Use in Transport Applications. Update of the IMA Report “Life Cycle Assessment of Magnesium Components in Vehicle Construction (2013), https://www.researchgate.net/publication/346097191_Carbon_Footprint_of_Magnesium_Production_and_its_Use_in_Transport_Applications?channel=doi&linkId=5fbb8dfa458515b79762c3eb&showFulltext=true , February 2022

Erickson et al. (2015), Review—Development of Advanced Rechargeable Batteries: A Continuous Challenge in the Choice of Suitable Electrolyte Solutions, J. Electrochem. Soc. 162 A2424, https://iopscience.iop.org/article/10.1149/2.0051514jes, June 2022

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

Eurostat (2019)b. Statistics on the production of manufactured goods (PRODCOM NACE Rev.2), [online] Available at: http://ec.europa.eu/eurostat/data/database

Eurostat (2020), Comext International Trade [Online]. Available at: https://ec.europa.eu/eurostat/web/international-trade-in-goods/data/database

Farid Safari et al. (2020), A review and comparative evaluation of thermochemical water splitting cycles for hydrogen production, Energy Conversion and Management, Volume 205, 2020, 112182, ISSN 0196-8904, https://doi.org/10.1016/j.enconman.2019.112182, June 2022

Fortune Business Insights (2021), Magnesium Market Size, Share & COVID-19 Impact Analysis, By Application (Aluminum Alloying, Die Casting, Desulfurization, Metal Reduction, and Others) and Regional Forecast, 2020-2027, https://www.fortunebusinessinsights.com/magnesium-market-104713, June 2022

Frankel et al. (2015), Introductory lecture on corrosion chemistry: a focus on anodic hydrogen evolution on Al and Mg, Faraday Discuss., 2015, 180, 0, 11-33, The Royal Society of Chemistry, http://dx.doi.org/10.1039/C5FD00066A, June 2022

Gao, et al. (2009), Life cycle assessment of primary magnesium production using the Pidgeon process in China. The International Journal of Life Cycle Assessment 14, 480–489., https://doi.org/10.1007/s11367-009-0101-9 , February 2022

German Environment Agency (2020), Environmental Criticality of Raw Materials. An assessment of environmental hazard potentials of raw materials from mining and recommendations for an ecological raw materials policy. Report No. FB000275/ANH,ENG. TEXTE 80/2020. , https://www.umweltbundesamt.de/en/publikationen/environmental-criticality-of-raw-materials#:~:text=It%20is%20proposed%20to%20designate,methodology%20developed%20and%20applied%20here. , February 2022

Hasan Ozcan et al. (2018), Experimental investigation of an improved version of the four-step magnesium-chlorine cycle, International Journal of Hydrogen Energy, Volume 43, Issue 11, 2018, Pages 5808-5819, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2017.08.038, June 2022

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

Hong et al. (2019), Nonlithium Metal–Sulfur Batteries: Steps Toward a Leap, Adv. Mater. 2019, 31, 1802822, https://doi.org/10.1002/adma.201802822, June 2022

Huie et al. (2015), Cathode materials for magnesium and magnesium-ion based batteries, Coordination Chemistry Reviews, Volume 287, 2015, Pages 15-27, ISSN 0010-8545, https://doi.org/10.1016/j.ccr.2014.11.005, June 2022

IMA (2016), [online] Available at: http://www.intlmag.org/

IMA (2019), Communication during the review

InfoMine (2017), Charts & Data. [online] Available at: http://www.infomine.com/ChartsAndData/ChartBuilder.aspx?z=f&gf=110543.USD.kg&dr=max&cd=1

Kavanagh et al. (2018), Lithium Sources - Industrial Use and Future in the Electric Vehicle Industry: A Review, Resources 2018, 7, 57, https://doi.org/10.3390/resources7030057, June 2022

Kelemen et al. (2019), An Overview of the Status and Challenges of CO2 Storage in Minerals and Geological Formations, Frontiers in Climate, 1, https://doi.org/10.3389/fclim.2019.00009, June 2022

Li et al. (2020), A review on current anode materials for rechargeable Mg batteries, J of Magnesium and Alloys, Volume 8, Issue 4, 2020, Pages 963-979, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2020.09.017, June 2022

Liu et al. (2021), Challenges and Recent Progress on Key Materials for Rechargeable Magnesium Batteries, Adv. Energy Mater. 2021, 11, 2000787 , https://doi.org/10.1002/aenm.202000787, June 2022

Liu et al. (2021), Hydrogen storage in incompletely etched multilayer Ti2CTx at room temperature, Nat. Nanotechnol. 16, 331–336 (2021), https://doi.org/10.1038/s41565-020-00818-8, June 2022

Liu, J. et al. (2018). Techno-Economic Analysis of Magnesium Extraction from Seawater via a Catalyzed Organo-Metathetical Process, JOM, 70, pp. 431–435.

Lu et al. (2021), Divalent Nonaqueous Metal-Air Batteries, Frontiers in Energy Research, 8, 2021, https://doi.org/10.3389/fenrg.2020.602918, June 2022

Magpowersystem Inc. (2013), , http://www.magpowersystems.com/, June 2022

material-properties.org, available at: https://material-properties.org/types-of-magnesium-alloys-definition/

McPhail et al. (2020), Slurry Design for a Low Cost, High Capacity Magnesium Semi-Solid Flow Battery, Meet. Abstr. MA2020-02 300, https://iopscience.iop.org/article/10.1149/MA2020-022300mtgabs/meta, June 2022

Nguyen et al. (2017), A review on technology maturity of small scale energy storage technologies, Renew. Energy Environ. Sustain. 2 36 (2017), https://www.rees-journal.org/articles/rees/full_html/2017/01/rees170039s/rees170039s.html, June 2022

Passarini, F. et al. (2018), Material Flow Analysis of Aluminium, Copper, and Iron in the EU-28, EUR 29220 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-85744-7, doi:10.2760/1079, JRC111643

Roskill (2013), Magnesium Metal: Global Industry Markets and Outlook

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

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

Salama et al. (2019), Metal–Sulfur Batteries: Overview and Research Methods, ACS Energy Letters 2019 4 (2), 436-446, https://pubs.acs.org/doi/full/10.1021/acsenergylett.8b02212, June 2022

Scott et al. (2021), Transformation of abundant magnesium silicate minerals for enhanced CO2 sequestration, Commun Earth Environ 2, 25, https://doi.org/10.1038/s43247-021-00099-6, June 2022

SeKwon Oh et al. (2017), Fabrication of Mg–Ni–Sn alloys for fast hydrogen generation in seawater, International Journal of Hydrogen Energy, Volume 42, Issue 12, 2017, Pages 7761-7769, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2016.11.138, June 2022

SeKwon Oh et al. (2018), Design of Mg-Cu alloys for fast hydrogen production, and its application to PEM fuel cell, Journal of Alloys and Compounds, Volume 741, 2018, Pages 590-596, ISSN 0925-8388, https://doi.org/10.1016/j.jallcom.2017.12.257, June 2022

Sevastyanova et al. (2017), Hydrogen generation by oxidation of “mechanical alloys” of magnesium with iron and copper in aqueous salt solutions, International Journal of Hydrogen Energy, Volume 42, Issue 27, 2017, Pages 16961-16967, ISSN 0360-3199, https://doi.org/10.1016/j.ijhydene.2017.05.242, June 2022

Shah et al. (2021), Magnesium-Ion Batteries for Electric Vehicles: Current Trends and Future Perspectives, Advances in Mechanical Engineering, (March 2021), https://doi.org/10.1177/16878140211003398, June 2022

Shand (2006), The Chemistry and Technology of Magnesia – Chapter 2: Formation and occurrence of magnesite and brucite.

Song-Lin Li et al. (2019), Mg-Mg2X (X=Cu, Sn) eutectic alloy for the Mg2X nano-lamellar compounds to catalyze hydrolysis reaction for H2 generation and the recycling of pure X metals from the reaction wastes, Journal of Alloys and Compounds, Volume 772, 2019, Pages 489-498, ISSN 0925-8388, https://doi.org/10.1016/j.jallcom.2018.09.154, June 2022

Sushma A. Rawool et al. (2021), Direct CO2 capture and conversion to fuels on magnesium nanoparticles under ambient conditions simply using water, Chem. Sci., 2021, 12, 16, 5774-5786, The Royal Society of Chemistry, http://dx.doi.org/10.1039/D1SC01113H, June 2022

Tan et al. (2021), Applications of Magnesium and Its Alloys: A Review, Appl. Sci. 2021, 11, 6861, https://doi.org/10.3390/app11156861, June 2022

Totalmateria.com, available at: https://www.totalmateria.com/page.aspx?ID=CheckArticle&site=ktn&NM=138

USGS (Since 2000), Mineral Commodity Summaries, U.S. Department of the Interior, U.S. Geological Survey

Wang et al. (2019), Materials Design for Rechargeable Metal-Air Batteries, Matter, Volume 1, Issue 3, 2019, Pages 565-595, ISSN 2590-2385, https://doi.org/10.1016/j.matt.2019.05.008, June 2022

Witte (2010), The history of biodegradable magnesium implants: A review, Acta Biomaterialia, Volume 6, Issue 5, 2010, Pages 1680-1692, ISSN 1742-7061, https://doi.org/10.1016/j.actbio.2010.02.028, June 2022

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

WMD (2022), Federal Ministry of Agriculture, Regions and Tourism of Austria (Ed.): World Mining Data.-(since 1984)

Wulandari et al. (2010), Magnesium: current and alternative production routes. [online] Available at: http://ro.uow.edu.au/cgi/viewcontent.cgi?article=2295&context=engpapers

Xiaohui Mei et al. (2022), Phase transition and dissolution behavior of Ca/Mg-bearing silicates of steel slag in acidic solutions for integration with carbon sequestration, Process Safety and Environmental Protection, Volume 159, 2022, Pages 221-231, https://doi.org/10.1016/j.psep.2021.12.062, June 2022

Xiaojiang Hou et al. (2019), Microstructure evolution and controlled hydrolytic hydrogen generation strategy of Mg-rich Mg-Ni-La ternary alloys, Energy, Volume 188, 2019, 116081, ISSN 0360-5442, https://doi.org/10.1016/j.energy.2019.116081, June 2022

Xiaojiang Hou et al. (2020), Comparative investigation on feasible hydrolysis H2 production behavior of commercial Mg-M (M = Ni, Ce, and La) binary alloys modified by high-energy ball milling - Feasible modification strategy for Mg-based hydrogen producing alloys, Int J Energy Res. 2020; 44: 11956– 11972, https://doi.org/10.1002/er.5843, June 2022

Xiaojiang Hou et al. (2022), Mg alloy waste modified by (Mg10Ni)90Ce10: A green hydrolysis hydrogen production strategy, Fuel, Volume 311, 2022, 122517, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2021.122517, June 2022

Xu et al. (2019), Overview of advancement and development trend on magnesium alloy, Journal of Magnesium and Alloys, Volume 7, Issue 3, 2019, Pages 536-544, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2019.08.001, June 2022

Yang et al. (2021), Research advances in magnesium and magnesium alloys worldwide in 2020, Journal of Magnesium and Alloys, Volume 9, Issue 3, 2021, Pages 705-747, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2021.04.001, June 2022

Yuanyuan Shang et al. (2021), Mg-based materials for hydrogen storage, Journal of Magnesium and Alloys, Volume 9, Issue 6, 2021, Pages 1837-1860, ISSN 2213-9567, https://doi.org/10.1016/j.jma.2021.06.007, June 2022

Zarandi et al. (2017), Nesquehonite as a carbon sink in ambient mineral carbonation of ultramafic mining wastes, Chemical Engineering Journal, Volume 314, 2017, Pages 160-168, https://doi.org/10.1016/j.cej.2017.01.003, June 2022

Zhang et al. (2014), Magnesium–air batteries: from principle to application, Mater. Horiz., 2014, 1, 2, 196-206, The Royal Society of Chemistry, http://dx.doi.org/10.1039/C3MH00059A, June 2022

Zhao-Karger et al. (2019), Beyond Intercalation Chemistry for Rechargeable Mg Batteries: A Short Review and Perspective, Frontiers in Chemistry, 6, 2019, ISSN 2296-2646, https://www.frontiersin.org/article/10.3389/fchem.2018.00656, June 2022

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