SCRREEN2

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

RHENIUM

AUTHOR(S):

SCRREEN
Solutions for CRitical Raw materials - a European Expert Network

TABLE OF CONTENT

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RHENIUM

OVERVIEW

Rhenium (Re) is a silvery-white metal refractory metal. It has a very high melting point (3,185°C) and a heat-stable crystalline structure. It is ductile, dense (21.04 g/cm3) and highly resistant to corrosion. It is mostly found as trace impurities in copper and molybdenum sulphide ores. The market of rhenium is mostly driven by the demand for superalloys in the aerospace industry. Demand is forecasted to increase with the growth of the global passenger air traffic. Recycling and engine will satisfy most of this demand growth.

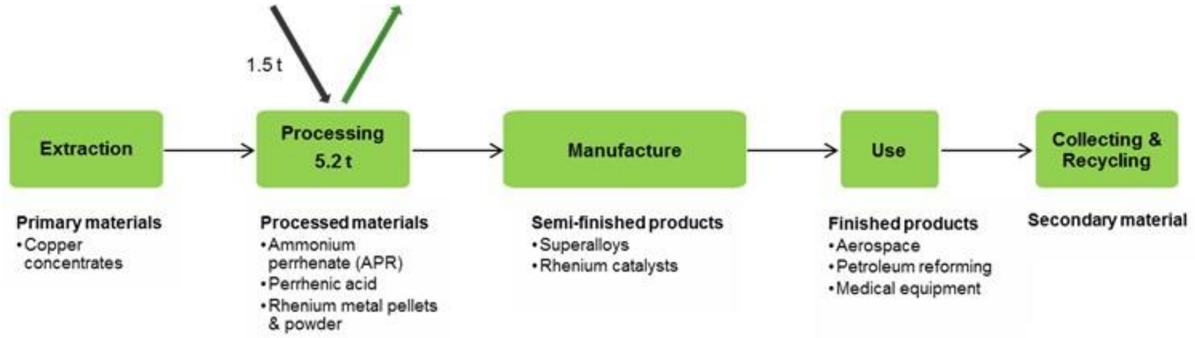

Figure 1. Simplified value chain for rhenium in the EU[1]

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
43.9 tonnes	Chile 49% USA 19% Poland 15%	No data at EU level			

Rhenium is not traded on any exchange market. There is no reliable statistics on rhenium products trade because the import tariff code for rhenium (metal) also covers niobium (CN 81129231). Rhenium is also imported into EU as NH_4ReO_4 (rhenium ammonium perrhenate - APR) under the tariff code number 2841908590 which is described under the classification list of ‘salts of oxometallic or peroxometallic acids. However, the trade figures are only available at 8-digit level in Eurostat database, aggregated with other compounds.

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

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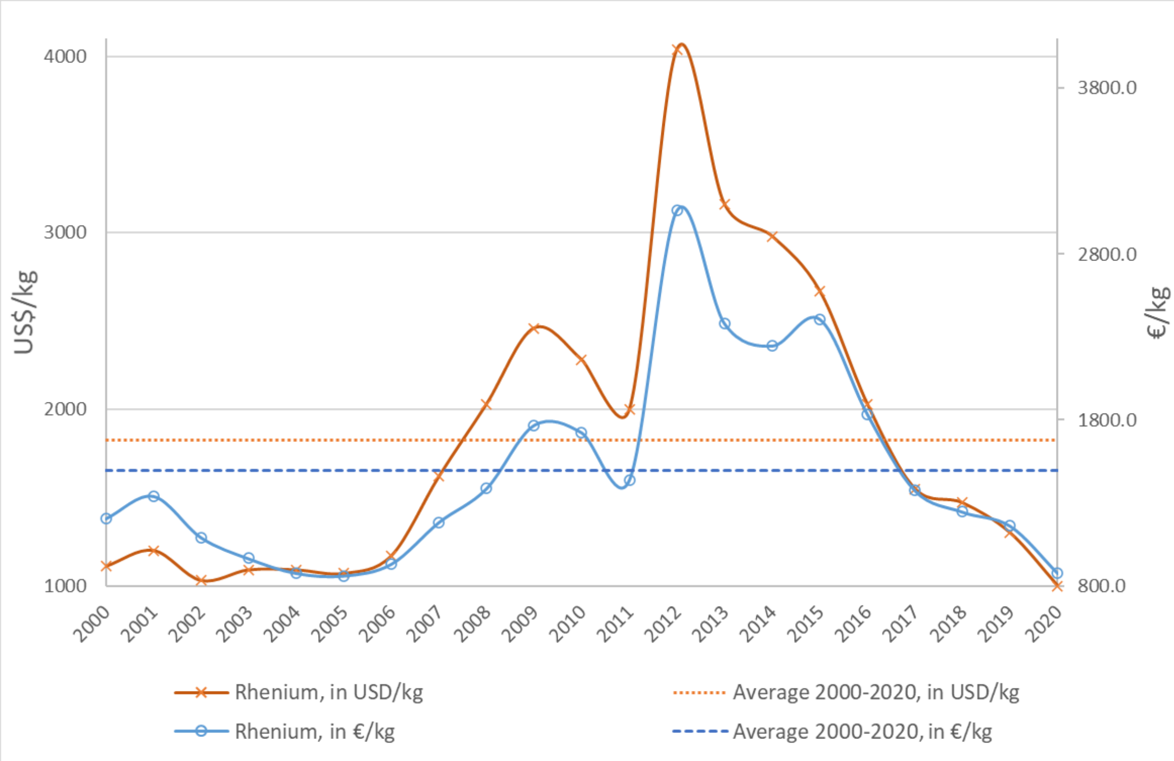

Figure 2. Annual average price of rhenium between 2000 and 2020 (USGS, 2021)[2].

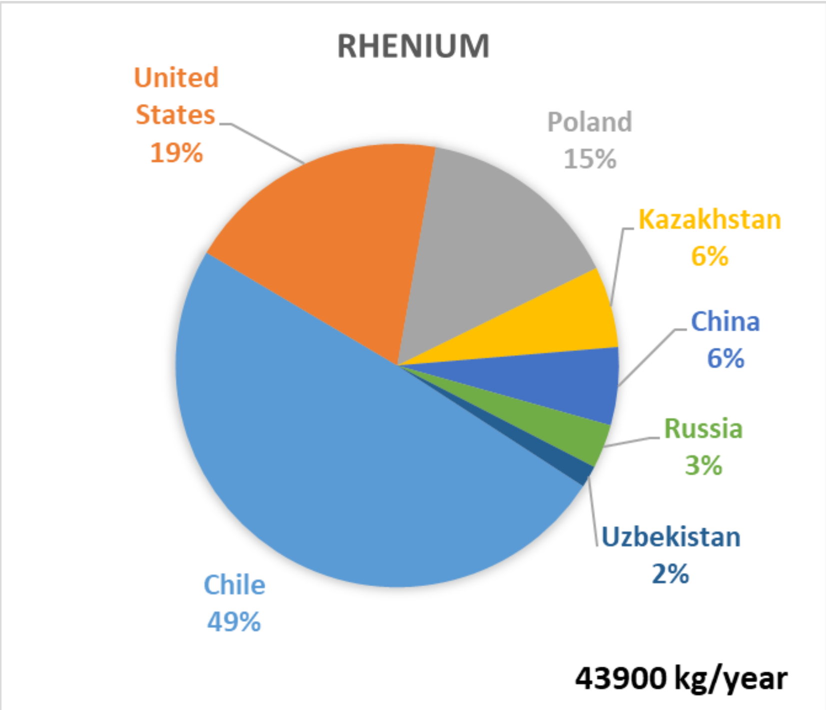

Figure 3. Global mine production

[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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Prices: The decreasing rhenium price over the last decade can be interpreted as a return to the long-run trend (or 'equilibrium') after a price peak in 2008 (European Commission, 2020; King, 2021): The price peak resulted from rising rhenium demand on the one hand and rigid supply on the other hand. The demand was driven by a new generation of rhenium-containing super alloys for turbine blades and the development of gas-to-liquids processes; the supply rigidity originated from the dependence of rhenium production on copper production (European Commission, 2020; King, 2021).

Primary supply: The world production of rhenium has ranged from 48.8 to 59 tonnes during the period 2016-2020 (USGS, since 2000). The global metallic rhenium production by country since 1984 according to WMD can be seen in **Erreur ! Source du renvoi introuvable.**, respectively. Chile, United States, Poland and Uzbekistan are the major producers. Rhenium in Chile is produced by Molymet (Molibdenosy Metales) from domestic and imported concentrates, while in United Stated it is produced by Freeport-McMoran Copper & Gold's Sierrita processing facilities in Arizona from molybdenite concentrates (USGS, since 2000).

Secondary supply: Recycling has become an important source of rhenium. The rate of recovery of rhenium from end-of-life products is superior to 50% (EoL-RIR) (UNEP, 2011). The rhenium recycling industry experienced considerable capacity growth when rhenium metal and APR spot prices were high (Roskill, 2015). Rhenium is recycled from end-of-life turbine blades, mill scraps and spent petrochemical catalysts.

Uses: About 80% of the world annual consumption of rhenium is used in high-temperature superalloys for the manufacture of turbine blades for aircraft and industrial gas turbine (jet) engines (Lipmann, 2016). It is also used along with platinum as a catalyst (bi-metallic catalyst with 0.3% Re and 0.3% Pt) in the production of high-octane unleaded gasoline.

Substitution: Several rhenium-free alloys, or alloys with a reduced rhenium content, have been developed over the last 20 years (General Electric, Onera, Pratt & Whitney etc.). Ceramic matrix composites (CMCs) parts are used in some types of commercial aircraft engine (CFM LEAP engine). However, there is currently very little substitution potential for rhenium in superalloys used in the hottest parts of large gas turbine engines (up to 1,600ºC).

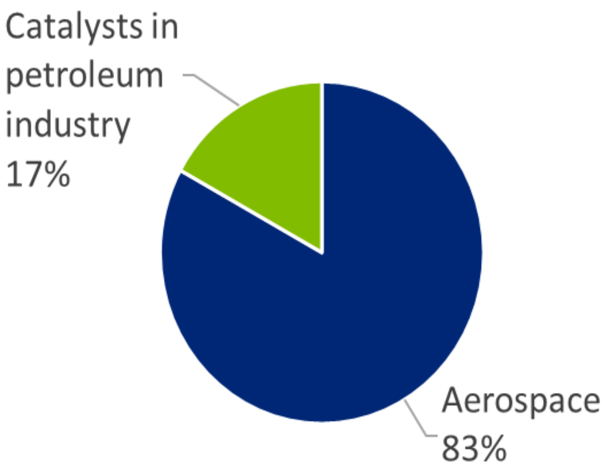

Figure 4: EU end uses of rhenium

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Table 2. Uses and possible substitutes

Application	Share*	Substitutes	SubShare	Cost	Performance
Superalloys	80%	Cobalt	3%	Similar or lower costs	Similar
Superalloys	80%	Tungsten	3%	Similar or lower costs	Similar
Superalloys	80%	Ruthenium	3%	Very high costs (more than 2 times)	Similar
Superalloys	80%	Rhodium	3%	Very high costs (more than 2 times)	Similar
Superalloys	80%		90%		No substitute
Catalysts in petroleum industry	15%		100%		No substitute

Global applications of rhenium, 2017 (Pratt & Whitney, 2018; validated by SCRREEN experts, 2022

Other issues: rhenium being mostly a by-product, it has no real direct impacts, either social or environmental. This is a very limited market. A few R&D projects are undergoing to use rhenium in low carbon technologies such as electrode material in supercapacitors, or anode buffer layer in PV cells.

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3. Rhenium supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
43.9 tonnes	Chile 49% USA 19% Poland 15%				

World consumption of rhenium was estimated at about 43.9 tonnes in average on the 2016-2020 period (WMD, 2022). The market of rhenium is mostly driven by the demand for superalloys in the aerospace Industry (EC, 2020). In 2020, the COVID-19 pandemics has impacted the aerospace and defence industry due to travel restriction measures and the reduced production of airplanes (USGS, 2021a).The sector was reported to get € 622 billion of revenue, down 8% from 2019, and $25 billion of operating profit, a decrease of 61%, mainly due to the impacts of COVID-19 on commercial aerospace (PWC, 2021).The industry is highly concentrated in terms of production, with Chile, USA and Poland as major suppliers. Key rhenium producers include Molymet, Freeport MCMoRan, KGHM and LS-Nikko (EC, 2021). Consequently, rhenium has a low-price elasticity of supply (CDMR, 2020).

EU TRADE

Trade in rhenium is controlled by copper/molybdenum producers who exploit copper porphyry deposits. There are a limited number of companies in this position, with Molymet, based in Chile, producing almost half the world's supply. The polish company KGHM is also among the producers, with a 4 t annual production capacity,, equivalent to nearly 7% of world production (Kesieme, et. al., 2019).

However, rhenium is not traded on any exchange market. There is no reliable statistics on rhenium products trade because the import tariff code for rhenium (metal) also covers niobium (Trade code 8112923100). Rhenium is also imported into EU as NH_4ReO_4 (rhenium ammonium perrhenate - APR) under the tariff code number 2841908590 which is described under the classification list of 'salts of oxometallic or peroxometallic acids. However, the trade figures are only available at 8-digit level in Eurostat database, aggregated with other compounds. The major use of rhenium is in aerospace sector. It is believed that aerospace Original Equipment Manufacturer (OEMs) place long-term agreements (LTA's) for rhenium directly with rhenium suppliers to cover their requirements (University of Birmingham, 2021).

Experts estimate 1.5 to 2 tonnes of import into EU and the UK per year, on average over 2012 to 2016. Possible sources of imports are South Korea, Japan, Kazakhstan, Russia, Armenia, Uzbekhistan, Iran and Chile (expert communication, 2016 in Non-Critical Raw materials profiles; European Commission, 2020).

PRICE AND PRICE VOLATILITY

The price of rhenium was driven p by a new generation of rhenium-containing super alloys for turbine blades and the development of gas-to-liquids processes; the supply rigidity was driven by the dependence of rhenium production on copper production (European Commission, 2020; King, 2021)Klicken oder tippen Sie hier, um Text einzugeben.. In contrast, the global economic recession, rhenium-saving alloy design and increased recycling have contributed to a rhenium-price 'normalisation' over the last decade (European Commission, 2020; King, 2021). The Covid-19 crisis has had effects on rhenium supply and demand (USGS, 2021a) and, thus, potentially, on the rhenium price. (European Commission, 2020; King, 2021): (European Commission, 2020; King, 2021). (European Commission, 2020; King, 2021). T(USGS, 2021a)

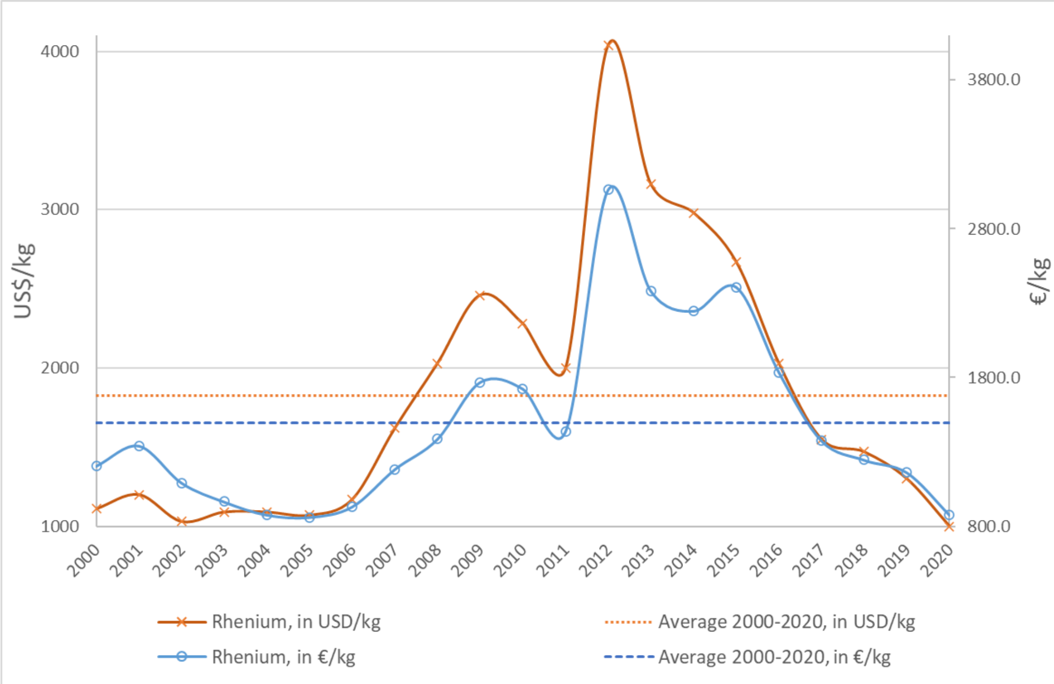

Figure 1. Annual average price of rhenium (gross weight, metal pellets, 99.99% pure) between 2000 and 2020, in US$/kg and €/kg (based on USGS, 2021b). Dash lines indicate average prices for 2000-2020.

The price development of ammonium perrhenate (as reported by USGS, 2021b) is very similar to the price development depicted in Figure 1. In particular, the price of ammonium perrhenate is monotonously decreasing over the period 2012-2020 with an average log return of -20.6%. However, the price dynamics of ammonium perrhenate show a higher 2016-2020-price volatility (of 19.7%) in comparison to the data depicted in Figure 1. Moreover, rhenium-price dynamics show (qualitative) similarities with the dynamics of the hafnium price discussed in this study.

OUTLOOK FOR SUPPLY AND DEMAND

In the short term, the demand for rhenium is likely to suffer from the difficulties of the aeronautics sector and to experience a notable slowdown (CDMR, 2021). The COVID-19 pandemic has caused a lower demand of rhenium due to travel restriction measures and the reduced production of airplanes (USGS, 2021a). Government restrictions on international travel will influence the outlook for international air travel (USGS, 2021a). IATA predicted that the situation in airline industry will be better from the second half of 2021 as some international markets open between advanced economies in Europe and North America and a few in other regions (IATA, 2021). However, passenger volumes are not expected to return to 2019 levels until 2024 at the earliest, with domestic markets recovering faster than international services (IATA, 2020).

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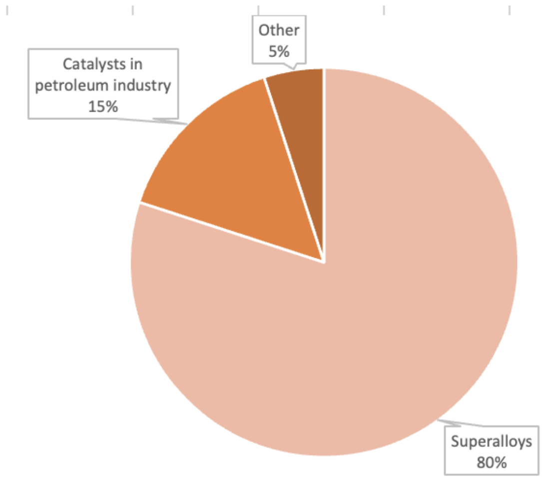
DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

According to experts, average rhenium consumption from 2012 to 2016 is likely to be of the order of a few tonnes. The EU apparent consumption (production + imports- exports) of rhenium for 2000-2020 cannot be calculated due to the lack of reliable trade data. In Eurostat Comext (2021) rhenium (metal) also covers niobium (CN 81129231 and CN 81129131).

GLOBAL AND EU USES AND END-USES



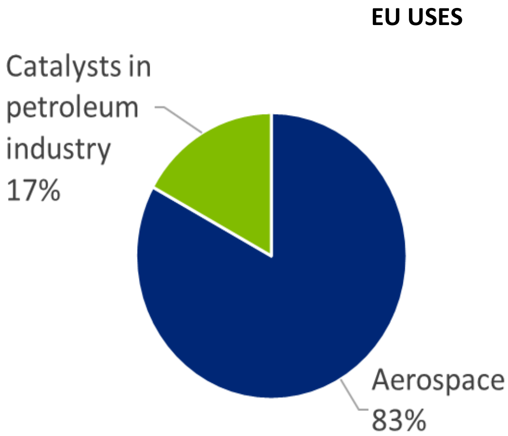


Figure 5. Estimations of Global and EU applications / end uses of rhenium. Left chart - Global 2017 (Pratt & Whitney, 2018; validated by SCRREEN experts, 2022). . Right chart - EU end uses of rhenium in 2012-2016 (Lipmann, 2016).

Rhenium is mainly used in the aerospace and petrochemical industries.

About 80% of the world annual consumption of rhenium is used in high-temperature superalloys for the manufacture of turbine blades for aircraft and industrial gas turbine (jet) engines (Lipmann, 2016).

Erreur ! Source du renvoi introuvable. presents the main uses of rhenium in the EU, with relevant industry s ectors described using the NACE sector codes (Eurostat, 2022).

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

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit NACE sectors
Aerospace	C30 - Manufacture of other transport equipment	49,129	C3030- Manufacture of air and spacecraft and related machinery
Catalysts in petroleum industry	C19 - Manufacture of coke and refined petroleum products	24,896*	C1920- Manufacture of refined petroleum products

**data to 2014 only*

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Figure 6. Value added per 2-digit NACE sector over time (Eurostat, 2022)

APPLICATIONS IN EU

AEROSPACE - SUPERALLOYS

Small additions of rhenium increase the 'creep strength' of superalloys, enabling them to withstand higher temperatures.

These superalloys are commonly grouped into generations based on their rhenium content: first-generation rhenium-free alloys gave way to second generation alloys in the 1990s, containing 2–3 % rhenium have seen the greatest market utilization. Third-generation alloys contain 6% rhenium, and the fourth generation is characterised by high rhenium (6%) and ruthenium (3-6%) contents (Mottura & Reed, 2014).

CATALYSTS – PETROLEUM INDUSTRY

Platinum-rhenium reforming catalysts are used in producing lead-free, high-octane gasoline.

It is also used along with platinum as a catalyst (bi-metallic catalyst with 0.3% Re and 0.3% Pt) in the production of high-octane unleaded gasoline. Other uses include thin filaments in a wide array of bulbs and mass spectrometers, in thermocouples, and in heating elements and X-ray targets for medical equipment.

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SUBSTITUTION

Table 5. Uses and possible substitutes of rhenium

Application	Share*	Substitutes	SubShare	Cost	Performance
Superalloys	80%	Cobalt	3%	Similar or lower costs	Similar
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Superalloys	80%		90%		No substitute
Catalysts in petroleum industry	15%		100%		No substitute

Global applications of rhenium, 2017 (Pratt & Whitney, 2018; validated by SCRREEN experts, 2022

SUPERALLOYS

Since the advent of third-generation superalloys which contain more rhenium, engine manufacturers have opted to reduce their rhenium consumption, primarily due to cost concerns.

Several rhenium-free alloys, or alloys with a reduced rhenium content, have been developed over the last 20 years (General Electric, Onera, Pratt & Whitney etc.).

Ceramic matrix composites (CMCs) parts are used in some types of commercial aircraft engine (CFM LEAP engine). However, there is currently very little substitution potential for rhenium in superalloys used in the hottest parts of large gas turbine engines (up to 1,600ºC).

CATALYSTS

Catalysts consisting of platinum only are less efficient in most applications and more expensive.

OTHERS

Substitutes in other applications include cobalt and tungsten for coatings on X-ray tubes, rhodium and rhodium-iridium for high-temperature thermocouples, tungsten and platinum-ruthenium for coatings on electrical contacts, tungsten and tantalum for electron emitters (USGS, 2022; Millensifer et al., Polyak, 2019).

Substitutes for rhenium in platinum-rhenium catalysts are continually being evaluated, with iridium and tin having success in one such application (USGS, 2022).

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SUPPLY

EU SUPPLY CHAIN

According to Eurostat data, about 4,8 tonnes of rhenium were averagely annually produced in EU between 2015-2019 (Eurostat, 2020). KGHM is the only European producer of the metal from its own resources. The company produces rhenium as a by-product, under metallic form of grey tablets, through the copper production process. The purity of the metallic product is 99.9% (KGHM, 2022). There is no data available concerning the exact imported amount of rhenium in EU, however it is known that it is imported as metallic rhenium, ammonium perrhenate, perrhenic acid and potassium perrhenate. Rhenium is also produced in EU (few tonnes annually) through the processing of industrial wastes and the recycling of end-of-life catalysts (MSP_REFRAM, 2016).

GEOLOGY, RESOURCES AND RESERVES OF RHENIUM

GEOLOGICAL OCCURRENCE

Rhenium has an estimated average concentration of 0.2 ppb in the Earth continental upper crust (Rudnick & Gao, 2003). It is dominantly hosted in the mineral molybdenite, where it isomorphically substitutes for molybdenum. Rhenium is not mined as concentrated ore but is recovered as a by-product of copper ore processing.

Porphyry copper-molybdenum deposits supply about 80% of the rhenium produced by mining. The metal is produced from molybdenum concentrates from several deposits in Chile and Peru (El Teniente, Toquepala), Western United States, Armenia, Kazakhstan, Uzbekistan and Iran (Sar Cheshmeh deposit).

Sediment-hosted strata-bound copper deposits are the other major primary source of rhenium, both the sandstone-types in Kazakhstan (Dzhezkazgan deposits) and the Kupferschiefer types in Poland (Lubin-Sieroszowice mining district). The nature of the rhenium mineral host in these type of deposits is still poorly understood (John et al., 2017). Although copper mineralization in Poland, Germany and Kazakhstan is strongly enriched in Re compared to the average crustal value, the geological processes which is responsible for this phenomenon remain not fully understood. The only natural Re mineral species is rheniite (ReS_2) which was recently identified in volcanic environment in Kudriavy volcano in Russia. Re is usually contained as trace element in copper and molybdenum ore phases (Foltyn et al. 2022). Rhenium is also found in some sandstone uranium deposits in Kazakhstan and Uzbekistan and at the Merlin high-grade molybdenum-rhenium deposit in Australia (Babo, 2017).

GLOBAL RESOURCES AND RESERVES

Global reserves of rhenium at the end of 2018 were estimated at around 2,400 tonnes (USGS, 2019), with Chile accounting for about half of the total (55%), followed by the United States (17%) and Russia (13%)**Erreur ! Source du renvoi introuvable.**). However, this table does not include reserves in Poland, Uzbekistan, China

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and in Australia where a high grade molybdenum and rhenium deposit has been newly discovered. Published probable reserves at the Merlin deposit in Queensland are estimated at 129 tonnes of rhenium (7.1 million tonnes with 18.1 g/t rhenium, JORC) (Queensland Government, 2017). The lack of grade and tonnage data for most deposits, prevents a thorough assessment of world rhenium resources.

Table 6. Global reserves of rhenium in year 2019 (USGS, 2022)

Country	Rhenium Reserves (tonnes, metal content)
Chile	1,300
United States	400
Russia	310
Kazakhstan	190
Armenia	95
Peru	45
Canada	32
China	N.A.
Poland	N.A.
Uzbekistan	N.A.
World total (rounded)	*2,400*

EU RESOURCES AND RESERVES

Notable rhenium deposits exist in Poland where the metal is extracted from sediment hosted stratabound copper deposits. Cu- Ag deposits in the Lubin-Sieroszowice district are operated by KGHM PM S.A. The origin of rhenium is mostly unknown in this deposit. A recent geochemical study on the Cu-Ag Lubin-Sieroszowice ore showed that djurleite phase (with up to 3.9 µg/g Re) could be the main rhenium carrier (Foltyn et al. 2022). There are no data concerning the existence of other potentially exploitable rhenium resources in EU.

WORLD AND EU MINE PRODUCTION

The world production of rhenium has ranged between 48.8 and 59 tonnes during the period 2016-2020 (USGS, since 2000). The global metallic rhenium production by country since 1984 according to WMD ca, be seen in **Erreur ! Source du renvoi introuvable.**. Chile, United States, Poland and Uzbekistan are the major producers. Rhenium in Chile is produced by Molymet (Molibdenosy Metales) from domestic and imported concentrates, while in United Stated it is produced by Freeport-McMoran Copper & Gold's Sierrita processing facilities in Arizona from molybdenite concentrates (USGS, since 2000). Rhenium was also recovered in South Korea by L S Nikko Copper Inc from imported concentrates and in Armenia, Kazakhstan, Mexico, Peru, and Uzbekistan. In Poland, rhenium is produced from copper concentrates produced from the Lubin mine, Polkowice-Sieroszowice mine and Rudna mine (Bartlett et al., 2013). The Polish company KGHM Polska Miedź (KGHM) also recovered rhenium from domestic copper concentrates. Polish copper concentrates contain between 4 and 12 ppm of rhenium (Śmieszek et al., 2017). KGHM is producing APR and metallic rhenium at the Głogów smelting facility (Anderson et al., 2013). Polish rhenium production in 2019 represented 13% of global production according to WMD and 15.6% according to USGS (WMD, since 1984; USGS, since 2000). There are

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a few aerospace approved producers of rhenium pellets in the EU, among them KGHM, Heraeus and Hoganas (previous HC. Starck). Hoganas are well known for the production of low micron powders of Re which are used in tungsten-rhenium alloys in Japan.

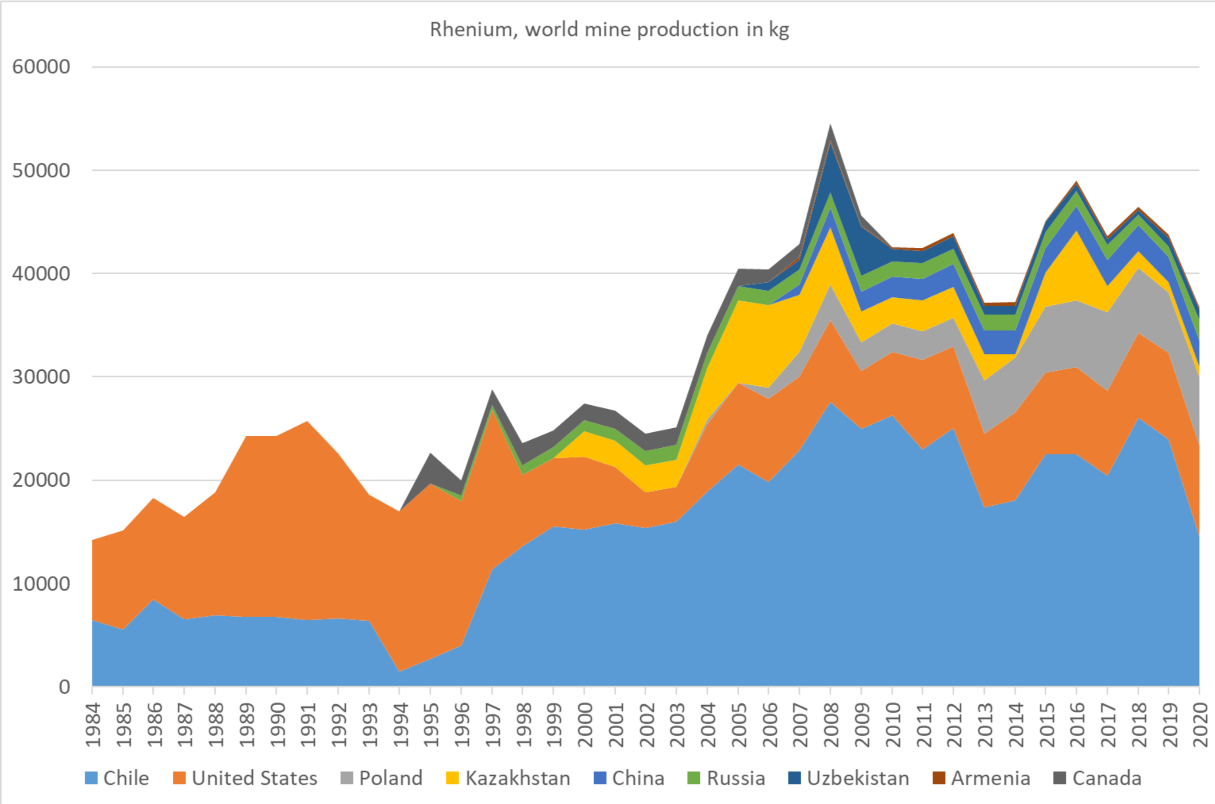

Figure 7. Global metallic rhenium production by country since 1984 and 2019 (WMD, since 1984).

OUTLOOK FOR SUPPLY

Rhenium production worldwide is expected to increase in short term. The Belgian Company Hoboken has recently started the industrial production of rhenium from semifinished products from the processing of ores in Congo (Kinshasa). The capacity of the installation the company set up is several hundred kilograms of metal per year. Additionally, Molybdenum Corp. of America plans the implementation of rhenium extraction from the molybdenite deposits of the Quest field, in which the average concentration of rhenium is 0,03 wt.% (Argimbaev et al. 2021).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

The global end-of-life recycling rate of Rhenium is estimated at 50% (Eurostat, 2021). The rhenium recycling industry experienced considerable capacity growth when rhenium metal and APR spot prices were high (Roskill, 2015). Rhenium is recycled from end-of-life turbine blades, mill scraps and spent petrochemical catalysts.

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The rhenium price spike between 2008 and 2012 led to a surge in the processing and use of 'engine revert', a high-quality post-consumer scrap produced from end-of-life gas turbine parts. Once scrapped engine parts have been checked for chemical uniformity, cleaned of their zirconia- or alumina-based heat-resistant coating and shot-blasted, one is left with pieces of 100% homogenous superalloy metal ready to be remelted. Estimates vary, but industry sources claim that in 2015 engine revert supplied around 20% of all superalloy feedstock (Tantalum-Niobium International Study Center -T.I.C., 2016).

The catalysts industry has a 80% recovery efficiency, reducing the virgin rhenium needs to replace spent catalysts (MMTA, 2016). About 15 tonnes of rhenium are thought to be recovered as ammonium perrhenate from petroleum-reforming catalysts containing rhenium and platinum (Anderson et al., 2013; MSP-Refram, 2016). The main incentive for recycling is the value of platinum. Catalyst regeneration is a closed loop process.

In Europe, rhenium was recycled in Germany (Buss & Buss Spezialmetalle, H.C. Starck and Heraeus Precious Metals)(Lefebvre et al., 2016). Toma Group in Estonia had the capability to recover rhenium from alloys and rhenium scrap into high purity ammonium perrhenate (Catalyst Grade purity), according to their website (Toma Group, 2012).

Rhenium is commercially recovered from two types of scraps: (b) Re-containing superalloys and (b) end-of-life catalysts that used in the petroleum refining industry for the improvement of the octane level of fuels. Heraeus Precious Metals GmbH is the leading company of Re recycling by catalysts activating in US and Germany. According to 2014 data, it has been estimated that around 20 tonnes or rhenium are obtained by the recycling processing of superalloys and catalysts (Millensifer et al. 2014). The recycling processing of end-of-life superalloys comprises the following steps: The scrap is initially submitted to high-temperature digestion in a molten salt melt containing NaOH, Na_2CO_3, and Na_2SO_4 at temperatures between 850 and 1100 °C in a directly fired rotary kiln in the presence of oxidizing agents. Alternatively, scrap material is subjected to roasting at a high temperature of 1000 °C under an oxidizing atmosphere. The melt product is subsequently cooled down and sent to a comminution process for size reduction. The material is then leached with water and filtered to separate the insoluble Co, Ni, Fe, Mn and Cr from the leach liquor. Magnetic separation is then applied to the insoluble components for further separation and concentration. The pregnant leach solution is sent to an ion exchange step, where the aqueous rhenium is selectively adsorbed obtained (**Erreur ! Source du renvoi introuvable.**) (Kesieme et al. 2019).

In case of spent petroleum-reforming catalysts recycling, Re is recovered simultaneously with platinum group metals. The initial step comprises the complete dissolution of the alumina substrate using sulphuric acid which also dissolves rhenium and at some extent, platinum. The rhenium-rich pregnant solution is separated from the platinum-containing residue and aqueous aluminium through ion exchange. Rhenium is eluted from the organic amine resin via the addition of hydrochloric acid. After elution, the rhenium-rich eluate is neutralized using ammonium hydroxide. The neutralized solution is subsequently evaporated to from supersaturated perrhenate. After successive redissolution and recrystallization processes, a high-purity ammonium perrhenate precipitate is obtained (**Erreur ! Source du renvoi introuvable.**) (Kesieme et al. 2019).

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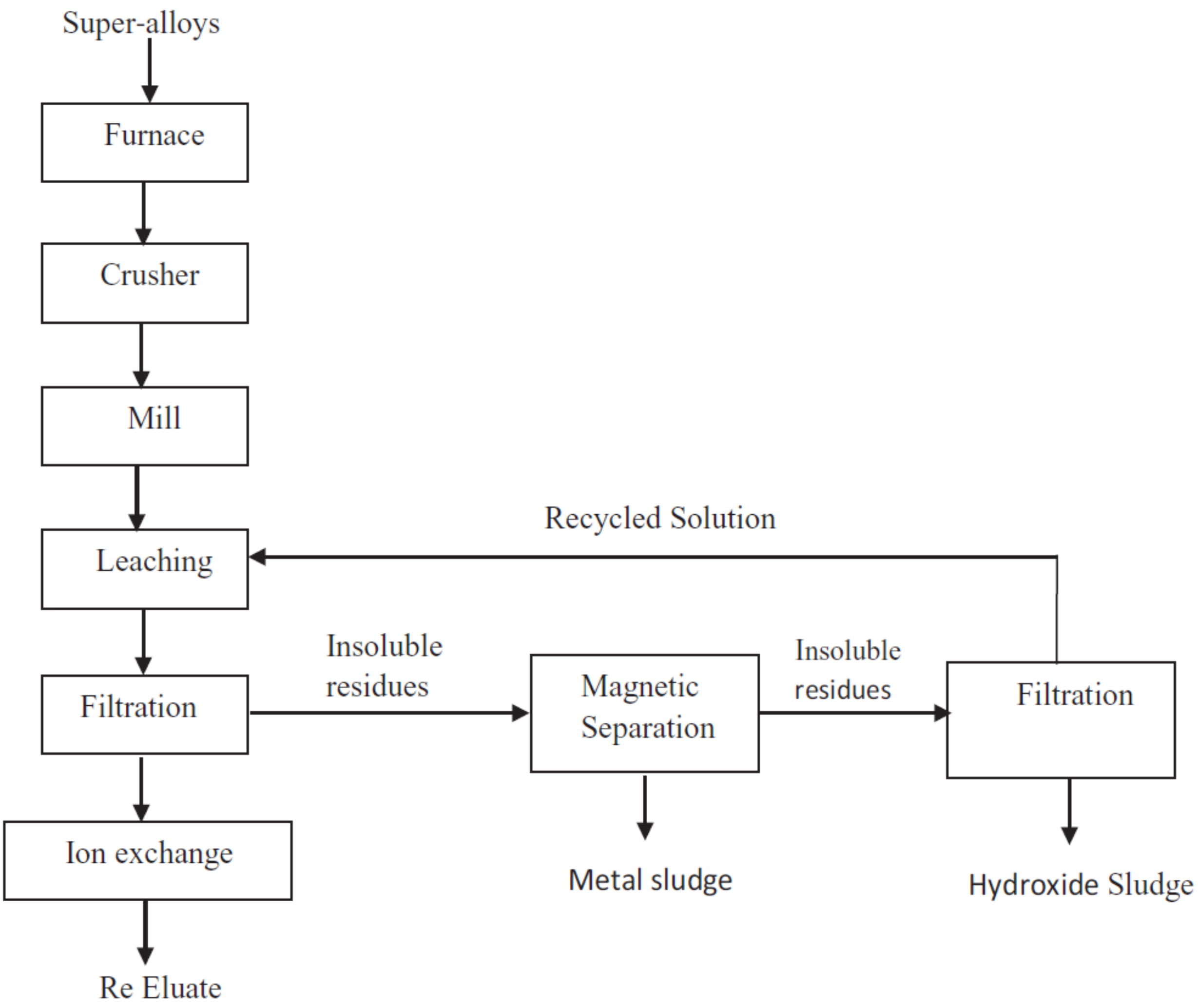

Figure 8. Simplified flowsheet for the recovery of Re by the recycling of spent Re-containing superalloys (Kesieme et al. 2019).

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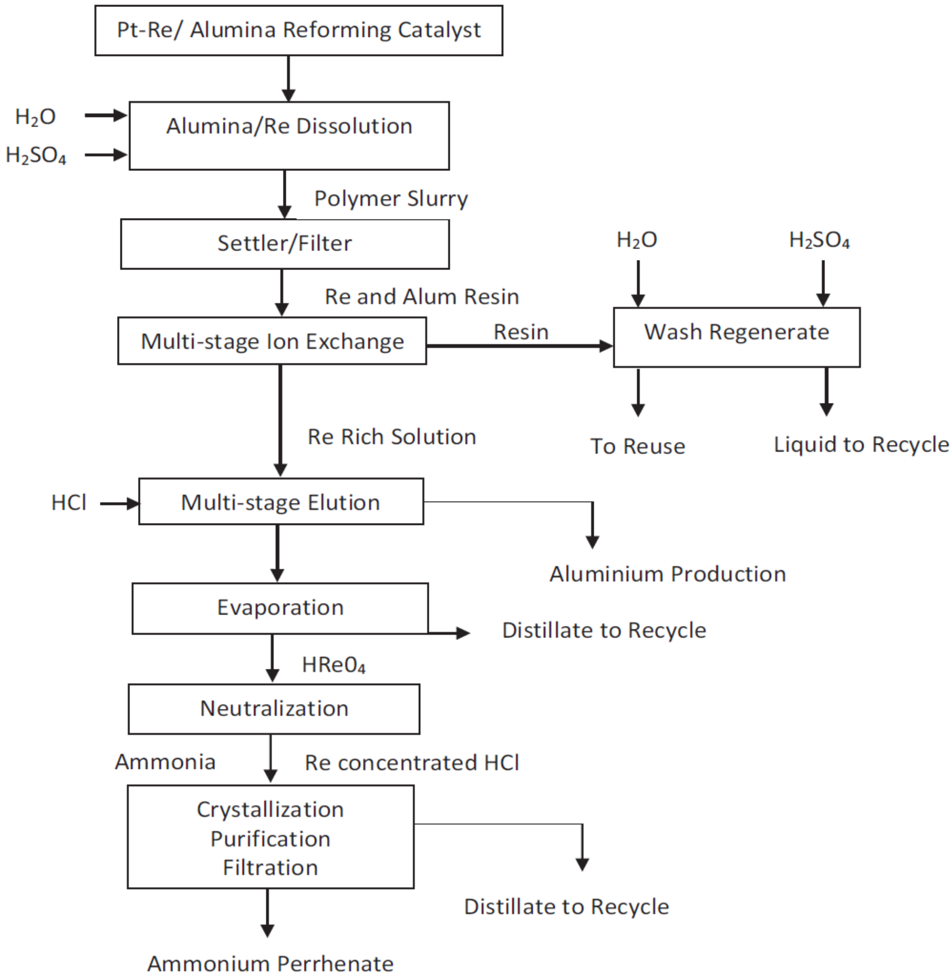

Figure 9. Simplified flowsheet for the recovery of Re by the recycling of end-of-life Re-containing catalysts of the petrochemical industry (Kesieme et al. 2019).

PROCESSING OF RHENIUM

Rhenium is mainly recovered from the gases and dusts produced during the processing of molybdenite concentrates (porphyry copper-molybdenum deposits) or of copper concentrates (sedimentary copper deposits) (Anderson et al., 2013, John et al., 2017).

Copper concentrates and molybdenum concentrates are separated using differential flotation. During roasting of the molybdenite concentrates to produce molybdenum oxide MoO3, the rhenium is oxidised to rhenium heptoxide Re2O7 which is extremely volatile and exits the furnace with the flue gas. Volatile rhenium heptoxide (Re_2O_7) received in the exit of the roaster with sulfur dioxide and dissolved in water forming crude perrhenic acid ($HReO_4$). Metallic rhenium is prepared by applying solvent extraction or solid-bed ion exchange techniques under which the intermediate product ammonium perrhenate (NH_4ReO_4) is crystallized. Successive recrystallizations are necessary in order high purity (99.95%) NH_4ReO_4 be produced. Recently, molybdenum industry has applied high-pressure oxidation of molybdenite concentrate aiming to the increasing of Re recovery yield. Metallic Re is finally produced after the reduction of NH_4ReO_4 with hydrogen in conventional

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boats-in-tubes type furnaces. The furnaces are filled with NH_4ReO_4 which is pushed through the tube chamber to a flow of hydrogen gas, while the tubes are heated externally at the appropriate temperature. Depending on the particle size of the Re powder that should be obtained – in relation to various applications – reduction can be performed in one or two steps. Usually, pellets with diameter in the range of 3-20 mm are formed. Pellets can be sintered to wire or bars forms. Rhenium can also be deposited on various modulus through chemical vapor deposition (Millensifer et al. 2014). At this point it should be mentioned that ammonium perrhenate or ammonium tetraoxorhenate (NH_4ReO_4) (APR), which has a form of a free-flowing white crystal salt, consist worldwide an intermediate product of rhenium as it is stable, non-hazardous and suitable for shipment by air. It can be readily used, after a necessary treatment, in two main industries: for the construction of superalloys for single-crystal turbine blades for aero-engines and in the manufacturing of catalysts.

When molybdenum is not recovered during the ores processing, as it is the case with Polish ore, rhenium is recovered from copper concentrate smelter flue gases.

Recovery yield of rhenium from flue gases has increased to approximatively 80%. Ammonium perrhenate (APR) can be used directly in the production of platinum-rhenium catalysts or serves as a precursor material in the manufacture of rhenium metal powder and pellets. Rhenium metal is generally produced by hydrogen reduction of ammonium perrhenate (APR). Rhenium pellets and high-purity rhenium powder are used in the superalloy industry. Perrhenic acid is used in the manufacture of Pt-Re reforming catalysts.

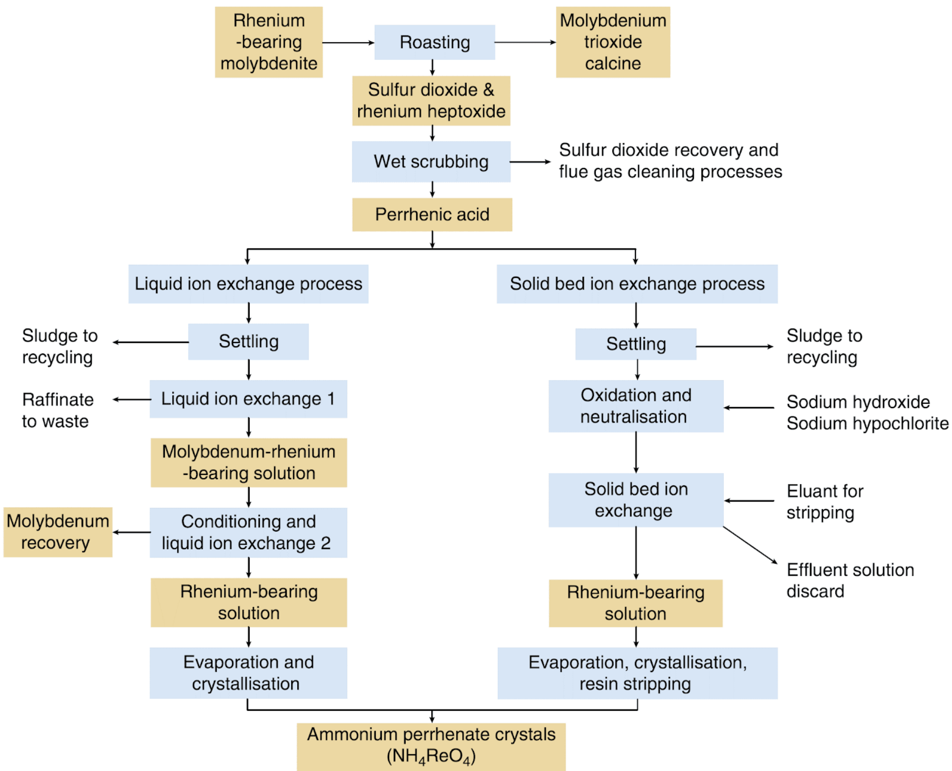

Figure 10. Flowsheet of the metallurgical processing or rhenium-bearing off gases originated by the processing of molybdenite concentrate (Millensifer et al. 2014).

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OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Exposure to rhenium fine dust or fume causes slightly too mild irritation to the eyes and skin (John, Seal II, and Polyak 2017; United States National Institute for Occupational 2016). Rhenium VII sulphide can ignite spontaneously in air and then emits toxic fumes of oxides of sulphur when heated (ILO, 2011).

ENVIRONMENTAL ISSUES

No environmental issues were found in the scientific literature review.

STANDARDS AND NORMATIVE REQUIREMENTS RELATED TO THE USE AND PROCESSING OF RHENIUM

No standards could be found in the scientific literature review.

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF RHENIUM FOR EXPORTING COUNTRIES

No data are available.

SOCIAL AND ETHICAL ASPECTS

Not relevant.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Solar driven renewable energy storage using rhenium disulphide nanostructure based rechargeable supercapacitors (Pazhamalai et al. 2020)
  The research elucidates the potential use of rhenium disulphide nanostructures as an electrode material for high-performance supercapacitor devices. Hydrothermally prepared rhenium disulphide nanostructures using Li2SO4 and triethylethanaminium tetrafluoroborate (TEABF4) electrolytes exhibit high-performance supercapacitive properties with high specific capacitance of 51.4 F g−1 and 28.55 W h kg−1. A solar cell charged ReS_2 supercapacitor can efficiently power electronic devices for a long time, improving its effectiveness for the development of backup energy systems.

- Rhenium isotope energy storage **(**National Centre for Nuclear Research, Poland)
  The metastable rhenium-186m isotope has a half-life of approx. 200 thousand years, but can be forced

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into a fast decaying nuclear state, which releases a much greater energy in its decay than the energy required to initiate the process. Because of this property, rhenium nuclei can be a viable energy storage.

- Solution-Processed Rhenium Oxide: A Versatile Anode Buffer Layer for High-Performance Polymer Solar Cells with Enhanced Light Harvest (Tan et al. 2013)
  High efficiency polymer solar cells using solution processed s-ReO_x as the anode buffer layer are demonstrated. The s-ReO_x layer can effectively change the light distribution within the photoactive layer and enhance its absorption. The solution-processable s-ReO_x is a promising anode buffer layer material for high performance polymer solar cells.

- Synthesis and characterization of rhenium(I) 4,4′-dicarboxy-2,2′-bipyridine tricarbonyl complexes for solar energy conversion (Komreddy et al. 2020)
  The synthesis of a series of rhenium(I) tricarbonyl complexes containing 4,4′-dicarboxy-2,2′-bipyridine and various halide or pseudohalide ligands is reported. The results showed that different functional groups on the ligand could significantly impact the physical properties of the complex. The iodo complex would warrant investigation as a CO_2 reduction catalyst, as well as a possible TiO_2 sensitizer for other kinds of photocatalytic reactions. In addition, these complexes should be studied for the applications of photosensitizers, solar energy converters, luminescent sensors and biological probes.

OTHER RESEARCH AND DEVELOPMENT TRENDS

No data are available.

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