Horizon 2020
Programme

SCRREEN2

This project has received funding from the European

Union's Horizon 2020 research and innovation programme

under grant agreement No 958211.

Start date: 2020-11-01 Duration: 36 Months

SCRREEN
Solutions for CRitical Raw materials - a European Expert Network

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

SULPHUR

TABLE DES MATIÈRES

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SULPHUR

OVERVIEW

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

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
79,700,102	China 18% US 11% Russia 9% Saudi Arabia 8% United Arab Emirates 7% Canada 6% India 5% Kazakhstan 4% Japan 4%	4,866,421	7.8%	Russia 52% UK 23% Kazakhstan 12% Serbia 3% USA 3% Norway 2%	0%

Prices: Highest sulphur price was observed in 2007 around 250 USD/t and post that there have been three more price peaks. Price was at all-time low in 2009 post the financial crisis and currently it appears to be reaching 100 USD/t by end of 2021.

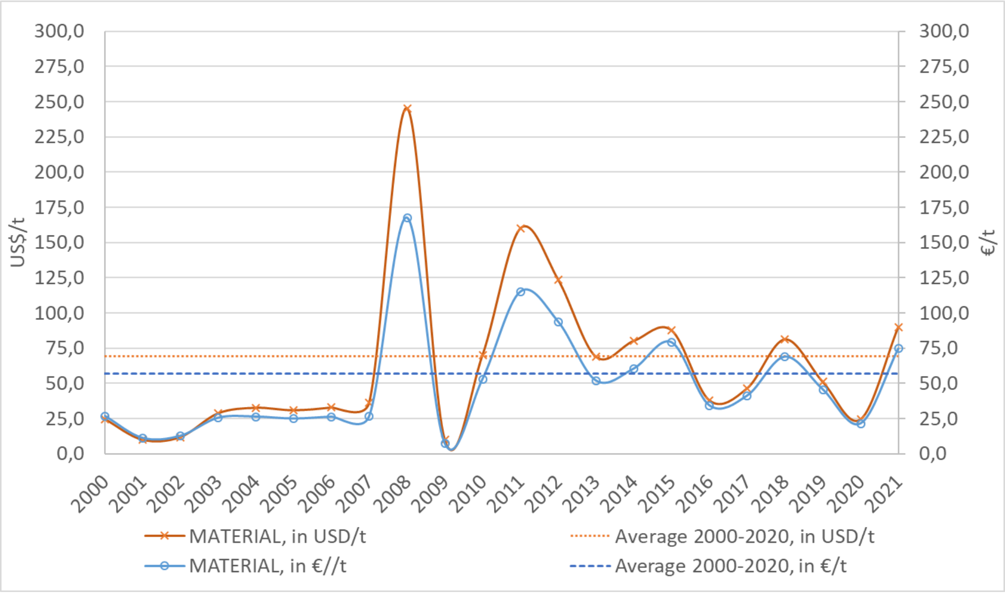

Figure 2. Annual average price of sulphur between 2000 and 2020 (USGS 2021)[2].

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

[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)

Primary supply: In 2018, the sulphur production from discretionary sources (mining of sulphur or pyrites is the sole objective) represented only 8% of the total supply. In the non-discretionary sector, sulphur or sulphuric acid is recovered as an involuntary by-product and the amount of sulphur produced is subject to demand for the primary product and environmental regulations that limit atmospheric emissions of sulphur compounds. Worldwide the biggest sulphur producers are China, the United States, Russia, and Saudi Arabia. The annual amount produced worldwide is 79.7 Mt on average between 2016 and 2020. The EU has a large domestic sulphur production with 13 countries producing an average of 5,779 kt per year between 2016 and 2020 (WMD 2022). According to BGS Poland and Finland are the only EU countries also producing sulphur from discretionary sources (817 kt per year).

Secondary supply: The end-of-life recycling input rate for sulphur is estimated to be 5%. This refers to spent sulphuric acid, which is reclaimed from petroleum refining and chemical processes during any given year.

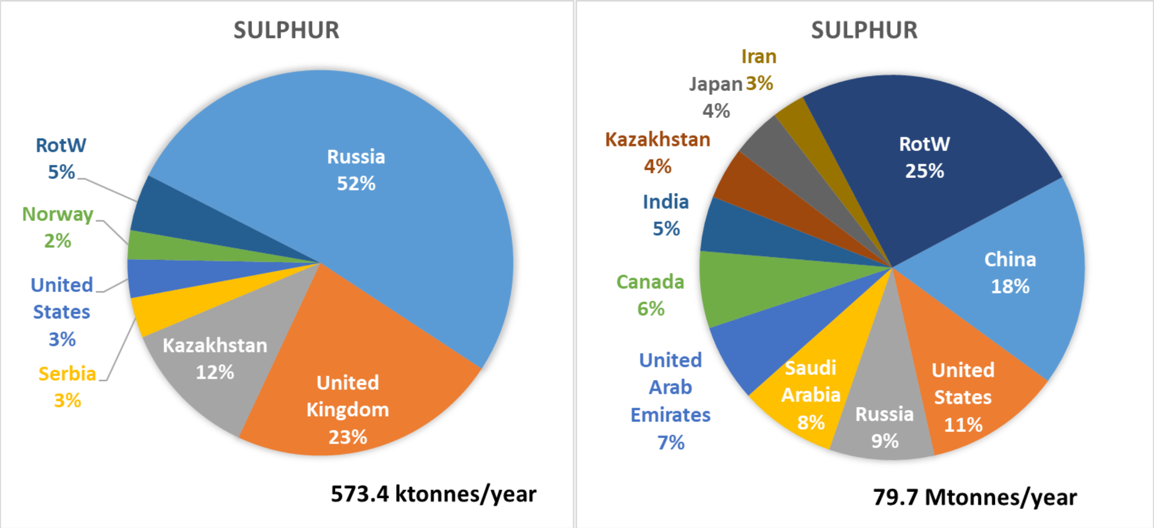

Figure 3. EU sourcing of sulphur and global mine production

Uses: Sulphur is mainly used by the chemical sector as sulphuric acid ($H2SO4$).

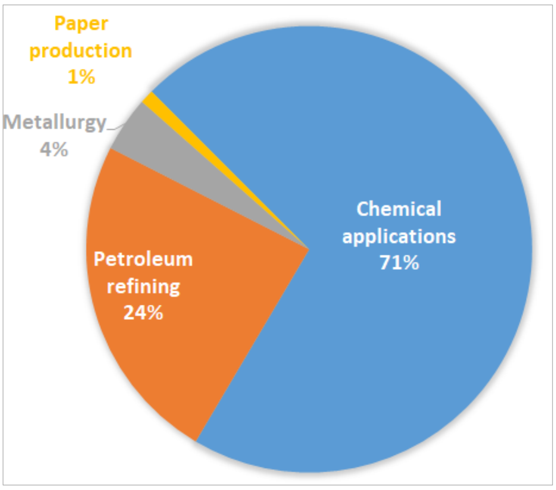

Figure 4: EU uses of sulphur

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Substitution: Sulphur cannot easily be substituted as it is an essential plant nutrient. Over 50% of produced sulphur is used in agriculture for food production each year (The Sulphur Institute, 2015). The use of sulphuric acid can be substituted by various other acids, although usually at a higher cost (SCRREEN experts, 2022).

Table 2. Uses and possible substitutes

Use	Share*	Substitutes	Sub share	Cost	Performance
Chemical applications	71%	other acids	10.0%	Slightly higher costs (up to 2 times)	Reduced
Petroleum refining	24%	NO substitutes			
Metallurgy	4%	NO substitutes			
Paper production	1%	NO substitutes			

*Estimated global end use shares (outputs of SCRREEN Experts Validation Workshop, 2022)

Other issues: Sulphur is classified under Annex VI of Regulation (EC) No 1272/2008 (CLP Regulation) with code H315 because this substance causes skin irritation (ECHA, 2023). Sulphuric substances can have negative effects on human health, including neurological effects and behavioural changes, disturbance of blood circulation, heart damage, and many more. Elemental Sulphur is not toxic, but some sulphur compounds are, for example sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) This is illustrated by the fact that elemental sulphur (and by-product sulphuric acid), produced as a result of efforts to meet environmental requirements, contribute to world supply. Atmospheric sulphur oxides, SO_2 in particular, are emissions that need to be reduced to increase health standards in parts of the EU. The level of sulphur in the environment is strictly regulated.

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3. Sulphur (processing) supply and demand in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
79,700,102	China 18% US 11% Russia 9% Saudi Arabia 8% United Arab Emirates 7% Canada 6% India 5% Kazakhstan 4% Japan 4%	4,866,421	7.8%	Russia 52% UK 23% Kazakhstan 12% Serbia 3% USA 3% Norway 2%	0%

In 2018, global sulphur trade value was estimated at US$ 2.51 billion (OEC, 2022). Sulphur exports increased by 38.9% between 2017 and 2018 (OEC, 2022). In this period, top sulphur exporters were Kazakhstan (15.2%), Russia (13.2%), Canada (12.8%), United States (11.9%), and Japan (5.8%) (OEC, 2022). The top importers were China (16.9%), Morocco (11.7%), Brazil (9.4%), United States (7%), and Belgium (5.6%) (OEC, 2022).

In 2021, global sulphur production increased marginally compared with 2020 due to the increasing demand and is likely to steadily increase for the coming years (USGS, 2022a). New sulphur demand associated with phosphate fertilizer projects is expected mostly in Africa, and sulphur demand likely will also increase in Asia and Eastern Europe (USGS, 2022a).

3.2. EU TRADE

For this assessment, Sulphur is evaluated at processing stage.

Table 4. Relevant Eurostat CN trade codes for Sulphur

Processing/refining	
CN trade code	**title**
25030010	Crude or unrefined sulphur
25030090	Sulphur of all kinds

Export of Crude or unrefined sulphur has been considerably higher than imports over last 20 years with some fluctuations. Although, in last few years exports have declined dramatically and imports have increased simultaneously reversing the trend in 2021.

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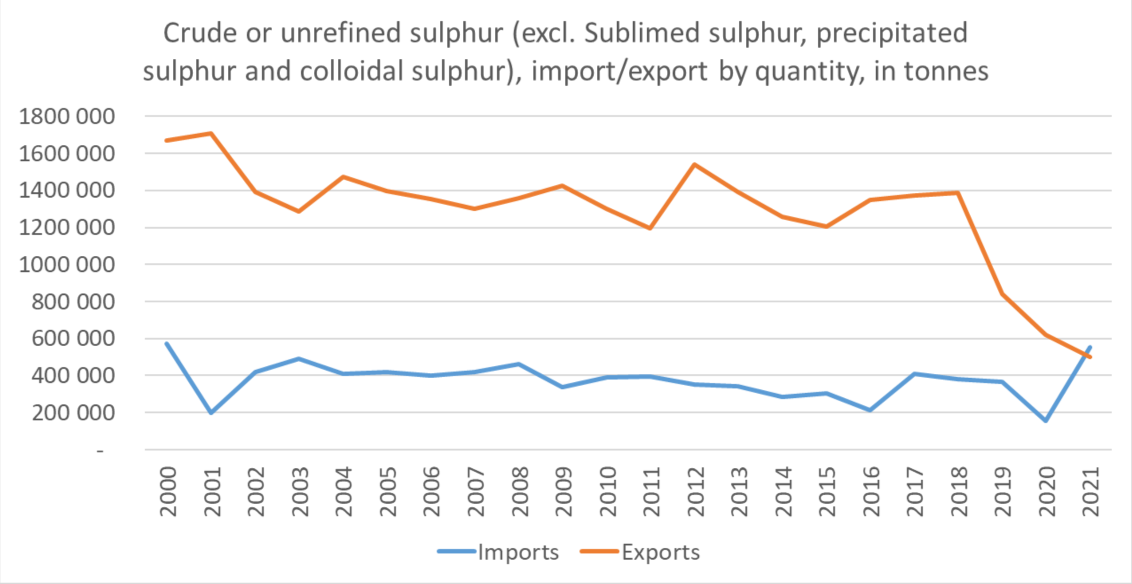

Figure 5. EU trade flows of crude or unrefined sulphur (CN 25030010) from 2000 to 2021 (Eurostat, 2022)

Most of the sulphur comes from Russia followed by Kazakhstan and Norway. Supply from these countries have declined a little since 2017. However, in last 2 years, there is an increase in supply from these countries.

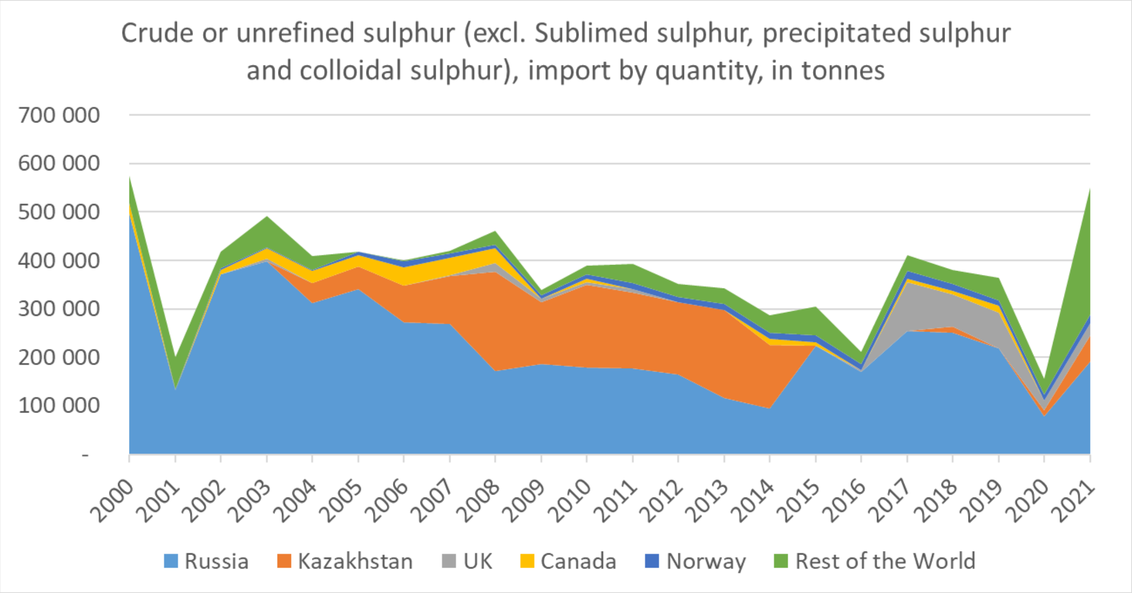

Figure 6. EU trade flows of crude or unrefined sulphur (CN 25030010) from 2000 to 2021 (Eurostat, 2022)

Export of all kinds of Sulphur excluding the unrefined ones have been higher than the imports since 2000 before reversing the trend in 2018. Post 2018 Imports have been higher than the exports

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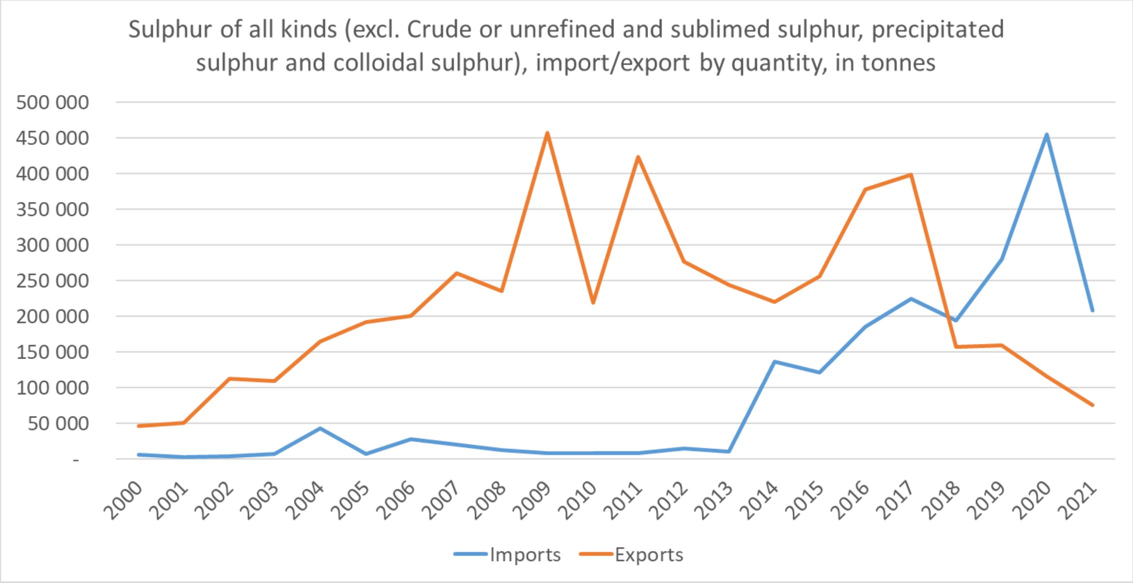

Figure 7. EU imports of sulphur of all kinds (CN 25030090) by country from 2000 to 2021 (Eurostat, 2022)

EU import of Sulphur of all kinds has picked up since 2013 before which it was almost non-existent from any of the sources. Prior to 2019, Kazakhstan was a major supplier but was later taken over by Russia. There has been a general decline for all the countries in 2020.

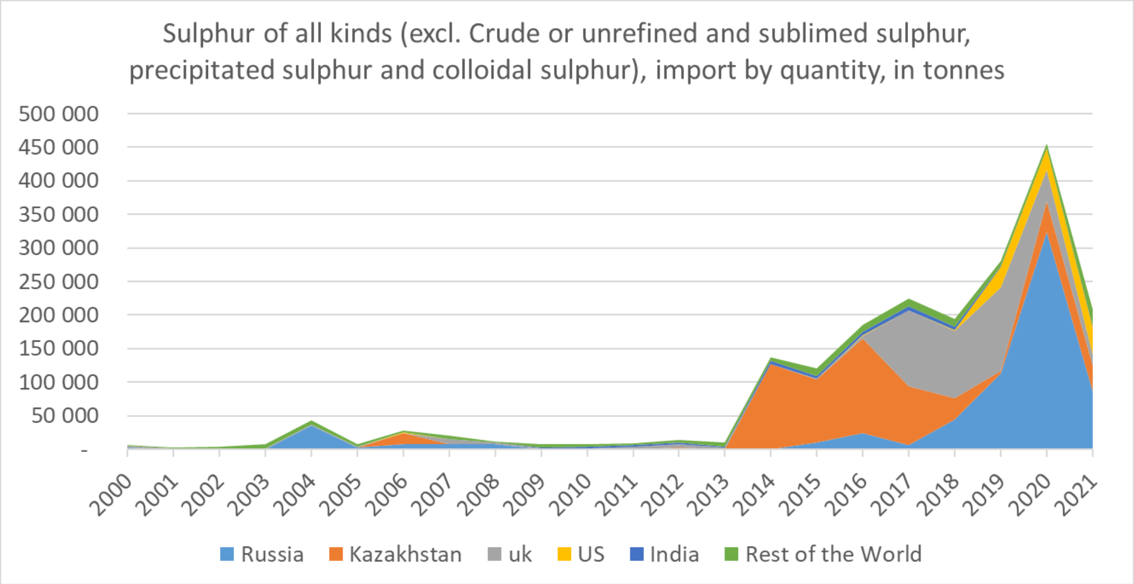

Figure 8. EU imports of sulphur of all kinds (CN 25030090) by country from 2000 to 2021 (Eurostat, 2022)

PRICE AND PRICE VOLATILITY

Highest sulphur price was observed in 2007 around 250 USD/t and post that there have been three more price peaks. Price was at all-time low in 2009 post the financial crisis and currently it appears to be reaching 100 USD/t by end of 2021.

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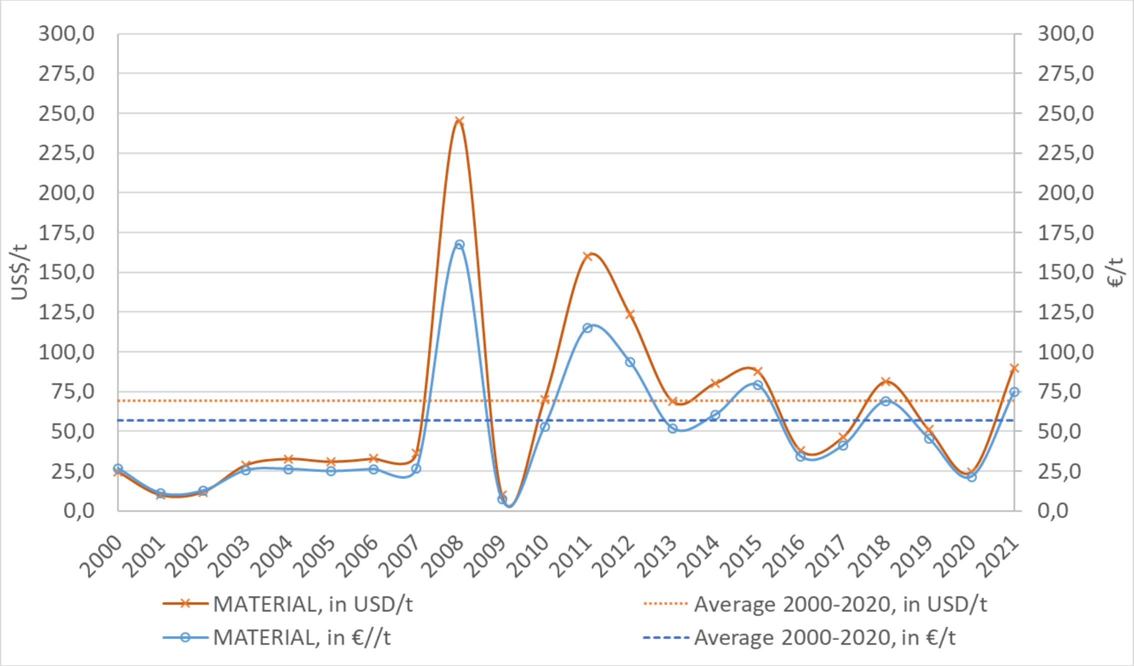

Figure 9. Annual average price of Sulphur between 2000 and 2021, in US$/t and €/t[3]. Dash lines indicate average price for 2000-2021 (USGS, 2022b)

DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

Sulphur EU consumption is assessed at processing stage. Sulphur processing stage EU consumption is presented by HS codes CN 25030010 - Crude or unrefined sulphur (excl. sublimed sulphur, precipitated sulphur and colloidal sulphur) and CN 25030090 - Sulphur of all kinds (excl. crude or unrefined, and sublimed sulphur, precipitated sulphur and colloidal sulphur). Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022).

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[3] 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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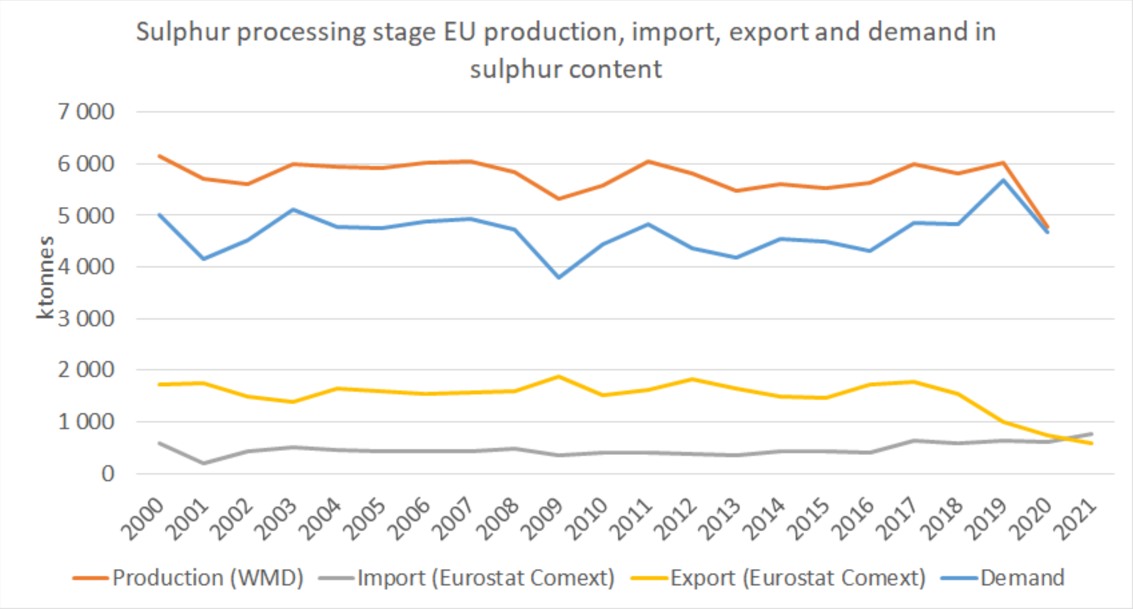

Figure 10. Sulphur (CN 25030010, CN 25030090) processing stage apparent EU consumption. Production data is available from WMD (2022). Consumption is calculated in sulphur content (EU production+import-export).

Average import reliance of at processing stage 0 % for 2016-2020.

EU USES AND END-USES

Sulphur is mainly used by the chemical sector as sulphuric acid (H2SO4).

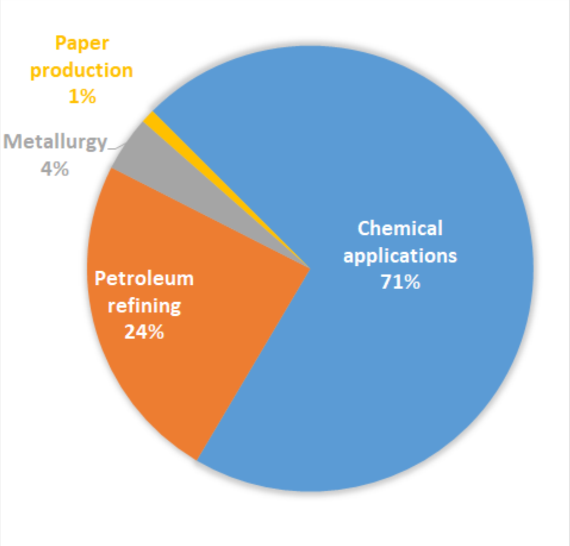

Figure 11. EU27 applications of sulphur, averages 2016-2020 (SCREEN experts, 2022)

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors.

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Table 5. Value added per 2-digit NACE sector over time (Eurostat, 2022)

Applications	2-digit NACE sector	Value-added of sector (millions €) -2019	Examples of 4-digit NACE sector
Use of sulphuric acid (fertiliser production, etc.)	C20 – Manufacture of chemicals and chemical products	117,150* (*data to 2014 only)	C2013 – Manufacture of other inorganic basic chemicals; C2015 – Manufacture of fertilisers and nitrogen compounds; C2041 – Manufacture of soap and detergents, cleaning and polishing preparations; C2051 – Manufacture of explosives
Petroleum refining and other petroleum and coal products	C19 – Manufacture of coke and refined petroleum products	24,896	C1920 – Manufacture of refined petroleum products
Non-ferrous metallurgical applications	C24 – Manufacture of basic metals	63,700	C2444 – Copper Production
Pulp mills and paper products	C17 – Manufacture of paper and paper products	47,452	C1711 – Manufacture of pulp; C1712 – Manufacture of paper and paperboard

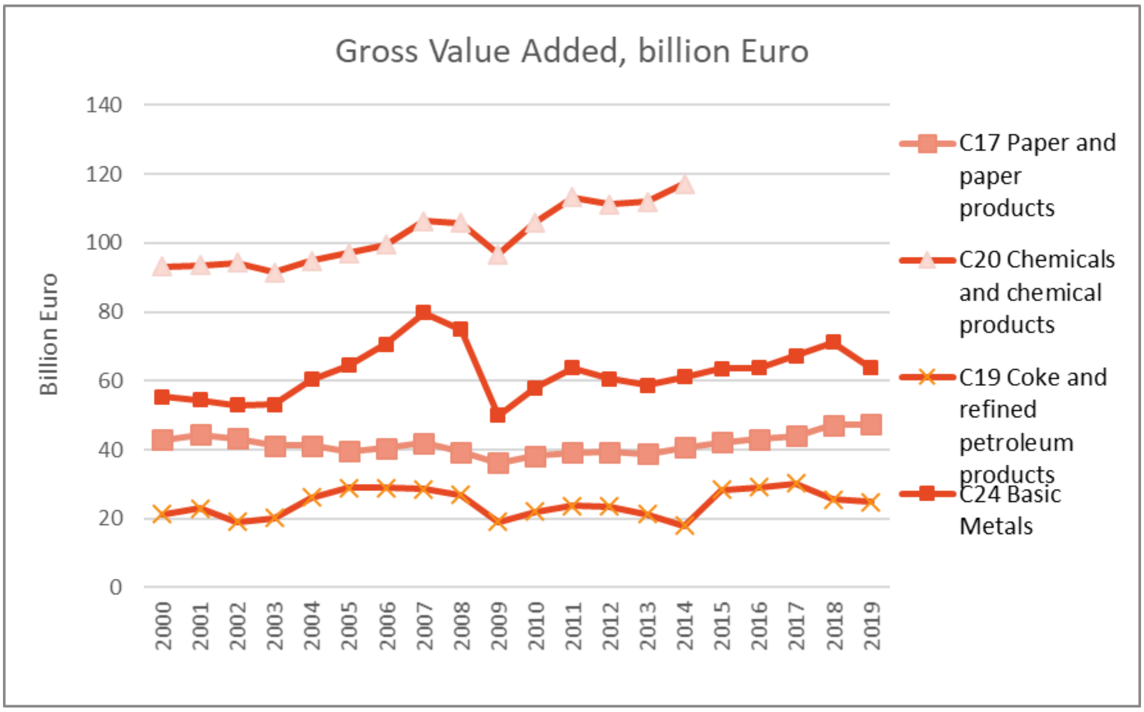

Figure 12. Sulphur applications, 2-digit and associated 4-digit NACE sectors, and value added per sector (Eurostat 2022).

FERTILISER PRODUCTION

Sulphur is a key raw material for the fertiliser and chemical industries and is the primary source for sulphuric acid (the world's most widely used chemical) in numerous manufacturing processes.

Sulphuric acid is used by the fertiliser industry to manufacture phosphates and/or phosphoric acid, and other fertilisers like ammonium sulphate. (D L Messick, C de Brey, M X Fan, 2002). Sulphur fertilisers are added to plants to improve growth and minimise crop yield loss. (Khan, S. H., Amani, S., & Amani, M.,2021).

PETROLEUM REFINING AND OTHER PETROLEUM AND COAL PRODUCTS

Sulphur is a naturally occurring component in crude oil and one of the most important parameters used to measure the value, suitability and environmental credentials of petroleum products.

All gasoline and diesel fuels contain sulphur (unless it is removed) with concentrations varying depending on the characteristics of the product. Using the sulphur content, crude oils can be classified as sweet (<0.5%wt S) and sour (>0.5% %wt S). The distillation process segregates sulphur species in higher concentrations into the higher-boiling fractions and distillation residual. Removing sulphur from petroleum products is one of the most important processes in a refinery to produce fuels compliant with environmental regulations. (D L Messick, C de Brey, M X Fan, 2002)

NON-FERROUS METALLURGICAL APPLICATIONS

The metallurgy industry is a consumer of sulphur, especially copper production, where sulphuric acid is needed for ore leaching.

PULP AND PAPER PRODUCTS

To remove excess chlorine from the bleaching process, sulphur dioxide is used to wash the pulp and help maintain the colour in the paper after it is bleached.

SUBSTITUTION

Table 6. Uses and possible substitutes

Use	Share*	Substitutes	Sub share	Cost	Performance
Chemical applications	71%	other acids	10.0%	Slightly higher costs (up to 2 times)	Reduced
Petroleum refining	24%	NO substitutes			
Metallurgy	4%	NO substitutes			
Paper production	1%	NO substitutes			

*Estimated global end use shares (outputs of SCRREEN Experts Validation Workshop, 2022)

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Sulphur cannot easily be substituted as it is an essential plant nutrient. Over 50% of produced sulphur is used in agriculture for food production each year (The Sulphur Institute, 2015).

The use of sulphuric acid can be substituted by various other acids, although usually at a higher cost (USGS, 2022; SCRREEN experts, 2022). The applications of sulphuric acid in industrial processes are numerous and it is difficult to ascertain to what extent these can be changed by substituting H_2SO_4. .

SUPPLY

EU SUPPLY CHAIN

The EU has a large domestic sulphur production with 13 countries producing an average of 5,779 kt per year between 2016 and 2020 (WMD 2022). According to BGS Poland and Finland are the only EU countries also producing sulphur from discretionary sources (817 kt per year). Poland utilises the Frasch process and Finland produces sulphur from mined pyrites.

The sulphur amount imported is comparatively small, with an average of 457 kt per year in the period of 2016-2020. The main supplier is Russia (65%) followed by Kazakhstan (15%), other trade partners include the United States (5%), Serbia (4%) and Norway (3%). Between 2016 and 2020 the EU exported sulphur to more than 100 countries. The number one consumer of EU's sulphur is Morocco with about 38% market share. Further major buyers are Turkey (14%). Egypt (13%), Israel (12%), and Tunisia (5%). (Eurostat, 2022)

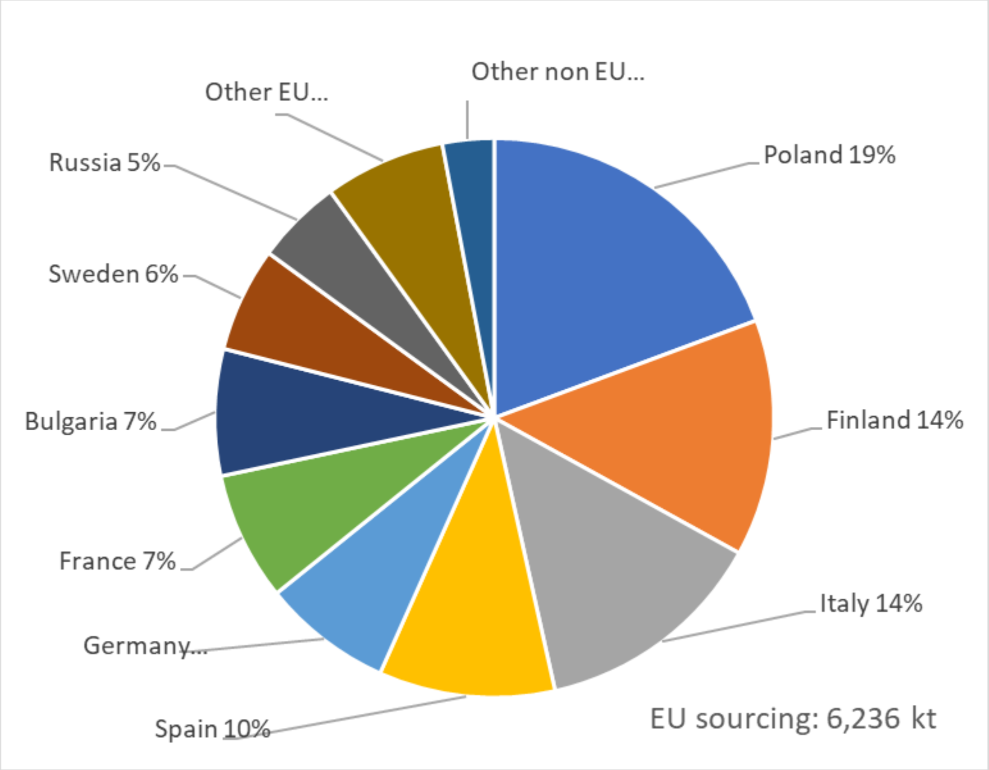

Figure 13. EU sourcing (domestic production + imports) of Sulphur (average 2016-2020) Eurostat (2022) and WMD (2022)

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SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES

GEOLOGICAL OCCURRENCE:

Sulphur occurs naturally in the environment and is the thirteenth most abundant element in the earth's crust. Native sulphur is a product of a volcanic origin. However, the majority is created in the process of sulphate reduction (mainly gypsum and anhydrite) with the participation of bacteria and hydrocarbons. (Polish Geological Institute, 2019)

Most of the native sulphur occurs as massive deposits. Many sulphide minerals are known: pyrite and marcasite are iron sulphides; stibnite is an antimony sulphide; galena a lead sulphide; cinnabar a mercury sulphide, and sphalerite is a zinc sulphide. Other, more important sulphide ores are chalcopyrite, bornite, pentlandite, milarite, and molybdenite (Lenntech, 2016).

It can be mined in its elemental form, though this production has reduced significantly in recent years. Since early in the 20th century, the Frasch process has been used as a method to extract sulphur from underground deposits, when it displaced traditional mining principally in Sicily. Most of the world's sulphur was obtained this way until the late 20th century, when sulphur's recovery from petroleum and gas sources (recovered sulphur) became more commonplace. (The Sulphur Institute, 2019)

GLOBAL RESOURCES AND RESERVES

Elemental sulphur resources occur in evaporite and volcanic deposits, moreover, sulphur can be found in natural gas, petroleum, tar sands, and metal sulphides. These resources amount to approximately 5,000 Mt. Sulphur is also associated with gypsum and anhydrite providing almost limitless resources. Another source of sulphur is from coal, oil shale, and shale rich inorganic matter, containing about 600,000 Mt.

Sulphur reserves in crude oil, natural gas and sulphide ores are large. Most of sulphur production results from fossil fuel processing that implies sulphur supply should be adequate for the foreseeable future. However, the sulphur production may not be in the country to which the reserves were attributed, as petroleum and sulphide ores can be processed long distances from where they were produced. (USGS, 2019)

EU RESOURCES AND RESERVES

In Poland anticipated economic resources of sulphur amount to 502.5 million t in 2018. (Polish Geological Institute, 2019)

WORLD AND EU MINE PRODUCTION

When considering sulphur production two different sectors have to be differentiated – the discretionary and the nondiscretionary sector. In 2018, the sulphur production from discretionary sources (mining of sulphur or

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pyrites is the sole objective) represented only 8% of the total supply. In the non-discretionary sector, sulphur or sulphuric acid is recovered as an involuntary by-product and the amount of sulphur produced is subject to demand for the primary product and environmental regulations that limit atmospheric emissions of sulphur compounds, e.g. petroleum refineries and natural gas treatment plants. (USGS, 2022a)

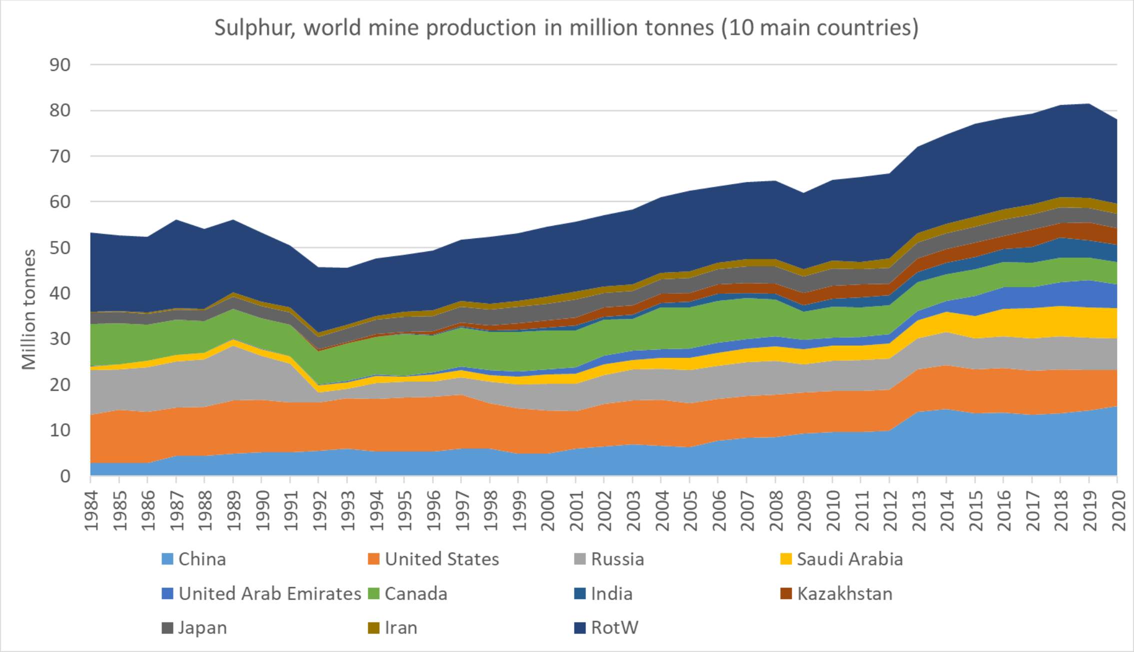

Figure 14. Global sulphur production since 1984 according to WMD

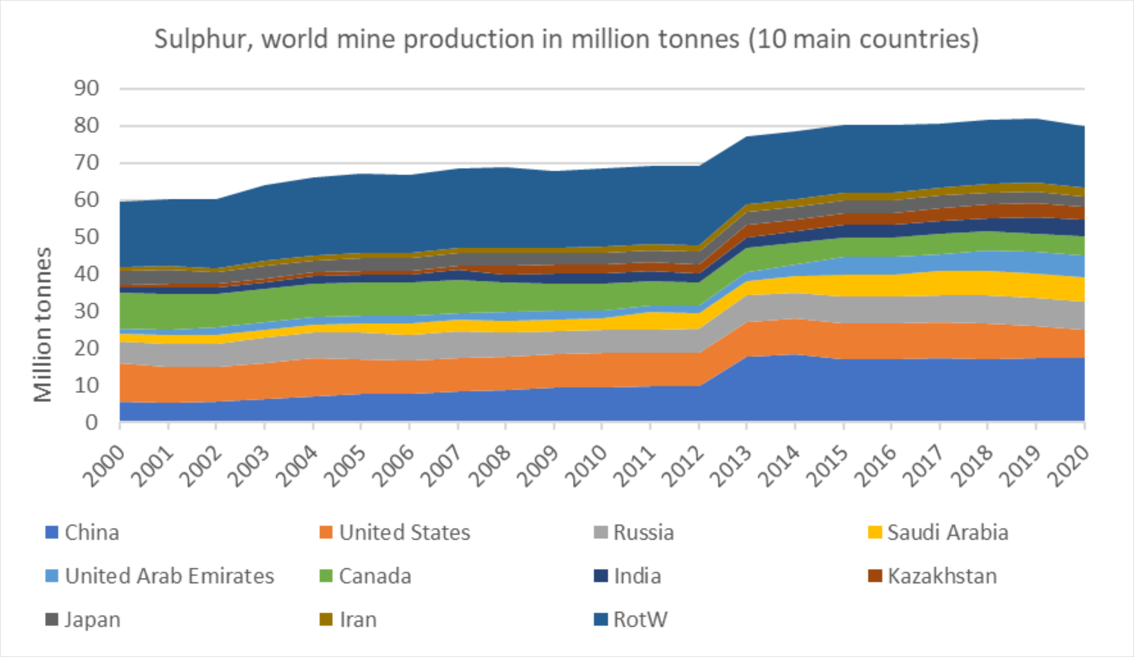

Figure 15. Global sulphur production since 2000 according to USGS

Poland is the largest producer in the EU with about 19% of EU production, Finland and Italy contribute with 14% each, followed by Spain and Germany (10% and 8%). However, Finland´s pyrite mine is scheduled for

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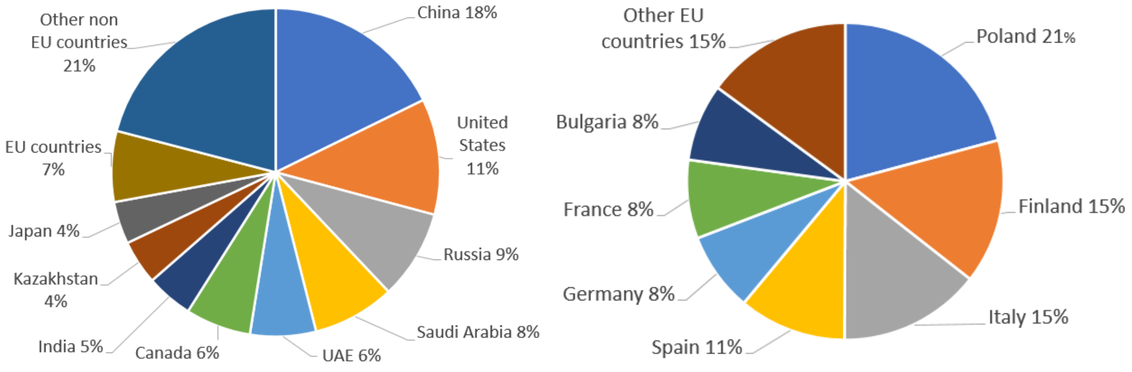
closure and even if supply will extend until 2025, it will be based on reclaiming pyrite from tailings. (First Quantum Minerals Ltd., 2022)

The last active large mining site for native sulphur worldwide is Osiek mine in Poland, where sulphur is mined from the surface using Frasch hot water method. The output amounts to 617 thousand t. (Polish Geological Institute, 2019)

Worldwide the biggest sulphur producers are China, the United States, Russia, and Saudi Arabia. The annual amount produced worldwide is 79.7 Mt on average between 2016 and 2020.

In the medium term, experts anticipate significant capacity additions in China and the Middle East as a result of increasing oil and gas production. On the contrary, Europe could see a capacity reduction due to the transition to renewable energy sources and the closure of oil refineries (Argus 2022, Maslin 2022).

Figure 16 shows the distribution of sulphur production.



Global production: 79,700 kt

EU production: 5,779 kt

Figure 16. Global and EU mine production of Sulphur in kt and percentage. Average for the years 2016-2020. (WMD 2022)

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

The end-of-life recycling input rate for sulphur is estimated to be 5%. This refers to spent sulphuric acid, which is reclaimed from petroleum refining and chemical processes during any given year.

However, this number requires some further interpretation. The voluntary extraction of sulphur containing ores is made less relevant by the large volumes of sulphur that become available as by-product. The recycling input rate from that perspective is much larger (SCRREEN workshops 2019).

PROCESSING

Sulphur is a by-product in most cases, and a co-product in virtually all the other cases. It is estimated that recovered elemental sulphur or by-product sulphuric acid increases the percentage of by-product sulphur production to about 90%. Sulphur production as a result of processing of fossil fuels, especially natural gas, accounts for 50% of the annually produced volumes. This had a severe effect on discretionary mining operations (operations with the primary goal of extracting sulphur). The large fossil fuel and metal processing industries in the world can be described as non-discretionary: sulphur is obtained as involuntary by-product.

Discretionary sources are either pyrite mines or operations using so called Frasch process.

Non-discretionary sources (apart from fossil fuels and natural gas) are mainly metal refining processes; for instance, the refining of nickel, lead, silver, tin, and copper ores containing sulphides. By far the largest use of manganese (more than 90%) in steel production is as reduction and desulphurisation agent, promoting the separation and collection of sulphur. These sources account for about 40% of the world's supply.

In the Frasch process, native sulphur is melted underground with superheated water and brought to the surface by compressed air. As of 2011, the only operating "Frasch" mines worldwide are in Poland and since 2010 in Mexico. The last mine operating in the United States closed in 2000 (Sulphur Institute 2016).

OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

Sulphur is classified under Annex VI of Regulation (EC) No 1272/2008 (CLP Regulation) with code H315 because this substance causes skin irritation (ECHA, 2023).

Sulphuric substances can have negative effects on human health, including neurological effects and behavioural changes, disturbance of blood circulation, heart damage, and many more. Effects of sulphur on animals are mostly brain damage, and damage to nervous system (Lenntech, 2019).

ENVIRONMENTAL ISSUES

Sulphur is present in many ecologically relevant flows in soil, water, and air. Elemental Sulphur is not toxic, but some sulphur compounds are, for example sulphur dioxide (SO_2) and hydrogen sulphide (H_2S) This is illustrated by the fact that elemental sulphur (and by-product sulphuric acid), produced as a result of efforts to meet environmental requirements, contribute to world supply. Atmospheric sulphur oxides, SO_2 in particular, are emissions that need to be reduced to increase health standards in parts of the EU. The level of sulphur in the environment is strictly regulated. This requires the use of other raw materials to purify water and soils. For instance, a growing amount of limestone is used to remove sulphur dioxide from flue gases, for sewage treatment and for drinking water treatment.

Besides surplus, instances of dearth of sulphur in the environment are also reported. The incidence of soil sulphur deficiency has rapidly increased in recent years. Three major factors are responsible for increased sulphur deficiency: a) intensified cropping systems worldwide demand higher sulphur nutrient availability; b) increased use of high-analysis, sulphur-free fertilisers, and c) reduction of sulphur dioxide emissions, particularly in developed regions, reduces atmospheric sulphur deposition, a "natural" sulphur source. (Lenntech, 2019; TSI 2023)

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NORMATIVE REQUIREMENTS

The sulphur mining industry, in Indonesia, has a high level of autonomy; this situation has been exacerbated by new laws, which have been widely viewed as aimed to give mining entities more power and far lesser obligations. This can set a dangerous precedence, allowing hazardous practices against labour right and the environment. International organizations such as the ILO are lobbying with the government to further regulate the mining activities (Jong 2020).

The (UNECE 2015) developed a set of recommendations on the transport of dangerous goods, addressed to governments and IOs concerned with regulating the transport of such goods. Sulphur is included in the substances mentioned within the document.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Lithium-sulphur batteries

Lithium–sulfur (Li–S) batteries are one of the most promising next-generation energy-storage devices due to their ultrahigh energy density. Low electrolyte volume is essential to realize an energy density over 500 Wh kg−1 in Li–S batteries. Despite the extraordinary progress in the last few years, the energy density of Li–S batteries is still far from satisfactory enough to meet the demand for practical applications. Considering the sulfur electrochemistry is highly dependent on solid-liquid-solid multi-phase conversion, the electrolyte amount plays a primary role in the practical performances of Li–S cells. Therefore, a lean electrolyte volume with a low electrolyte/sulfur ratio is essential for useful Li-S batteries yet achieving acceptable electrochemical performances regarding sulfur kinetics and discharge capacity is challenging under these conditions' Coulombic efficiency, and cycling stability, especially for high-sulfur-loading cathodes (Zhao M. et al 2020).

- Copper Antimony Sulphur Ternary Compounds for Photovoltaic Applications

Design of efficient solar energy-conversion materials has attracted much interest in the last few decades. Among these materials, copper-based semiconducting chalcogenides as $CuSbS_2$, Cu_3SbS_3, and Cu_3SbS_4 have been investigated as alternatives for copper indium gallium selenide (CIGS) thin-film solar cells due to their low-toxicity and earth-abundant absorber components (Mohamadkhani et al., 2021). The Cu-Sb-S system compounds are p-type semiconductors with an optical band gap (Eg) ranging between 0.5 eV and 2.0 eV and a large absorption coefficient over 104 cm^{-1} at visible wavelengths, which shows a comparable efficiency (i.e., 22.9 %) to that of CIGS and Copper zinc tin sulfoselenide (CZTSSe). Yet, due to a lack of knowledge in fundamental physical properties comprehension, these compounds have not reached the stage of integration into devices. Therefore, further developments in PV technology based on these compounds call for a deep understanding of the electronic and optical properties of these materials and of their structural properties and relationships (Khairy, M.et al. 2022).

- HySelect project: Efficient water splitting via a flexible solar-powered Hybrid thermochemical-Sulphur dioxide depolarized Electrolysis Cycle[4] (EU, 2023-2026)

HySelect will demonstrate the production of hydrogen (H_2) by splitting water via concentrated solar technologies (CST) with an attractive efficiency and cost, through the hybrid sulphur cycle (HyS). The HyS consists of two central steps: the high temperature -yet below-900 °C -decomposition of sulphuric acid forming sulphur dioxide (SO_2) and the subsequent low temperature (50-80 °C) SO_2 depolarised electrolysis (SDE) of water to produce H_2. HySelect will introduce, develop, and operate under real conditions a complete H_2 production chain focusing on two innovative, full scale plant prototype core devices for both steps of the HyS cycle: an allothermally heated, spatially decoupled from a centrifugal particle solar receiver, sulphuric acid decomposition-sulphur trioxide splitting (SAD-STS) reactor and a sulphur dioxide depolarized electrolyser (SDE) without expensive Platinum Group Metals (PGMs). Furthermore, a heat recovery system will be integrated to exploit the temperature difference within the cycle and boost the overall process efficiency. In the course of the work, non-critical materials and catalysts will be developed, qualified, and integrated into the plant scale prototype units for both the acid splitting reactor and the SDE unit.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- Sulphirulence[5] project: Re-engineering of fungal sulphur metabolism to limit mould viability and virulence (EU, 2016 – 2018)

Aspergillus fumigatus, the major mould pathogen of human lungs, is responsible for > 2 million illnesses per annum in Europe. I have discovered that sulphur is an essential host-derived element during A. fumigatus infection . This finding is novel, and highly exploitable as a) Synthesis of the sulphur-containing molecule methionine appears to be essential for viability of A. fumigatus b) Regulation of sulphur assimilation is essential for A. fumigatus virulence and c) The foremost candidate sulphur source in mammalian lungs (H2S) is gaseous, and recently identified as a novel signalling molecule in eukaryotic cells. I now wish to harness world-class clinical and scientific expertise in the field of fungal pathogenicity to identify the precise molecular source of sulphur exploited by A. fumigatus during experimental and clinical infection, with a view to designing novel antifungal therapies.

- Sulfur: a neglected driver of the increased abundance of antibiotic resistance genes in agricultural reclaimed subsidence land located in coal mines with high phreatic water levels (Lin et al. 2023)

Due to the shallow burial of groundwater in coal mines with a high phreatic water level, a large area of subsidence lakes is formed after the mine collapses. Agricultural and fishery reclamation activities have been carried out, which introduced antibiotics and exacerbated the contamination of antibiotic resistance genes (ARGs), but this has received limited attention. This study analyzed ARG occurrence in reclaimed mining areas, the key impact factors, and the underlying mechanism. The results show that sulfur is the most critical factor impacting the abundance of ARGs in reclaimed soil, which is due to changes in the microbial community. The species and abundance of ARGs in the reclaimed soil were higher than those in the controlled soil. The relative

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[4] https://cordis.europa.eu/project/id/101101498

[5] CORDIS EU research results, 10.3030/660396

abundances of most ARGs increased with the depth of reclaimed soil (from 0 to 80 cm). In addition, the microbial structures of the reclaimed and controlled soils were significantly different. *Proteobacteria*, was the most dominant microbial phylum in the reclaimed soil. This difference is likely related to the high abundance of sulfur metabolism functional genes in the reclaimed soil. Correlation analysis showed that the differences in ARGs and microorganisms in the two soil types were highly correlated with the sulfur content. High levels of sulfur promoted the proliferation of sulfur-metabolizing microbial populations such as *Proteobacteria* and *Gemmatimonadetes* in the reclaimed soils. Remarkably, these microbial phyla were the main antibiotic-resistant bacteria in this study, and their proliferation created conditions for the enrichment of ARGs. Overall, this study underscores the risk of the abundance and spread of ARGs driven by high-level sulfur in reclaimed soils and reveals the mechanisms.

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