SCRREEN2

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SCANDIUM

AUTHOR(S):

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SCANDIUM

OVERVIEW

Scandium (chemical symbol Sc, from the Latin 'Scandia' for Scandinavia where it was historically discovered) is a silvery-white light transition metal. Its main properties are its light weight (density of 2.99 g/cm^3, close to the one of aluminium), high melting point (1,541 °C) and small ionic radius. Scandium is not particularly rare; its abundance in the upper continental crust is 14 ppm[1] (Rudnick, 2003). However, due to the small size of its ions, it does not selectively combine with the common ore-forming anions, and rarely forms concentrations higher than 100 ppm in nature. Consequently, scandium deposits are rare. It shares similar characteristics with Rare Earth Elements (REEs) but has quite specific mineralogical and industrial properties, which justify a distinct classification.

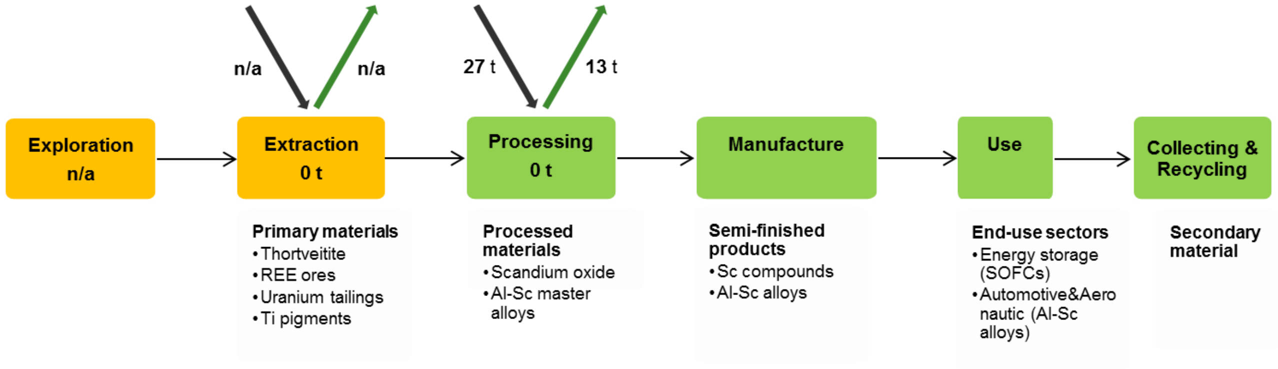

Figure 1. Simplified value chain for scandium in the EU[2]

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

Global production of extracted ore	Global Producers	EU consumption (processing)	EU Share	EU Suppliers	Import reliance
24	China 67% Russia 17% Canada 4% Kazakhstan 4% Philippines 4% Ukraine 4%	3.7	15%	UK 92% USA 5% Hong Kong 2%	100%

Prices: Scandium is typically priced as an oxide and normally specified at +99% purity, with 99.9% grades used for electrical applications. Prices are negotiated confidentially between buyers and sellers and pricing quotes can vary by over 100% depending on purity, available inventories, and lot size on individual sales (Scandium International Mining, 2022). Scandium prices have been consistently on a decline during the 2014-2020 period.

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[1] parts per million

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

In 2018, prices quoted for most scandium products in the US remained relatively unchanged or decreased compared with those in 2017. In 2019 and 2020, prices quoted for scandium oxide in the US decreased further.

Primary supply: The global supply of scandium originates from primary sources such as ore feedstock, and secondary sources from mining production such as concentrates, metallurgical slags and residues. Scandium is typically produced as a co-product or by-product during processing of various ores (e.g., iron ore, REEs, titanium, zirconium, uranium, thorium, aluminium, tungsten, tin, tantalum, apatite, nickel and cobalt) and/or recovered from previously processed tailings and residues (USGS 2021 & 2022). Various independent authors quote global market volumes of 2-10 tonnes per year. The estimate number of 15 tonnes was confirmed by EMC Metals Corporation (Duyvesteyn and Putnam, 2014) based on discussions with their potential customers, the level of metals trader activity and interest, and the fact that certain scandium consumers are believed to be sourcing their own scandium through small controlled recovery operations. Currently, there is no reported mining of scandium in the EU and official production numbers are not available at the EU level.

Secondary supply: The secondary sources of scandium are scarce. Possible scandium secondary sources can be divided into the following groups: bauxite residue or red mud, waste electrical and electronic equipment (WEEE), nickel laterite, municipal wastes, phosphogypsum and phosphate rocks, coals and fly ashes (Botelho Junior et al. 2021). Another secondary source of scandium which is discussed recently is coal ash and slag in which as a result of thermal treatment of coal various elements including REE and scandium (up to ca 300 ppm) are concentrated (Pyrzyńska et al. 2019).

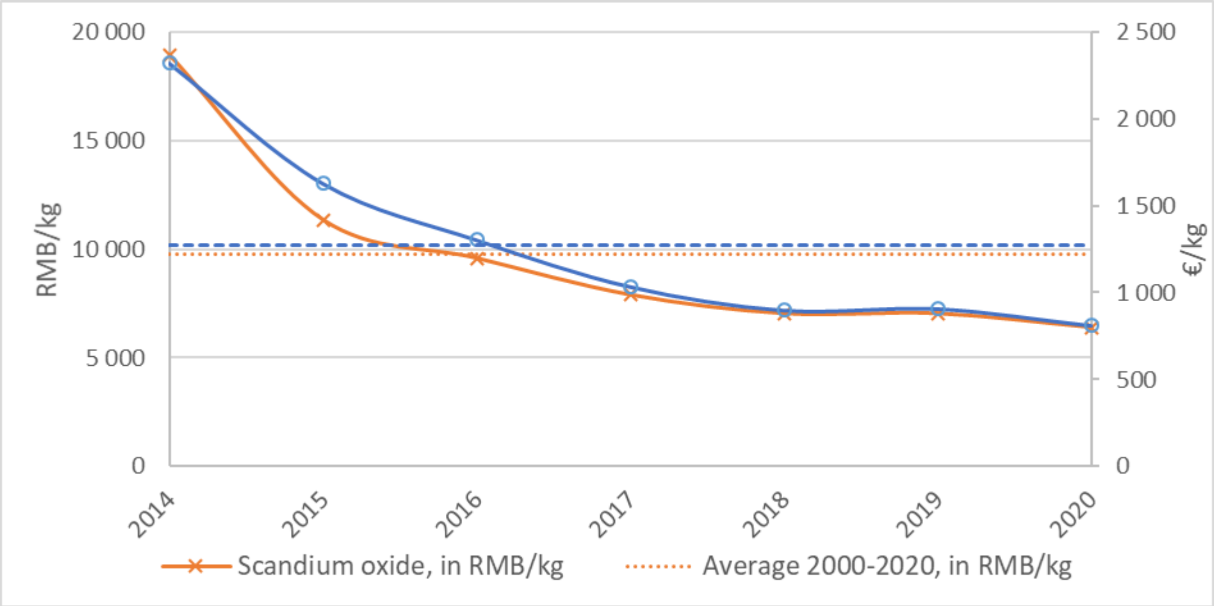

Figure 2. Annual average price of scandium between 2000 and 2020 (USGS, 2021)[3].

Uses: the main use of scandium is in solid oxide fuel cells (91% at global level and 100% at EU level).

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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)

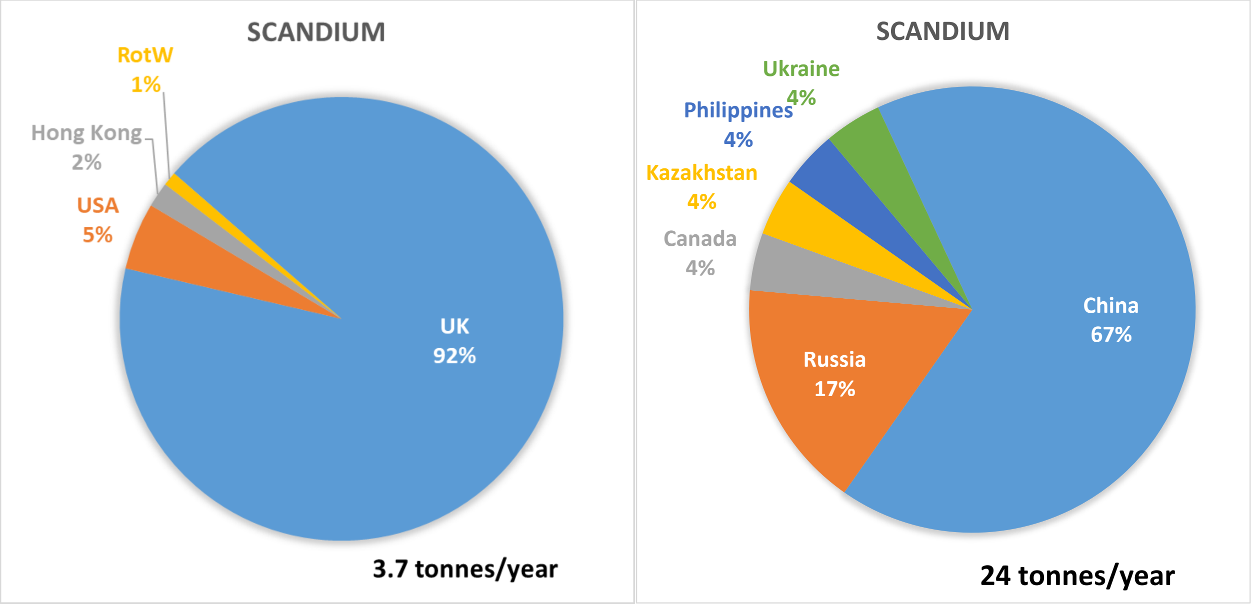

Figure 3. EU sourcing of scandium and global mine production (average 2016-2020)

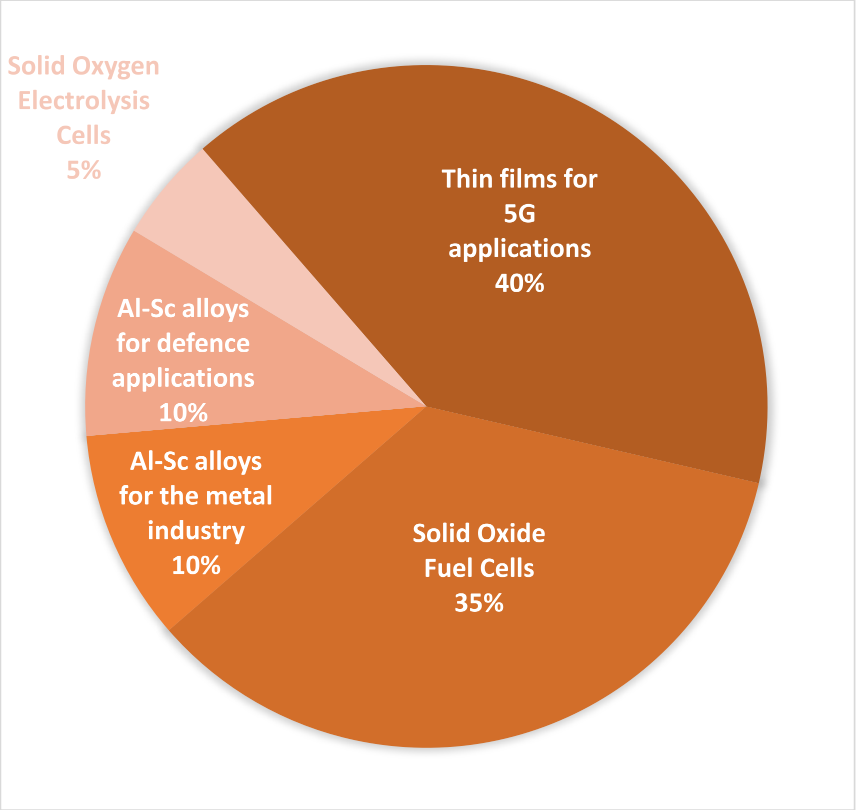

Figure 4: Global uses of scandium

Substitution: As the use of scandium is new and still a "niche market", the use of scandium is in most of its applications a way to innovate and enhance performances and properties of already existing end-products. Therefore, scandium is rather considered as a substitute itself, and alternatives exist for almost all its uses. The decision for scandium at the choice of material is mainly driven by performance, price, or availability.

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Table 2. Uses and possible substitutes

Application	Share	Substitutes	SubShare	Cost	Performance
Thin films for 5G applications	40%	No substitute			No substitute
Solid Oxide Fuel Cells	35%	Gadolinium doped ceria	0%	Similar or lower costs	Reduced
		Yttria-Stabilized Zirconia	20%	Similar or lower costs	Reduced
		No substitute	50%		No substitute
Al-Sc alloys for the metal industry	10%	Titanium/Aluminium high strength alloys	5%	Similar or lower costs	Reduced
		Carbon-fibre material	90%	Similar or lower costs	Reduced
Al-Sc alloys for defence applications	10%	Titanium/Aluminium high strength alloys	5%	Similar or lower costs	Reduced
		Carbon-fibre material	5%	Similar or lower costs	Reduced
Solid Oxygen Electrolysis Cells	5%	No substitute			No substitute

Other issues: According to (Rim et al. 2013), “elemental scandium is considered non-toxic, and little animal testing of scandium compounds has been done. The half lethal dose (LD50) levels for scandium (III) chloride for rats have been determined as 4 mg/kg for intraperitoneal, and 755 mg/kg for oral administration”. Scandium extraction is associated with relatively high concentrations of uranium and thorium (German Environment Agency, 2020; Blazy and Hermant, 2013), but with low potential for Acid Mine Drainage (AMD; German Environment Agency, 2020). Scandium is emitted to the environment either by production activities, in particular at the purification process step, or from scandium containing equipment at their end-of-life (Blazy and Hermant, 2013). Scandium subsequently gradually accumulates in soil and water, and its concentration in consequence increases in humans, animals and plants (Blazy and Hermant, 2013).

MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

Table 3: Scandium supply and demand in metric tonnes, 2016-2020 average

Global production of extracted ore	Global Producers	EU consumption (processing)	EU Share	EU Suppliers	Import reliance
15	China 66% Russia 23% Ukraine 7% Kazakhstan 1%	5.7	37%	UK 94% US 4%	100%

Data on scandium (Sc) production is very patchy and incomplete. According to the USGS (2022) the annual Sc production is estimated to 10-20 t; DERA (2021) assumes the figure to be around 14-16 t. Sc demand and supply are highly concentrated. With about 75% (>10 t) of the global annual production China is the largest producer of Sc. Other producers Russia (1-2 t/y) and the Philippines (ca. 1 t/y) (DERA, 2021).

China produces Sc as a by-product from titanium ad zirconium ore processing, but capacity utilisation there is only at about 20 % (CM Group, 2021). Russia obtains Sc from residuals of in-situ leaching of uranium deposits and Rusal produces Sc from red mud at the Ural Aluminium Smelter. In the Philippines Taganito HPAL Nickel Corporation produces small amounts of scandium oxalate from nickel-cobalt ores and aims at increasing the annual capacity to up to 7.5 t. The scandium oxalate will be processed in Japan to obtain scandium oxide. Rio Tinto produced its first Sc oxide at its demonstration plant in Sorel-Tracy, Canada in 2022. The company aims to produce about 3 t of Sc per year from waste streams of titanium dioxide production.

According to the CM Group (2021), around 90 % of global Sc oxide supply scandium today is used for SOFC. Al-Sc alloys for aeronautics and sports equipment represent a minor share in Sc use. Sc demand increased during the past years due to its use in solid oxide fuel cell technology (SOFC). SOFC and solid oxide electrolysis (SOEL) use both yttrium-stabilised and scandium-stabilised zirconia as the electrolyte. According to DERA (Marscheider-Weidemann, 2021) the Sc demand could increase to 34 to 72 t only for SOFC and SOEL technologies until 2040. The demand could be even higher, if Sc oxide would substitute Y oxide as doping element. These applications would result in a tighter market and spare capacities, predominantly in China, would be absorbed by the market quickly.

EU TRADE

The relevant commodities of Scandium and their CN code are listed in Table 4.

Scandium is a speciality metal clubbed together with rare earth elements. The main applications are solid oxide fuel cells and scandium aluminium alloys used by aircraft industry and applications defence industry in tiny quantities. There is no EU trade in Scandium ores and concentrates and the assessment only considers trade in refined products.

Table 4. Relevant Eurostat CN trade codes for Scandium.

Mining		Processing/refining	
CN trade code	**title**	**CN trade code**	**title**
		28053040	Scandium, a purity of weight >=95% (excl. Intermixtures and interalloys)
		2846903	Scandium compounds, inorganic or organic

There is no detailed data available for scandium in Euro stat. Only since 2016, scandium specific trade codes are applied at Eurostat Comext by the introduction of codes on pure scandium (CN 2805 30 40) and scandium compounds (CN 2846 90 30). Previous estimates by Lipman for Russia (200 kilogram per year) and Kazakhstan (100 kilogram per year), mainly in the form of scandium oxide, were maintained aiming to complete the uncertain data set.

According to this joint dataset, the United Kingdom is by far the most important supplier of scandium to the EU, taking almost 99% (26.6 tonnes per year) of the imports to the EU, averaged over 2012-2016 (see Figure 451) (Eurostat, 2019). Minor source countries are Russia, Kazakhstan, United States and Hong Kong. As the United Kingdom does not have own scandium production, the supply are considered re-exports. The world's main producers of scandium, China, seems to direct its extractions to other destination outside the EU or use the commodity themselves.

In terms of trade restrictions, Chinese export quotas on REEs also applied to scandium. These were lifted in 2015, replaced by resources taxes based on sales value (Metal Pages, 2015). There are no export quotas or prohibition in place between the EU and its suppliers (OECD, 2016). From the EU's suppliers, only China has an export tax (≤ 25%) (OECD, 2016).

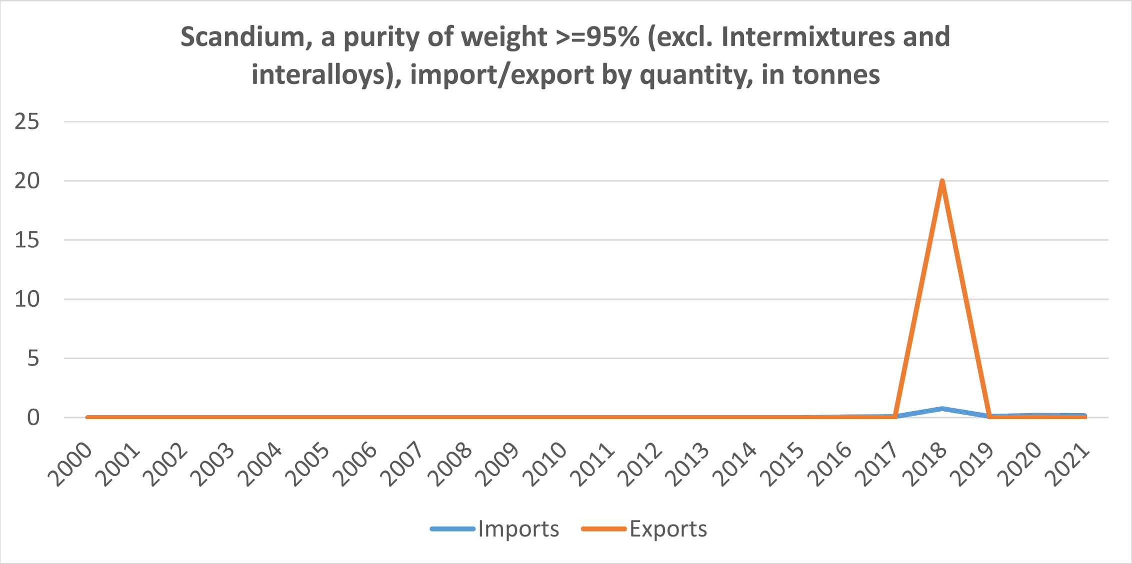

Figure 5. EU trade flows of Scandium, a purity of weight >=95% (excl. Intermixtures and interalloys) from 2000 to 2021 (Eurostat, 2022)

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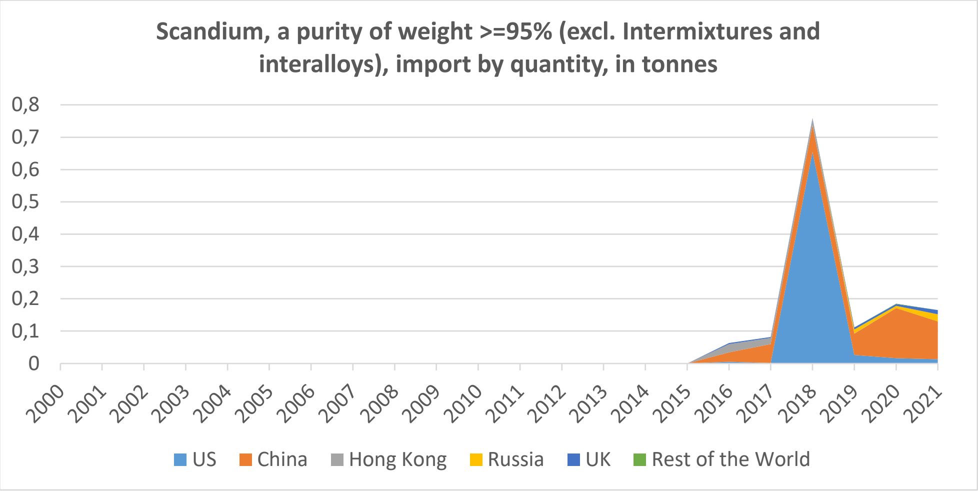

Figure 6. EU imports of Scandium, a purity of weight >=95% (excl. Intermixtures and interalloys) by country from 2000 to 2021 (Eurostat, 2022)

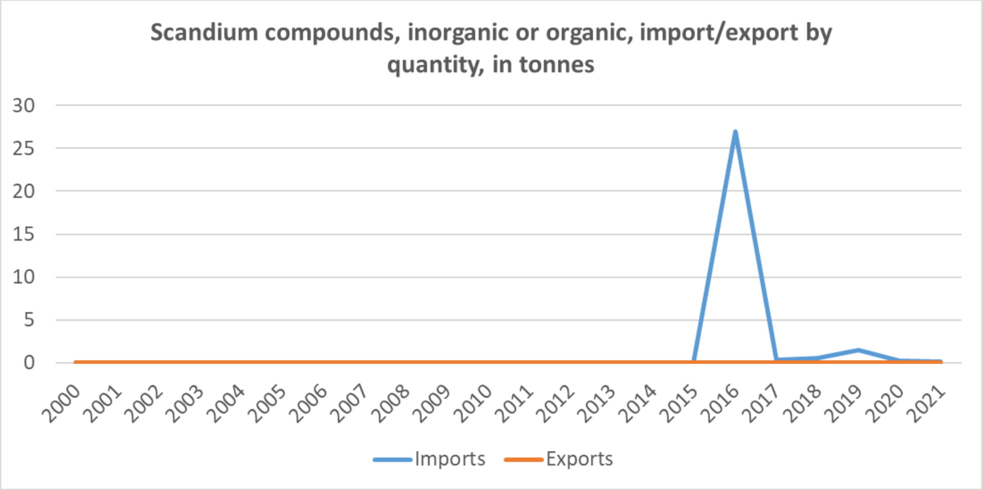

Figure 7. EU trade flows of Scandium compounds, inorganic or organic from 2000 to 2021 (Eurostat, 2022)

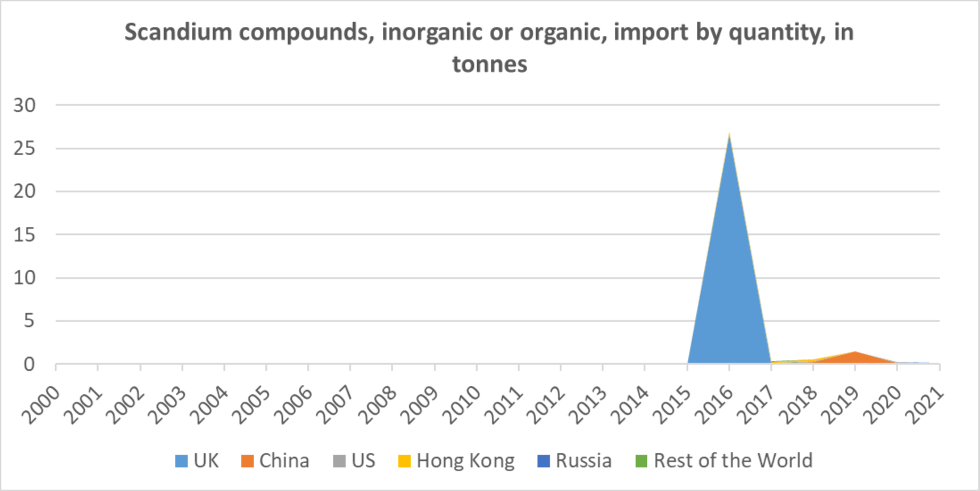

Figure 8.EU trade flows of Scandium compounds, inorganic or organic from 2000 to 2021 (Eurostat, 2022)

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PRICE AND PRICE VOLATILITY

Scandium is typically priced as an oxide and normally specified at +99% purity, with 99.9% grades used for electrical applications. Prices are negotiated confidentially between buyers and sellers and pricing quotes can vary by over 100% depending on purity, available inventories, and lot size on individual sales (Scandium International Mining, 2022). The three main products are:

- Oxide powders are required in certain technical applications, usually at higher grades.
- Pure metal scandium is much more costly and challenging to produce.
- Scandium master alloy is the preferred form for aluminium alloy manufacturers and contains 2%.

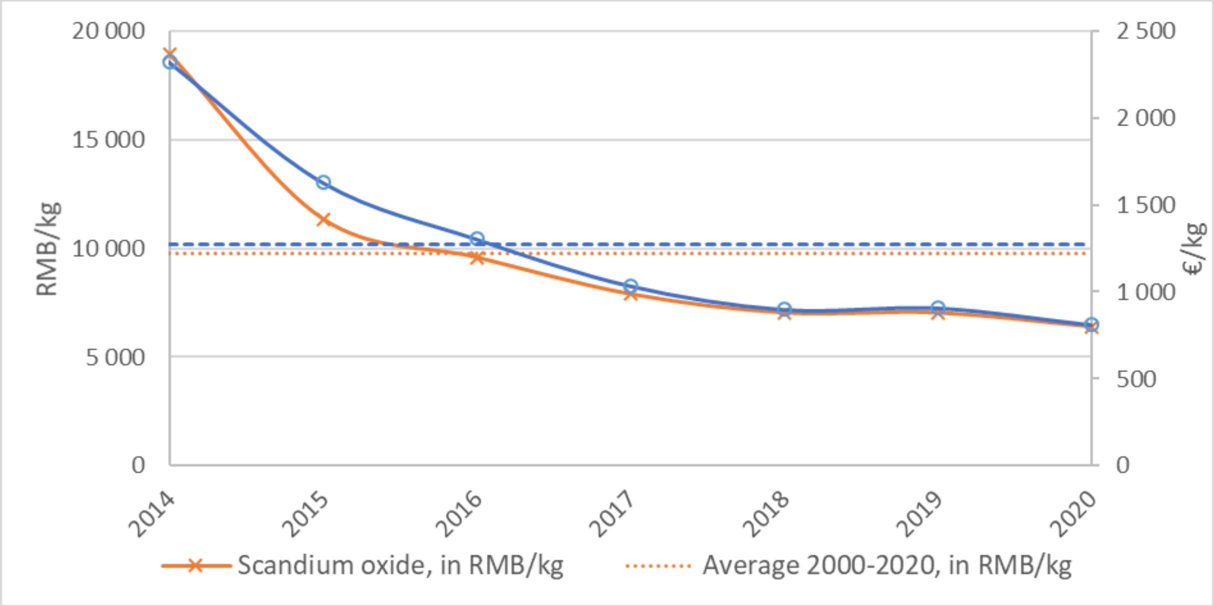

Figure 9. Annual average price of scandium oxide between 2014 and 2020, in RMB/kg and €/kg[4]. Dash lines indicates average price for 2014-2020 (DERA, 2022)

Scandium prices have been consistently on a decline during the 2014-2020 period. In 2018, prices quoted for most scandium products in the US remained relatively unchanged or decreased compared with those in 2017. In 2019 and 2020, prices quoted for scandium oxide in the US decreased further. Although exploration continued, the COVID-19 pandemic slowed down the development of new projects and the global scandium market remained relatively small compared to most other metals. In 2021, scandium oxide prices continued the downward trend and significantly declined compared with those of 2020. Owing in part to low-capacity utilization, China's ex-works prices for scandium oxide were substantially less than prices quoted in the US (USGS, 2022).

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[4] 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)

OUTLOOK FOR SUPPLY AND DEMAND

With the rapid uptake of electric vehicles, it is expected that there will be a higher demand for lightweighing materials because weight reduction contributes to the extension of battery range. Scandium, in combination with aluminium, creates lighter and stronger alloys which are essential in reducing the weight of electric vehicles. Bloomberg forecasts that the scandium market could grow to reach 1,800 tonnes per annum by 2035 representing a 51 times increase in demand when compared to the current market (InvestorIntel, 2020). If the sale of electric vehicles surges to 30 million by 2030, the demand for scandium would increase to 5,250 tonnes per annum – a 150-fold increase on current demand based on just a 0.2% scandium oxide-aluminium alloy in each electric vehicle (InvestorIntel, 2020). These staggering figures do not even include scandium demand for other applications such as aerospace, defence, and electronics. Another critical factor that is responsible for the global scandium market growth is the increasing demand for alternative energy sources which can lead to a surge in the production of solid oxide fuel cells. On the other hand, the inconsistency of scandium supply is expected to be a restraining factor for the market's growth (Business Wire, 2021).

DEMAND

EU DEMAND AND CONSUMPTION

USGS (2022) estimates the annual average worldwide consumption of scandium as about 15 - 25 tonnes. Yagmurlu et al. (2021) estimates that annual EU consumption of scandium is about 780 kg.

Most of the imported quantities (a few hundred tonnes) are currently used either in R&D projects or in small markets (scandium-aluminium alloys, SOFCs) or minor other applications, such as high-quality sports equipment.

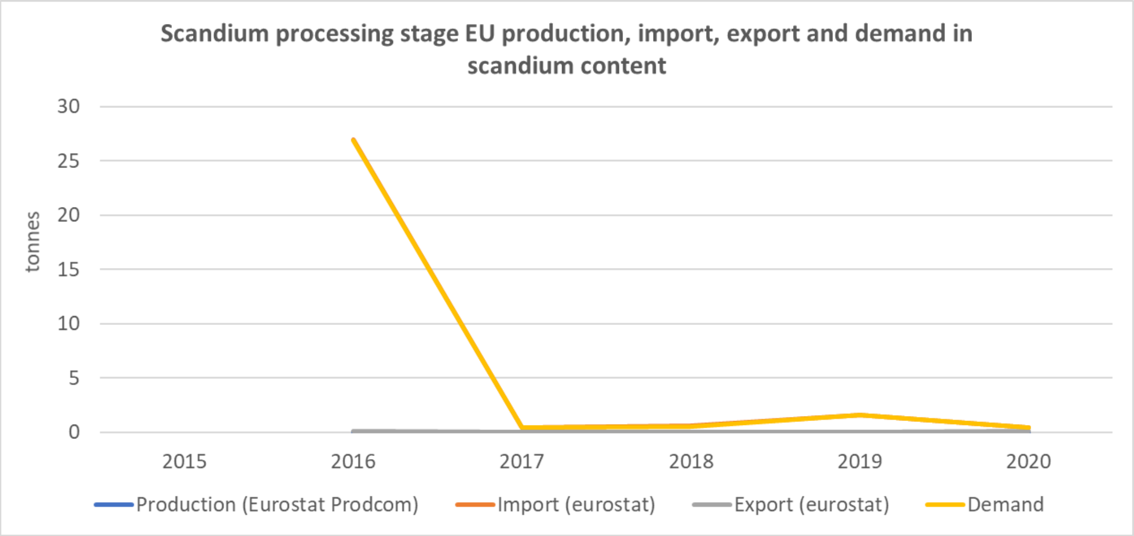

Figure 10. Scandium (CN 28053040 and CN 28469030) processing stage apparent EU consumption. Production data is available from Eurostat Prodcom (2022). Consumption is calculated in Scandium content (EU production+import-export).

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Scandium processing stage EU consumption is presented by HS codes CN 28053040 Scandium, of a purity by weight of ≥ 95% (excl. intermixtures and interalloys) and CN 28469030 Scandium compounds, inorganic or organic. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022).

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of scandium at processing stage 100 % for 2016-2020.

EU USES AND END-USES

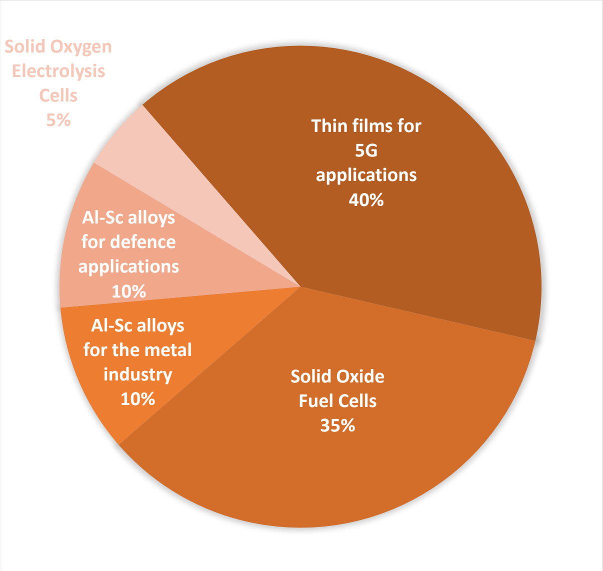

Figure 11: Global end uses (SCRREEN2 Validation Workshop, EU CRM study (2022))

APPLICATIONS OF SCANDIUM IN THE EU

SOLID OXIDE FUEL CELL (SOFC)

- A fuel cell is an electrochemical cell that converts a fuel source and an oxygen source into an electrical current, plus water, CO_2 and heat. They, in particular SOFCs, are seen as an alternative electrical power supply, notably for automotive transportation.
- The central part of a SOFC is a solid electrolyte generally composed of zirconia, which on its own could not withstand high operating temperatures without being stabilised with a metal.
- The stabilising and conducting metal of choice for the electrolyte has traditionally been yttrium, but, since scandium use has been prevalent since price spikes on REEs and yttrium in the early 2010s.
- Scandium can lower the operating temperature of the cell and increase its lifespan and efficiency by improving the power density.
- Scandium has proven to be a considerably better ionic electrical conductor than yttrium and importantly, allows the electrolyte to conduct at significantly lower temperatures (750-800 °C) so that the cost, efficiency and lifespan of materials for thermal shielding can be reduced (Duyvesteyn, 2014).

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- Barriers for expansion of scandium in this market remain price and availability of this element.

HIGH PERFORMANCE (AL-SC) ALLOYS

- The second most important use application of scandium is as alloying element combined with aluminium.
- Aluminium-scandium (and magnesium) alloys are amongst the lightest metal resources known and can help to increase fuel efficiency in aerospace and automotive transportation.
- Scandium refines the crystal structure of aluminium to the point where the alloyed metal can be welded without loss in strength. It also increases plasticity in the moulding of complex shapes, improves corrosion resistance, and increases thermal conductivity.
- In 2014, Airbus patented and developed ScalmalloyTM, a specific scandium-magnesium-aluminium alloy family for use in aerospace (Airbus, 2016), which has since been expanded into additive manufacturing / 3D printing application.
- Aluminium-scandium alloys are still extremely expensive, and the main market at present is mostly high-quality sports equipment (bikes, baseball bats, etc.).

OTHERS

- In ceramics, a very hard mixed carbide can be created by mixing about 20 percent scandium carbide with titanium carbide.
- Scandium is a key part of the laser material gadolinium scandium gallium garnet (GSGG) that is estimated to be more than three times as effective as a similar material made with yttrium and aluminium.
- Scandium can be a used in computer switches where undulating light passes through garnet and microwave equipment to make these switches work.
- Scandium is useful for creating high-intensity lights that mimic natural light, used for example in camera lighting, and in movie and television studio lights.

Table 5: Scandium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector (Eurostat 2022).

Applications	2-digit NACE sector	Value added of sector (M€) – at 2019	4-digit NACE sector
Solid Oxide Fuel Cells (SOFCs)	C27 - Manufacture of electrical equipment		27.90 - Manufacture of other electrical equipment
Al-Sc alloys *2014 data only	C25 - Manufacture of fabricated metal products, except machinery and equipment		25.11 - Manufacture of metal structures and parts of structures

The relevant industry sectors and their 2- and 4-digit NACE codes are summarised in Table 5 and visualised in Figure 12.

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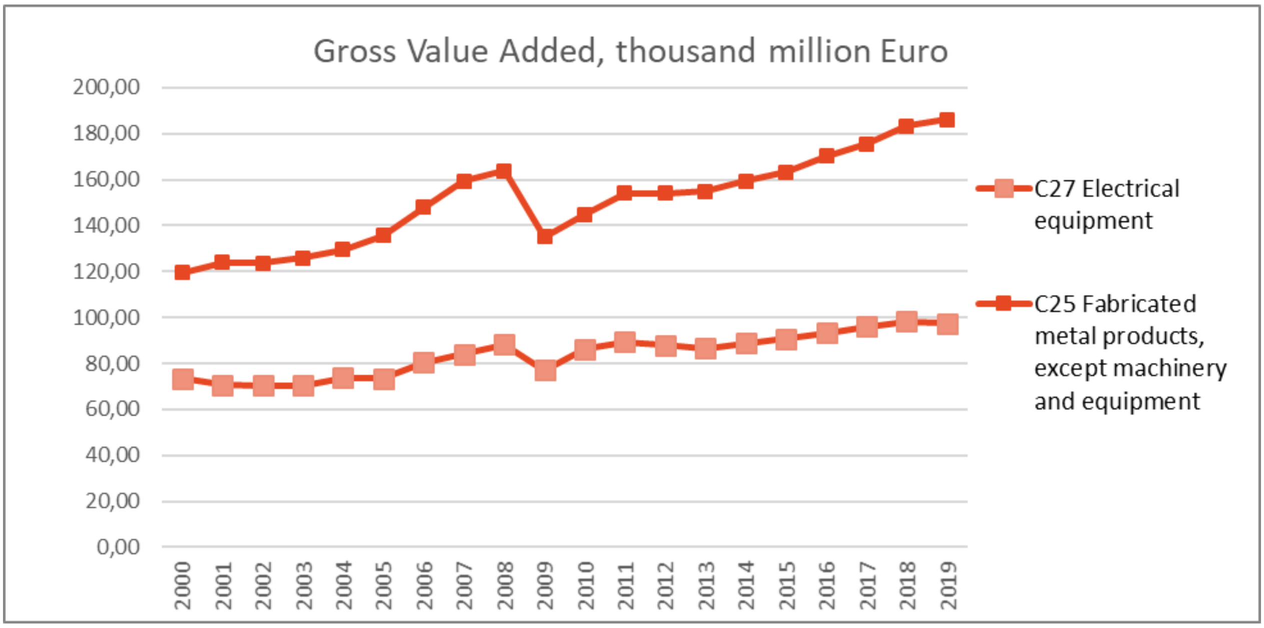

Figure 12: Value added per 2-digit NACE sector over time (Eurostat, 2022).

SUBSTITUTION

Table 6: Substitution options for scandium by application.

Application	Share*	Substitutes	SubShare	Cost	Performance
Thin films for 5G applications	40%	No substitute			No substitute
Solid Oxide Fuel Cells	35%	Gadolinium doped ceria	0%	Similar or lower costs	Reduced
		Yttria-Stabilized Zirconia	20%	Similar or lower costs	Reduced
		No substitute	50%		No substitute
Al-Sc alloys for the metal industry	10%	Titanium/Aluminium high strength alloys	5%	Similar or lower costs	Reduced
		Carbon-fibre material	90%	Similar or lower costs	Reduced
Al-Sc alloys for defence applications	10%	Titanium/Aluminium high strength alloys	5%	Similar or lower costs	Reduced
		Carbon-fibre material	5%	Similar or lower costs	Reduced
Solid Oxygen Electrolysis Cells	5%	No substitute			No substitute

* EU end use consumption share.

As the use of scandium is new and still a “niche market”, the use of scandium is in most of its applications a way to innovate and enhance performances and properties of already existing end-products. Therefore, scandium is rather considered as a substitute itself, and alternatives exist for almost all its uses. The decision for scandium at the choice of material is mainly driven by performance, price, or availability.

Recycled scandium is unsuitable to substitute the virgin metal in 3D printing applications or in catalysis. In contrast it can be used in Aluminium-Scandium alloys.

SOLID OXIDE FUEL CELLS (SOFC)

- In SOFCs, yttrium and scandium can be used alternatively because they play the same role in stabilizing the zirconia-based electrolyte. The use of one or the other also depends on performance, price, or availability criteria and can evolve in time.

HIGH PERFORMANCE ALLOYS

- In high-performance alloys, substitutes for scandium can be titanium, lithium (especially for aluminium alloys) or carbon fibre materials.
- They achieve comparable results in terms of resistance and low weight for aerospace and automotive structures. Titanium and aluminium high-strength alloys, as well as carbon-fibre materials, may substitute in high performance scandium-alloy applications (Gambogi, 2019).

SUPPLY

EU SUPPLY CHAIN

Currently, there is no reported mining of scandium in the EU and official production numbers are not available at the EU level. The import reliance of EU-27 for scandium is therefore 100%. At the same time, the global supply and consumption of scandium oxide has been estimated to be about 15 to 25 tons per year (USGS, 2022).

There are, however, some pilot projects in Europe which target scandium production. For example, in Greece, at Agios Nikolaos, a pilot plant successfully demonstrated recovery of scandium from bauxite residue in industrial waste at aluminium plant as part of the European Union's Horizon 2020 research and development program. The Kiviniemi scandium project in eastern Finland has featured a resource of 13.4 million tons at a grade of 163 parts per million scandium where scandium is present as substitution element in the lattice of clinopyroxene and amphibole (USGS 2022).

Scandium specific trade codes are applied at Eurostat Comext by the introduction of codes on pure scandium (CN 2805 30 40) and scandium compounds (CN 2846 90 30). Previous estimates for Russia (200 kilogram per year) and Kazakhstan (100 kilogram per year), mainly in the form of scandium oxide, based on expert consultation were maintained aiming to complete the uncertain data set on imports (Lipmann, 2016). According to this joint dataset, the United Kingdom is by far the most important supplier of scandium to the EU, taking almost 98% (26.6 tonnes per year) of the imports to the EU, which is almost double the reported global production. The quality of the trade data is estimated weak, but no better official data, especially on magnitude was available. Other minor source countries are Russia (0.2 tonne per year), Kazakhstan, United States and Hong Kong (each 0.1 tonne per year).

Not much is known about scandium transformation in the EU. At present, it is still commercialized at a very modest level, focusing more attention at the R&D level, both for uses in alloys and Solid Oxide Fuel Cells (SOFCs). The EU-based company Airbus developed the ScalmalloyTM alloy family since 2012, with registration of the patent in 2014 (Airbus, 2016). But only one company is known to offer patented ScalmalloyTM alloys for sale, namely RSP Technology250 in the Netherlands. SCALE (https://scaleup.tesmet.gr/) is an EU funded project that aims for efficient exploitation of a selection of high concentration scandium containing resources including bauxite residues from alumina production and acid wastes from TiO_2 pigment production. Based on a number of innovative extraction, separation, refining and alloying processes, the project investigates options for improvements along the overall supply chain with the ultimate goal to develop a stable and secure EU scandium supply chain to serve the needs of EU aerospace and high tech industry.

In terms of trade restrictions, Chinese export quotas on REEs also applied to scandium. These were lifted in 2015, replaced by resources taxes based on sales value (Metal Pages, 2015). At the moment, there are no export quotas or prohibition in place between the EU and its suppliers (OECD, 2016). From the EU's suppliers, only China has an export tax (≤ 25%) (OECD, 2016).

The exact numbers for scandium recycling are not known. Up to now, scandium has been considered as not recyclable, and most of scandium-bearing waste is disposed in a landfill dumps (European Commission, 2014).

SUPPLY FROM PRIMARY MATERIALS

The global supply of scandium originates from primary sources such as ore feedstock, and secondary sources from mining production such as concentrates, metallurgical slags and residues. Scandium is typically produced as a co-product or by-product during processing of various ores (e.g., iron ore, REEs, titanium, zirconium, uranium, thorium, aluminium, tungsten, tin, tantalum, apatite, nickel and cobalt) and/or recovered from previously processed tailings and residues (USGS 2021 & 2022).

The different types of scandium sources can be grouped into (i) by-products from aluminium (red mud) or titanium slags, and (ii) leachants from various products from mining routes, including residues, slags, and tailings, from nickel laterites, titanium pigment waste acids, zirconium chloride production, uranium mining (Matos et al. 2021). Besides leaching, technologies applied for this second case involve also solvent extraction, precipitation, and calcination methods (Wang et al., 2011). For several years, by-production from rare earth elements (REEs) and iron was a major source of supply (Bayan Obo mine) (Gambogi 2019). In 2021, China, the Philippines, and Russia were the leading producers (USGS, 2022). Recently, laterite and bauxite deposits seem to be a promising source of scandium. The lateritic and bauxitic weathering processes have the ability of relative Sc enrichment in the weathered rock up to a factor of ~10 compared to the original source rock (Teitler et al., 2019).

GEOLOGY, RESOURCES AND RESERVES OF SCANDIUM

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GEOLOGY

Scandium is a light transition metal and due to its properties often associated with the Rare Earth Elements in various classifications. Average scandium concentration in the continental crust is 22 ppm (Rudnick & Gao 2003). Scandium occurs in more than 100 minerals with the main minerals being thortvellite and lolbeckite, a scandium silicates (Sc,Y)2Si2O7 with up to 45 % of Sc2O3. Scandium occurs as a trace element in ferromagnesian minerals such as clinopyroxene and amphibole, rock forming minerals in igneous and metamorphic rocks. Scandium concentrations in these minerals (amphibole-hornblende, pyroxene, and biotite) are typically in the range of 5-100 ppm. As an effect of intense chemical weathering scandium can be highly enriched in surface soils, for example in lateritic clays and bauxites.

Genetic types of scandium deposits are difficult to classify (Borisenko, 1989) because the element is widely dispersed in the lithosphere and forms solid solutions in over hundred minerals such as rare-earth minerals, wolframite-columbite, cassiterite, beryl, garnet, muscovite, and the aluminium phosphate minerals. Sc occurs in magmatic, hydrothermal and supergene deposits. Magmatic deposits are estimated to contribute about 90% of the global Sc resources, in which Sc is primarily hosted in clinopyroxene and amphibole in mafic and ultramafic intrusions. Hydrothermal enrichment of Sc is often associated with W-Sn mineralization in quartz-vein systems. Supergene deposits include regolith-hosted bauxite and laterite deposits formed often from weathering of mafic and ultramafic parent materials and marine sediment-hosted deposits (Wang et al. 2021, Gentzmann et al., 2022). Regolith-hosted Sc deposits are knwon from Australia, New Caledonia, NE Argentina, Cuba, the Dominican Republic and China. Sc-rich marine sediments were recently discovered in the Pacific and Indian Oceans. Only in the North Pacific Ocean the estimates of scandium resources are at 2000-3928 t of Sc (Yasukawa et al., 2018; Wang et al. 2021).

So far there are only a few studies that investigated the Sc association in bauxites and laterites and in the weathering products. The Sc bearing minerals in primary bauxites comprise mainly goethite, hematite, and zircon (e.g., in Greek bauxite; Vind et al., 2018). However, there are also deposits where Al hydroxides boehmite and diaspore were additionally identified as major Sc hosts. Additionally, it has been shown that clay minerals such as smectites can also host Sc in laterites, whose formation is closely related to bauxite occurrences (Chassé et al., 2019). Some current exploration projects in Australia focus on nickel and cobalt lateritic deposits with high scandium concentrations (Duyvesteyn & Putnam, 2014; Gentzmann et al. 2022).

Comprehensive summary of the global Sc deposits and secondary resources is provided in Wang et al. (2021).

GLOBAL RESOURCES AND RESERVES:

Worldwide, there is about 2 million tons of scandium, with China accounting for 27.5% of the total reserves. Any resources with scandium concentration between 20–50 mg/kg can be considered as ore for exploitation (Ghosh et al. 2023). The world resources of scandium are abundant where scandium is recovered as bi-product from other ore type. Globally, the principal source of scandium is Bayan Obo niobium-rare earth element-iron ore (Nb–REE–Fe) located in Inner Mongolia (China), the largest REE resource and second largest resource of scandium in the world. It accounts for approximately 90% of global scandium production (Ghosh et al. 2023).

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Other scandium resources are reported from Australia (e.g. nickel laterite), Canada, China (iron ore, REE, niobium, titanium and zirconium ores), Finland, Guinea, Kazakhstan (uranium ore), Madagascar, Norway, the Philippines (nickel ore), Russia (apatite, uranium, and aluminium ores), Ukraine (iron and uranium ore), South Africa, and the United States. The global reserves of scandium with scandium as a main product are not available. (Gambogi, 2019). Instead, estimates exist for scandium volumes contained in mines, where other materials are the main products. Countries with major reserves include China, Australia, Russia, Philippines, India, Canada, Turkey, Ukraine, Jamaica and Greece, while significant parts of these have not been quantified yet (Matos et al. 2021).

In the United States, probable reserves of the polymetallic Elk Creek project in Nebraska were estimated to be 36 million tons containing 65.7 parts per million (2,400 tons) scandium. Production plans included downstream production of ferroniobium, titanium dioxide, and scandium oxide. The Bokan project in Alaska and the Round Top project in Texas also included scandium recovery in their process plans. In addition, research continued on the development of methods to separate scandium from coal and coal byproducts (USGS 2021 & 2022).

In the Russian Arctic, the niobium deposits seem to contain Sc2O3 in the high grade range of 0.1– 0.3%. The most important and largest source of scandium in Russia is the Kovdor baddeleyite–magnetite–apatite deposit. It contains a scandium reserve of 420 tons and the grade of the ore is 800 ppm of scandium. The other major source of scandium in Russia is Tomtor (carbonatite) with elevated concentrations of the REEs, including scandium up to 570 ppm (Kuzmin et al. 2019, Ghosh et al. 2023).

High scandium content (45%) has been found in thortveitite-rich pegmatites in Madagascar (Ghosh et al. 2023).

EU RESOURCES AND RESERVES

In the EU (without UK), there is no aggregated estimate of scandium resources. There are no scandium reserve figures published for the EU, but it is foreseen to extend the scandium production from red mud, a residue from aluminium production, from lab scale to production scale in near future (Matos et al. 2021). However, SCRREEN report D3.1 (Lauri et al. 2018) provides a short list of countries with scandium primary resources: Austria, Czech Republic, Finland, France, Germany, Greece, Hungary, Italy, Norway and Sweden. With few exceptions, the description of occurrences lacks detailed quantitative evaluation.

High scandium content (45%) has been found in thortveitite-rich pegmatites in Norway. The small Biggejav'ri REE-Sc-U deposit in Northern Norway has a non-compliant resource estimate of 0.05 Mt of ore at 0.013 % Sc. It is also reported that in the Iveland-Evje district of Norway, scandium-bearing pegmatites contain approximately 1000 ppm scandium (Jones & Vasyukoy, 2018; Lauri et al. 2018). In Finland, a resource of 13.4 Mtonnes is reported for the Kiviniemi deposit with a grade of 0.01627% scandium (Hokka & Halkoaho 2016). In Greece, a minor Sc commodity in the Perama Hills polymetallic deposits contains 107 t Sc (Cassard et al. 2013).

GLOBAL AND EU MINE PRODUCTION

In primary all scandium is recovered as a by-product. Various independent authors quote global market volumes of 2-10 tonnes per year. The estimate number of 15 tonnes was confirmed by EMC Metals Corporation (Duyvesteyn and Putnam, 2014) based on discussions with their potential customers, the level of metals trader activity and interest, and the fact that certain scandium consumers are believed to be sourcing their own scandium through small controlled recovery operations.

In the early 20th century, Sc was mainly mined from the thortveitite-bearing pegmatite in Evje-Iveland, Norway (Williams-Jones and Vasyukova, 2018). In 1976, aegirine-acmite and alkali amphibole at the Fe-U deposit in Zhovti Vody, Ukrain were identified as potential Sc sources mined until 2003 (Tarkhanov et al., 1992). Very high concentrations of Sc in wolframite and cassiterite were also discovered from W-Sn deposits in South China and Germany (Wang et al. 2021).

Currently, the main Sc producers are China (66%), Russia (26%) and Ukraine (7%) (Gambogi, 2019).

Chinese production of scandium was calculated at amount to 10 tonnes per year of Sc2O3 (66%), mainly as a by-product of REEs extraction (Bayan Obo mine, Inner Mongolia), but also from recovery of sulphate wastes from the manufacture of titanium pigments, from residues of iron ore, zirconium, tungsten and/or bauxite production (Gambogi 2019). In recent years, a large state-owned enterprise in Shanghai was producing 50 tons per year of scandium oxide raw material with a long-term expected capacity of 100 tons per year. Another company in Henan Province had a 10-ton-per-year scandium oxide capacity with plans to increase annual output to 20 tons (USGS 2022).

Russia produces 3-5 tonnes per year, mainly from uranium mill tailings and apatite (Gambogi 2019). The magnetite-apatite-carbonatite complex in Kovdor and the carbonatite deposit in Tomtor are the two major Sc deposits in Russia (Wang et al. 2021).

Kazakhstan is estimated to produce 100-200 kg scandium oxide annually (1%), also from uranium mill tailings (Lipmann, 2016, Gambogi 2019). Scandium is also extracted as by-product of uranium mining in Ukraine. Small stockpiles of this material may exist in Russia, Ukraine and Kazakhstan (Gambogi 2019).

In Australia, several mining companies are in various stages of development for new scandium supply. The Nyngan project in New South Wales has the reserves estimated at 590 tonnes of scandium (155 ppm of Sc) from 1.44 million tonnes of ore and it is expected to produce 39 tonnes per year of scandium oxide starting in 2020. The Syerston project, (New South Wales) reports 19,200 tonnes of scandium (300 ppm). In Queensland, the Scandium-Cobalt-Nickel (SCONI) Project was finishing its economic feasibility study, which expects to obtain 3,000 tonnes of scandium from 12 million tonnes of mineral resource (162 ppm) (Gambogi, 2019, Botelho Junior et al. 2021).

Scandium was produced in USA primarily from the scandium-yttrium silicate mineral thortveitite and from byproduct leach solutions from uranium operations. Limited capacity to produce ingot and distilled scandium metal existed at facilities in Ames, IA, Tolleson, AZ and Urbana, IL (USGS 2022).

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Table 7: Mature mining/metallurgical projects for the extraction of Sc as by-product (Ghosh et al. 2023).

Country	Name of Project	Primary Resource	Status
Australia	Nyngan scandium project	Typical tertiary laterite composed of limonites and saprolites	The feasibility study concludes that the project has the potential to produce an average of 37,690 kg of scandium oxide per year, at grades of 98.0–99.9%
Nebraska, US	US EIK Creek Niobium project	Carbonatite rocks	The mine is expected to produce 168,861 t of niobium in the form of ferroniobium, 3410 t of scandium oxide and 415,841 t of titanium dioxide over its operating life of 36 years
New South Wales, Australia	Owendale scandium project	Platina resources	Stage one will produce 20 tons per annum (tpa) of scandium oxide during the initial five years of operation, while stage two will double the annual production capacity to 40 t with the processing plant upgrade

OUTLOOK FOR SUPPLY

The extraction of scandium is related to implementation of various mining/metallurgical projects through which Sc will be extracted as by-product. Table 7 shows the most mature projects worldwide through which Sc is expected to be extracted (Ghosh et al. 2023).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

The secondary sources of scandium are scarce. Possible scandium secondary sources can be divided into the following groups: bauxite residue or red mud, waste electrical and electronic equipment (WEEE), nickel laterite, municipal wastes, phosphogypsum and phosphate rocks, coals and fly ashes (Botelho Junior et al. 2021).

There is growing interest to recover scandium from bauxite residues of different origin (Gentzmann et al. 2021; Gentzmann et al. 2022). The recent studies show that karstic bauxites have higher degree of Sc enrichment than lateritic bauxites. The processing of bauxites for production of alumina (Al2O3) leads to a twofold Sc enrichment in the accumulating bauxite residue (BR), which makes it a promising secondary raw material for Sc production. The BR, often also referred to as red mud, results from conventional Bayer processing of the bauxites and represents a major industrial waste stream with >160 million metric tons accumulation each year (Habashi 2016). These BRs have been a matter of intense research, especially with regard to reuse, recycling and circular economy approaches (Gentzman et al. 2021). In Russia, a possible secondary Sc-resource and recovery processing of BR have been implemented at a pilot plant scale at RUSAL’s facilities in Kamensk-Uralsky (Suss et al., 2018). The scandium fraction in red mud can be significant, e.g. Sc content in red mud from China is 41.2–92.5 ppm (Sc2O3), and in the range of 105–156 ppm (Sc2O3) in Greece (Wang et al. 2011).

Scandium contents for selected bauxite residues from Greece, Hungary, Germany, Russia, China, Jamaica, India and Australia have been reported in Gentzman et al. (2021).

Another secondary source of scandium which is discussed recently is coal ash and slag in which as a result of thermal treatment of coal various elements including REE and scandium (up to ca 300 ppm) are concentrated (Pyrzyńska et al. 2019).

The recovery of scandium by red mud at pilot scale has been conducted by the Greek aluminium industry company "Aluminium of Greece". The bauxite residue is leached with sulphuric acid to produce a Sc pregnant leach solution (PLS) which is further treated via II-VI selective-ion recovery (SIR) technology to obtain of a Sc-rich solution. The pilot leaching unit has a daily operation process of 236 kg of dry BR to produce around 4 g of Sc into PLS. About 10 m3 PLS of 8–12 mg/L Sc is passed through one column of the SIR at a flowrate of 30 L/h. The production of a solution with maximum Sc concentration of 3500 mg/L is achieved. Finally, a crude Sc hydroxide concentrate containing 22% Sc is received (Davris et al. 2022).

According to recent studies, they exist perspectives for the recovery of scandium from old flotation tailings in Bayan Obo mine in China. As exploitation methodology has been proposed the multi-step flotation and gravimetric separation. At this stage, the production of a secondary product with 0.05 wt.% Sc content is achieved. The subsequent metallurgical stage comprises the high-pressure acid leaching, the purification with the removal of iron and titanium content and Sc separation through precipitation with oxalic acid (Wang et al. 2020).

POST-CONSUMER RECYCLING (OLD SCRAP)

Until recently, no recycling of scandium in end-of-life products nor in 'new scrap' was known, due to its limited usage (UNEP, 2011). Scandium has been considered widely as not recyclable, accordingly scandium contained in waste ends up predominantly in landfill (European Commission, 2014). However, there is a growing interest in scandium recycling from electronic devices and municipal waste. Over time, certain recycling routes have been developed for old scrap.

Scandium can be potentially recycled from certain end-of-life products, namely from car catalysts, fuel cells and aluminium-scandium alloys. However, scandium recovery from Sc-Al alloys and $Sc2O3$ is a complex issue as: (a) there is lack of information on the amount of Sc-containing electronic wastes and whether this materials are collected and processed by the recycling companies, (b) the number of specific cutting-edge devices containing scandium is small and therefore the potential recovery amounts are limited. Scandium in fuel cells is not recycled due to missing economy of scale.

In Brazil, an attempt of scandium recovery from desktop computers has been made and trace amounts of scandium were detected in motherboards and processor sockets (Kohl and Gomes, 2018).

We conclude that this recycling is still a niche activity, and negligible or non-existent. Figures on recycling volumes are not available.

INDUSTRIAL RECYCLING (NEW SCRAP)

It is very difficult to recover scandium contained in intermediates, mixed scrap etc., i.e. scraps that are processed by specialty chemicals companies (e.g. Johnson Matthey) (Fontboté 2019).

PROCESSING OF SCANDIUM

Sc is extracted by the rare earth minerals monazite and bastnasite in which it is contained at concentrations between 20 and 50 mg/kg. The largest Sc amount globally is produced in Bayan Obo in China where is recovered by bastnasite/monazite concentrates. The most common extraction methodology involves roasting of the ore in concentrated sulphuric acid at 250–300 °C and then leaching with water (Li et al., 2004). Sc is separated by the mixture of REO through solvent extraction (Figure 13). Sc is extracted by ionic-adsorption rare earth ores – a unique type of RE ore found in China. Ion adsorption-type REE deposits consist of REE adsorbed to the surface of the clay minerals, kaolinite or halloysite. They are the world's main source of HREE and mined almost exclusively in southern China (and in Myanmar). Sc concentration in this type of ores reach 10 mg/kg (Wall, 2021). The extraction of Sc by ionic-adsorption rare earth ores is presented in the flowsheet of Figure 14. The ore is initially digested with (NH4)2SO4 and REEs with Sc are precipitated with oxalic acid. The produced concentrate is calcined and re-leached with HCl. Finally, Sc is separated by other REEs through a two-circuit solvent extraction system. A sulfated kerosene solution containing naphthenic acid and iso-octanol was used for the extraction process (Salman et al. 2022).

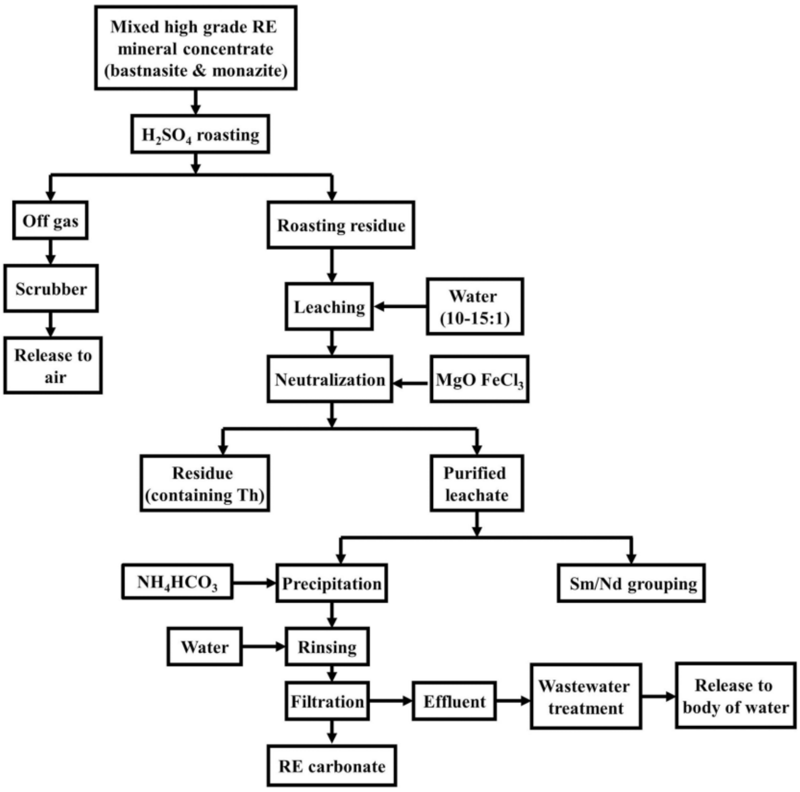

Figure 13: REEs extraction processing, including Sc, from Bayan Obo ore (Navarro, J., Zhao, F. 2014).

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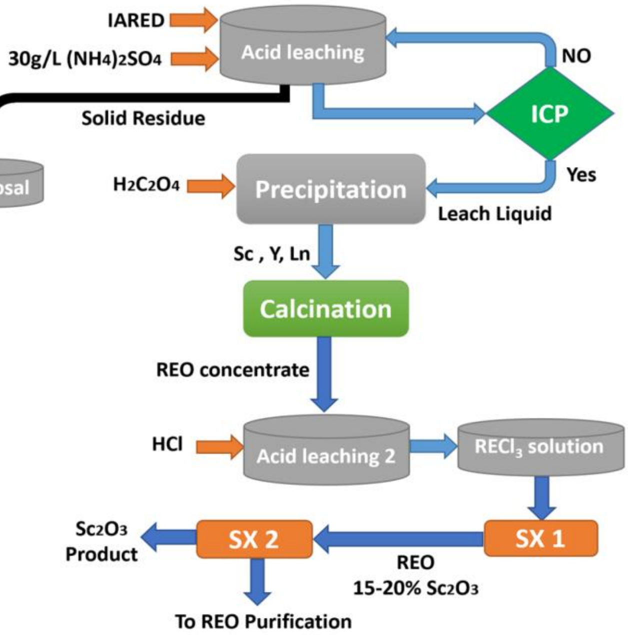

Figure 14: Sc extraction by ionic-adsorption rare earth ores (Salman et al. 2022).

Scandium is also recovered through the uranium extraction process since most uranium ores, including uraninite, contain Sc traces. The accumulated scandium and thorium, after the leaching of uranium ores with H_2SO_4, are stripped by hydrofluoric acid (Figure 15). Thorium and scandium react with hydrofluoric acid to form their precipitations, which contain 10% of Sc2O3 and 20% of ThO2. High pure scandium oxide is then recovered with multi steps of chemical separation techniques; the purity of Sc_2O_3 obtained was 99.5% (Lehto, J. 2003).

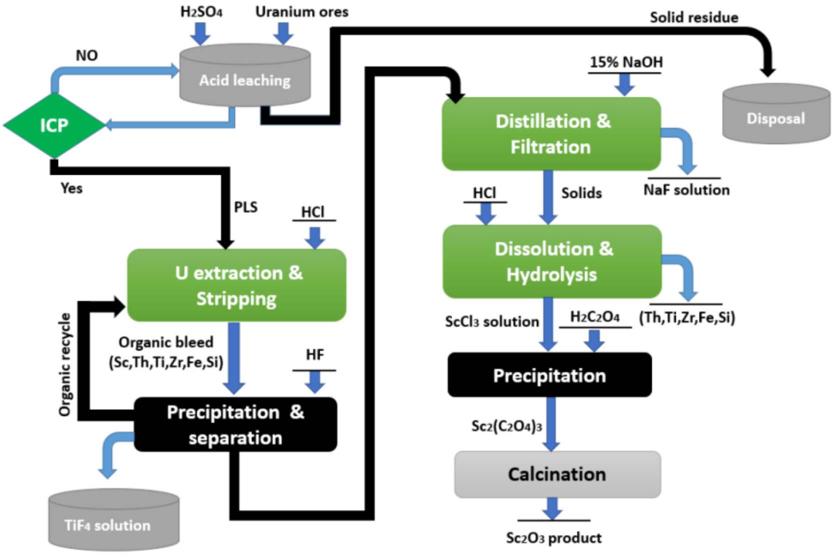

Figure 15: Sc extraction as a by-product through the uranium extraction process (Salman et al. 2022).

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OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES

According to (Rim et al. 2013) and (Blazy 2013), scandium is mostly dangerous in the working environment:

- Scandium, according to the classification provided by companies to ECHA in CLP notifications, is a flammable solid (ECHA, 2022). It is flammable in the form of dust, when exposed to flame or heat or when in contact with an oxide (Blazy, 2013).;
- The inhalation of damps and gases containing scandium can cause pulmonary embolisms, especially during prolonged exposure (Blazy, 2013);
- Scandium or its compounds, absorbed orally, tend to accumulate in the liver (Blazy, 2013).

According to (Rim et al. 2013), “elemental scandium is considered non-toxic, and little animal testing of scandium compounds has been done. The half lethal dose (LD50) levels for scandium (III) chloride for rats have been determined as 4 mg/kg for intraperitoneal, and 755 mg/kg for oral administration”.

ENVIRONMENTAL ISSUES

Scandium extraction is associated with relatively high concentrations of uranium and thorium (German Environment Agency, 2020; Blazy, 2013), but with low potential for Acid Mine Drainage (AMD; German Environment Agency, 2020). Scandium is emitted to the environment either by production activities, in particular at the purification process step, or from scandium containing equipment at their end-of-life (Blazy, 2013). Scandium subsequently gradually accumulates in soil and water, and its concentration in consequence increases in humans, animals and plants (Blazy, 2013).

A limited number of publications report LCA results of cradle-to-gate production of scandium. (Nuss 2014) observed in their LCA that, when considering five impact categories (global warming, cumulative energy demand, terrestrial acidification, freshwater eutrophication, and human toxicity – cancer and non-cancer), the impact intensity of scandium (impact per kg produced) is among the largest in comparison with other metals.

NORMATIVE REQUIREMENTS

Scandium is included in the range of materials under the Minor Metals Trade Associations (MMTA). The MMTA supports the UN Global Compact, and has developed a set of guidance reports related to topics such as responsible sourcing, circular economy, road transport etc. (MMTA 2022)

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF SCANDIUM PRODUCT EXPORTS FOR EXPORTING COUNTRIES

According to COMTRADE (2022), the shares of scandium product exports in the total value of exports remain below 0.1 % in each of the exporting countries so that the economic importance of these exports is limited.

SOCIAL AND ETHICAL ASPECTS

No information solely on scandium could be identified. Information sources consider scandium together with other rare earth elements (REE). In 1958 in China, the Baotou Iron and Steel Company began producing rare earths near the city of Baotou in Inner Mongolia; by 1980 crops in the nearby villages had already started to fail due to the pollution of soil and groundwater attributed to REE mining and processing. Today, the lands surrounding Baotou are stripped of topsoil while streambeds contain thousands of gallons of acid. Alahai village, located close to a Baotou rare earths tailing pond, has been named a “death village” due to the high incidence of lung cancer, brain cancer, respiratory illnesses and cardiovascular diseases suffered by local residents. Ganzhou, the so-called “rare earths kingdom,” has been described as a “site of devastation” by the China Dialogue, plagued as it is with crude open air mines, smelters, polluted water supplies and reduced crop yields. Coupled with the growth of environmental activism, rare earths mining in China could lead to increasing tensions at the local level. (Green Conflict Minerals 2018). The nature of deposits located in the southern province of Ganzhou make rare earth extraction relatively easier than in Inner Mongolia. These deposits are also free of radioactive thorium. However, as a result of the ease of extraction and rising global prices for rare earths, a substantial number of illegal rare earth mines emerged in the area. These mines are cited to sell to organized crime syndicates and exploit workers, some of which are children (Bradsher, 2010a; Schlanger, 2017). Some estimates suggest that tens of thousands of tonnes of rare earths are illegally mined and sold on China’s black market every year (Hongqiao, 2016). In response, both the central and provincial governments have taken measures against illegal mining operations, including instituting new regulations against illegal exploration as well as dispatching police to outlaw the illegal mines (Yan, 2012). The traceability of rare earths supply chains, however, is still relatively unexplored, and is not regulated to the same extent as other conflict minerals. In addition to the risks of exacerbating local and global grievances surrounding pollution and public health, China’s majority share of rare earth production has been used as political and economic leverage in past state-level disputes. In 2010, amid a territorial disagreement over disputed islands with Japan, China suspended its shipments of rare earths to its neighbour (Bradsher, 2010b). Chinese officials later lifted the embargo and denied that the ban was in response to the dispute with Japan, claiming they had instead reduced export quotas to mitigate pollution and environmental concerns (Bradsher, 2010b).

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Sputter-deposited ScN thin films application in nanophotonic

Scandium nitride (ScN) has attracted significant interest in recent years for its potential thermoelectric applications as a substrate for high-quality epitaxial gallium nitride (GaN) growth because of the degenerate semiconducting nature with a direct bandgap of 2.2 eV and indirect gap of 0.9 eV. N-type (oxygen) and p-type (magnesium)-doping in epitaxial ScN thin films lead to tunable high-quality low-loss short-wavelength-infrared plasmon− and long-wavelength-infrared high-quality phonon−polariton resonance. This opens the possibility for practical applications (in waveguides, hyperbolic, and epsilon-near-zero metamaterials, optical communication, solar-energy harvesting, and infrared photonic applications) (Maurya et al., 2022).

Sputter-deposited ScN thin films on MgO and sapphire substrates have shown a large thermoelectric power factor of ~ 3.3×10^{-3} W/m K^2 in the temperature range of 500–800 K, which is higher than that of many well-known thermoelectric materials such as Bi_2Te_3 in the same temperature range. Although the thermoelectric power factor was found to be appreciably high, the overall *figure-of-merit* was limited to 0.17 due to the high thermal conductivity of 7.3 W/m-K at 500 K. Further research on alloying or nano-structure formation will be required to reduce the thermal conductivity of ScN without compromising the power factor (Rao et al., 2020).

- A novel application of scandium in the optoelectronic field

The unique combination of ferroelectric properties of $Al_{1-x}Sc_xN$ in concert with the excellent compatibility to technology platforms should make the material highly relevant both as piezoelectric multilayer actuator stacks or non-volatile memory cells and for novel approaches based on controlling electrical polarization, e.g., in the fields of optoelectronics, multiferroic composites, and III-nitride technology (Fichtner et al., 2019; Rao et al., 2020).

- Scandium (Sc) application in hydrogen production

A theoretical study of Sc metallofullerenes (typically a single metal atom or metal clusters encapsulated in a spherical carbon cage) based on density functional theory (DFT) calculations, has been carried out to explore their potential properties as catalysts for a chemical reaction that produces hydrogen (hydrogen evolution reaction, HER). The results show that the endohedral scandium cluster-fullerenes such as $Sc_6@C_{80}$ and $Sc_7@C_{100}$ possess both good structural stabilities and HER activities. Based on the electronic analyses, a remarkable degree of charge transfer between the Sc_n cluster and the carbon cage occurs. As a result, the adsorption of hydrogen is weakened, and therefore there is good HER activity on the outside fullerene surface. The theoretical study not only provides new insights to the design of novel HER catalysts with high efficiency, but it also deepens the understanding of the HER catalytic mechanism at the atomic level (He et al., 2022).

- The effect of gallium (Ga) and scandium (Sc) doping as an alternative sensor

A theoretical work was utilized for scrutinizing the effect of Ga and Sc-doping on the sensing performance of an aluminium phosphide (AlP) nanotube (AlPNT) in detecting ethylene oxide (EO).

EO is a very hazardous compound, despite its wide applications. Previously, surface sound wave sensors, fluorescent-based chemosensors, and chromophorebased sensors have been used to detect EO, but these methods are expensive and complicated. An alternative sensor is based on the nanostructures which are less expensive and have simple instruments. Pristine AlPNT had a weak interaction with EO, and the sensing response (SR) was approximately 8.6. Sc-doping is a more favorable strategy compared to the Ga doping for increasing the sensitivity of AlPNT. The SR of Ga and Sc@AlPNT were 33.1 and 79.3, respectively. In real applications different challenges such as temperature effect, interfering molecules, and gas concentrations may occur (Jasim et al., 2022).

The adsorption of boron trifuoride (BF_3) was explored onto pure, Al-doped, and Sc-doped boron carbide (BC_3) nanosheets through density functional theory (DFT) computations. BF_3 is colorless toxic gas, so developing a simple, sensitive, fast, and accurate method for determining its concentration is important. Sc-doping

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advances the performance of the BC_3 and makes it more reactive and sensitive to BF_3. The Sc-doped BC_3 can generate electrical signals when the BF_3 molecules approach, being a promising sensor (Zhao et al., 2021).

- Manufacturing of Integral Stiffened Skin Panels - MISSP (EU, 2017-2020)[5, 6]

The main objective of this project was to develop cheaper and greener structures as an alternative to CFRP doors but also applicable for any stiffened skin panel structure. Researchers have been working on the development of a light metal alloys such as aluminium-magnesium-scandium alloy – a first-of-its-kind metal alloy in aircraft design. Its good specific stiffness, ductility and mechanical properties, as well as its excellent weldability and corrosion resistance come as a real boon compared to other aluminium alloys that are typically used. In addition, less weight results in lower fuel consumption, a big boost to the competitiveness of Europe's transport industry.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- Projects SCALE[7] (2016 – 2021, EU) and RemovAL[8] (2018 – 2023, EU): Production of scandium compounds and scandium from byproducts of primary aluminum production and from other metal sectors in the European metallurgical industry

The projects set about to develop and secure a European scandium (Sc) supply chain through the development of technological innovations which will allow the extraction of Sc from European industrial residues. Bauxite residues from alumina production (5 Million tons on dry basis per year in Europe) and acid wastes from TiO_2 pigment production (1.4 Million tons on dry basis per year in Europe) have Sc concentrations which are considered exploitable, given a viable extraction technology. The projects develop innovative technologies that can extract economically and sustainably Sc from dilute mediums (<100 mg/L) and upgrade them to pure oxides, metals and alloys at lower energy or material cost. All rare earth elements found in the by-products will be extracted along with Sc. Developed processing technologies for extracting base and critical metals from such industrial residues and valorising the remaining processing residues in the construction sector will be combined, optimized and scale-up developed.

- HiTech AlkCarb[9]: New geomodels to explore deeper for High-Technology critical raw materials in Alkaline rocks and Carbonatites (2016 – 2020, EU)

Heavy and light rare earth elements, niobium, fluorspar, and phosphate, as well as hafnium (Hf), tantalum (Ta), scandium (Sc) and zirconium (Zr) are commonly found in association with alkaline rocks and in particular

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[5] CORDIS EU research results, https://cordis.europa.eu/project/id/755641

[6] CORDIS EU research results, https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5cc21865f&appId=PPGMS

[7] CORDIS EU research results, https://cordis.europa.eu/project/id/730105

[8] CORDIS EU research results, https://cordis.europa.eu/project/id/776469

[9] CORDIS EU research results, https://cordis.europa.eu/project/id/689909

in carbonatites. In Central and Southern Europe, the presence of abundant alkaline volcanic rocks indicates the likelihood that deposits exist within about a km of the surface. The project will make a step-change in exploration models for alkaline and carbonatite provinces, using mineralogy, petrology, and geochemistry, and state-of-the-art interpretation of high resolution geophysics and downhole measurement tools, to make robust predictions about mineral prospectivity at depth. The results will be incorporated into new geomodels on multiple scales.

- Production of scandium radionuclides for theranostic applications: towards standardization of quality requirements (R. Mikolajzak et al. (2021)

In “precision medicine”, the scandium radionuclides have recently received considerable interest, providing personalised adjustment of radiation characteristics to optimize the efficiency of medical care or therapeutic benefit for particular groups of patients. Radionuclides of scandium, namely scandium-43 and scandium-44 (43/44Sc) as positron emitters and scandium-47 (47Sc), beta-radiation emitter, seem to fit ideally into the concept of theranostic pair. The paper is a review the work on scandium isotopes production, coordination chemistry, radiolabeling, preclinical studies and the very first clinical studies. Finally, standardized procedures for scandium-based radiopharmaceuticals have been proposed as a basis to pave the way for elaboration of perspective scandium radionuclides.

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