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**

TUNGSTEN

AUTHOR(S):

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TUNGSTEN

OVERVIEW

Tungsten (chemical symbol W), also known as wolfram, is a hard, rare metal. Tungsten is found naturally on Earth almost exclusively in chemical compounds. Its important ores include wolframite and scheelite. The free element is remarkable for its robustness and has the highest melting point of all the elements. Its high density is 19.3 g/cm³, comparable to uranium and gold. Tungsten was on the EU's list of CRMs in 2011, 2014 and 2017.

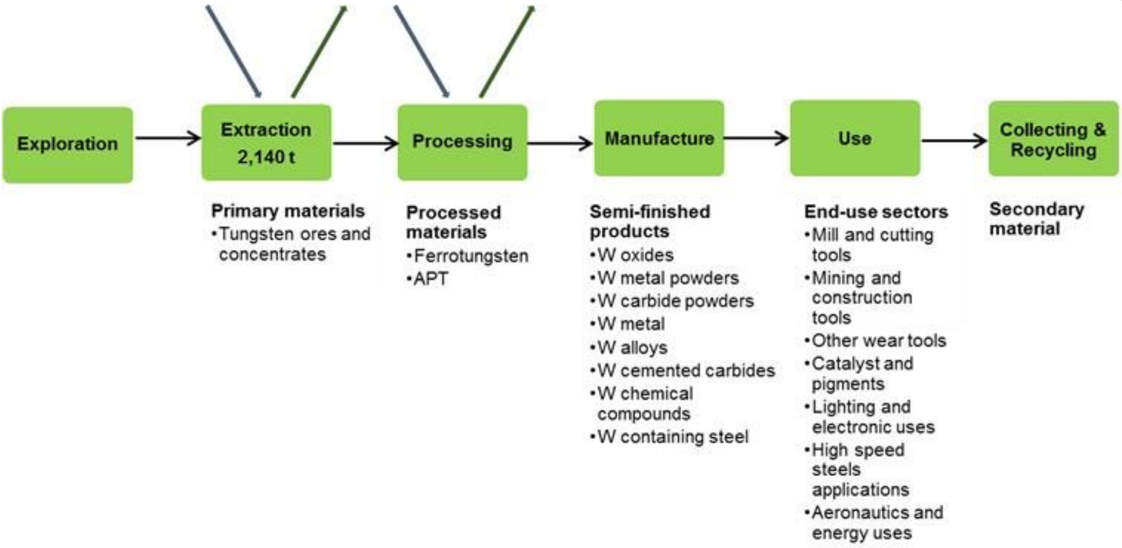

Figure 1. Simplified value chain for tungsten in the EU[1]

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
86,751	China 83% Vietnam 6% Russia 3%	17,273	20%	China 31% Vietnam 14% United States 9% Russia 9% Other 37%	88%

Prices: Average tungsten prices have appreciated consistently since early 2000 till 2011. In the first half of the decade starting from 2010 prices experienced a fall reaching lowest value by 2016. The fall in value around 2015 – 16 was due to economic turmoil in China. Price recovered temporarily after falling again due to COVID

Primary supply: Mining of tungsten is performed through both open-pit mining and underground mining. The ore from mine is crushed and milled, and then upgraded by means of gravity enrichment or flotation. For commercial trading 65-75% WO_3 content is required for further refining (European Commission, 2014). The ore beneficiation allows to increase the tungsten content of the concentrate up to 65-75% WO_3, which can be

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

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(BGS, 2011). China is by far the largest W producer representing over the 79% of the global production for 2020. Vietnam, Russia and Bolivia are notable producers representing cumulatively the 13% of the global production. From 2014, Vietnam went from a medium-scale to the world's second largest producer of tungsten concentrates outside China by the opening of the Nui Phao mine in 2013 (about 4000 tonnes in 2014 and more in 2016). In contrast, Canada will be "zero" from 2016 onwards, due to the closure of the Cantung mine in late 2015 (Wolfram, 2016).

Secondary supply: Secondary tungsten can be found in two main types of sources: in waste from processed materials (intermediates as ferrotungsten and APT) as well as in manufacturing residues (W cemented carbide, W metals, ...) and end-of-life products from urban mines (Sundqvist Oeqvist L., SCRREEN 2018). Tungsten scrap, due to its high tungsten content (40–95%) in comparison to ore (around 0.4–0.6%), is a very valuable source. The recycling activities inside EU have considerably increased since the global economic crisis in 2009. Based on the material flow analysis performed in the MSA study, a 42% EoL-RIR has been estimated, mainly from cemented carbide scrap (Ladenberger A., 2018). This is consistent with the estimation that nearly half of the tungsten contained in the total EU production of semi-finished products in Europe is recycled (Bio, 2015).

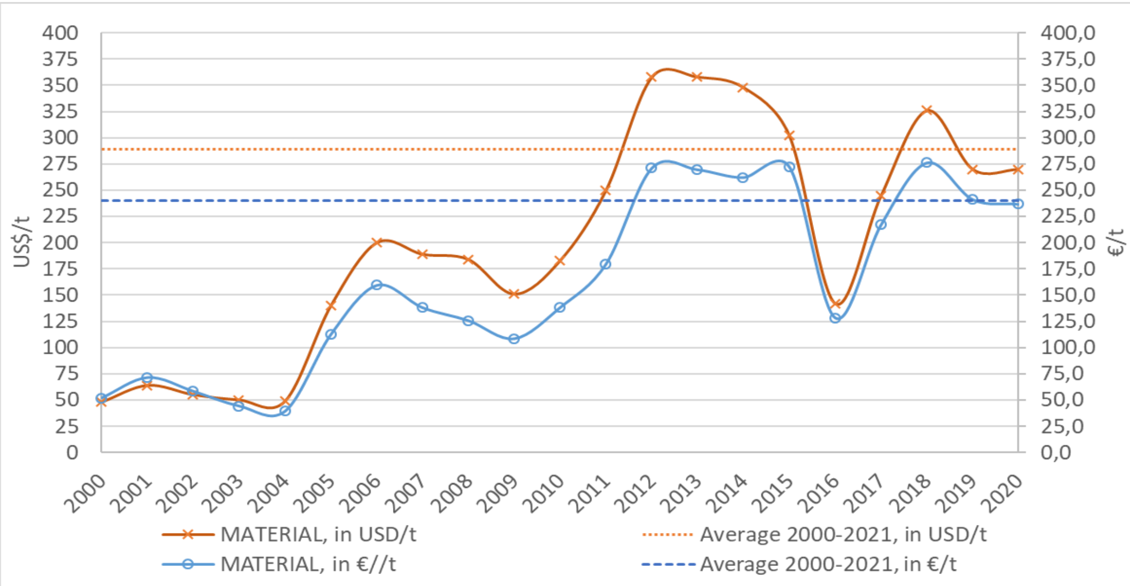

Figure 2. Annual average price of tungsten between 2000 and 2020 (USGS, 2021)[2].

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

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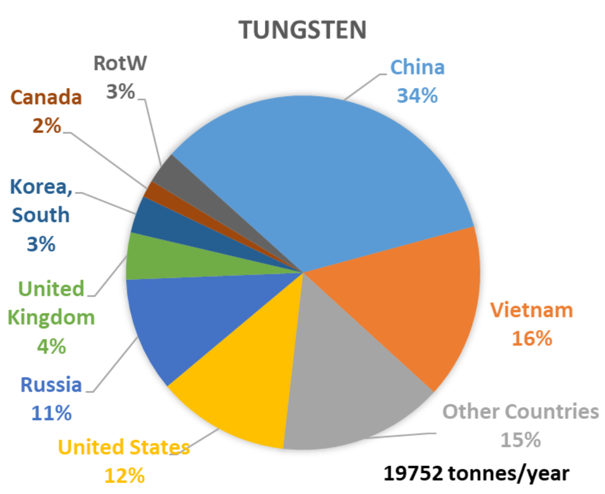

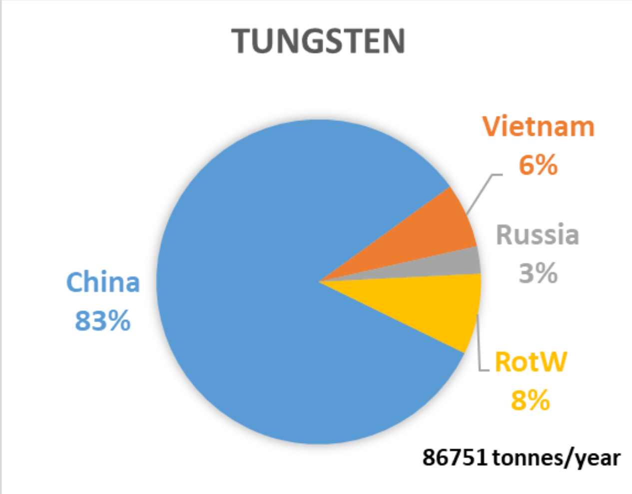

Figure 3. EU sourcing of tungsten (left) and global mine production (right), average 2016-2020

Uses: the end-uses of tungsten are quite stable along the last decade. Tungsten is mainly used in tools (mills & cutting, mining & construction, other), catalyst and pigments, lighting and electronic industry, steel production and aeronautics and energy.

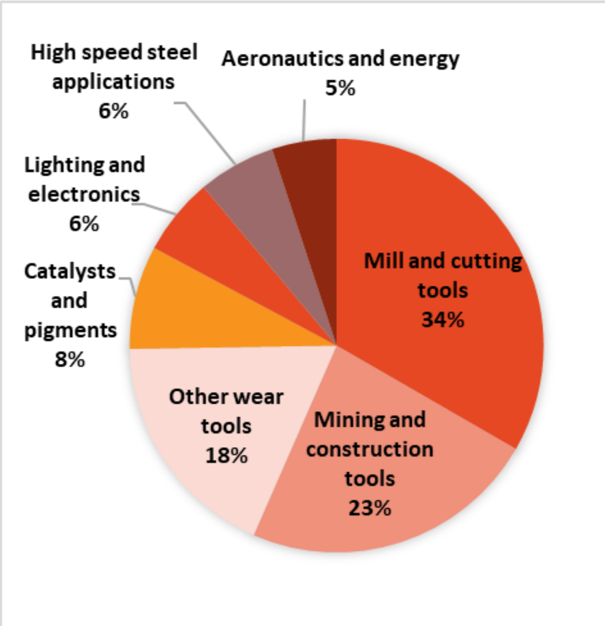

Figure 4: EU uses of tungsten

Substitution: there are may substitute to tungsten in most of its application. However, but a few exceptions, the performances are reduced; and the cost is similar or higher.

Other issues: According to the classification provided by companies, tungsten is a flammable solid, it is self-heating in large quantities and may catch fire. (ECHA, 2022a) (ECHA, 2022b). Nickel tungstate ($NiWO_4$) is cited as carcinogen in Appendix 1 of Annex XVII (List of restricted substances) as a nickel compound but is not currently being manufactured in and/or imported to the European Economic Area (ECHA 2022c). During the

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production and use of tungsten the main route for intake proceeds via the respiratory tract. In 2017 an extensive epidemiological study of hard metal workers was published where the researchers found no evidence that exposure to tungsten, cobalt, or nickel, at levels experienced by the workers examined increases lung cancer mortality risks. (ITIA 2022, Hadrup 2022). However, the United States Environmental Protection Agency (US EPA) did claim tungsten as an emerging toxicant (Wasel 2018). Tungsten is not expected to be hazardous to the environment. (LENNTECH 2022) However, the presence of tungsten in groundwater near background sources and anthropogenic sources suggests that under certain conditions, tungsten dissolves in water and is mobile in the environment. (UE EPA 2017). For Rwanda, the fourth world producer of tungsten, tungsten exports represent 1.4% of its total exports. Tungsten is one of the four minerals called conflict minerals (OECD 2016). Tungsten is a conflict mineral because its mining and trade are said to directly finance armed conflicts or contribute to human rights abuse through forced labour in countries that supply the ore. Such countries include Vietnam, China, Rwanda, etc. Section 1502 of U.S. Dodd Frank Act requires U.S. listed companies to disclose whether they use such conflict minerals and whether these minerals originate in the Democratic Republic of the Congo (DRC) or an adjoining country (SEC 2012).

Table 2. Main Uses and main possible substitutes

Application	%*	Substitute(s)	SubShare	Cost	Performance
Mill and cutting tools	33%	Molybdenum in molybdenum carbide	15%	Similar or lower costs	Reduced
		Silicon in ceramic-metallic composites (cermets)	10%	Similar or lower costs	Reduced
Mining and construction tools	23%	Molybdenum in molybdenum carbide	5%	Similar or lower costs	Reduced
		Silicon in ceramic-metallic composites (cermets)	10%	Similar or lower costs	Reduced
Other wear tools	18%	Molybdenum in molybdenum carbide	15%	Similar or lower costs	Reduced
		Silicon in ceramic-metallic composites (cermets)	10%	Similar or lower costs	Reduced

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MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

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

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
86,751	China 83% Vietnam 6% Russia 3%	17,273	20%	China 31% Vietnam 14% United States 9% Russia 9% Other 37%	88%

China is the biggest producer, exporter, and consumer of tungsten concentrates. For more than 10 years, China has not allowed the export of tungsten concentrates (Eurometaux, 2019). Tungsten has been defined in the "National Mineral Resources Planning" (2016-2020) as a strategic mineral resource. Therefore, China planned to control tungsten exploitation at 120,000 tonnes of tungsten concentrates, equal to 62,000 tonnes of tungsten content by 2020.

In 2016-2020, the main producers of tungsten ores and concentrates outside China were Vietnam (6%), and Russia (3%). Other countries include Bolivia, North Korea, Austria, Portugal, Russia, Rwanda and Spain.

In 2021, the production of tungsten concentrate was lower than expected outside China, remaining at less than 20% of the global production. Tungsten scrap continued to be a valuable raw material for the whole industry. However, at the beginning of 2020 and in 2021, the tungsten scrap supply was constrained since less scrap was generated during periods of low industrial activity (USGS, 2022a).

The global demand for tungsten in 2018 was estimated to be 104,500 tonnes of tungsten content. (ITIA, 2019). China is also the world's leading tungsten consumer. Analysts forecast a higher global tungsten consumption in 2021 than in 2020, resulting from a lower production due to the global COVID-19 pandemic. In 2021, there was a stronger demand in tungsten concentrates, scrap, and downstream tungsten materials together with transportation delays and increased freight costs which resulted in a price increase. Transportation delays and increased freight costs led to supply bottlenecks and price increases.

China is also a major exporter of tungsten intermediates such as tungsten oxides, tungstates, tungsten powder, tungsten carbide, and ferrotungsten. China's export of these intermediates was estimated at 25,969 tonnes in 2018 (of W content, tungsten carbides excluded) (ITIA, 2019).

Experts (Eurometaux, 2020) argue that the economic viability of western mines depends on opaque pricing mechanisms dominated by state-influenced decisions in China (e.g., "environmental inspections" to reduce inflow or release of stockpiles) and severe over-capacity of APT production in Asia (notably China). The refinery-level industry in the EU faces the risk to be cut off from concentrate supplies, if APT prices are (possibly artificially) depressed.

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EU TRADE

For this assessment, Tungsten is evaluated at both extraction and processing stage.

Table 3. Relevant Eurostat CN trade codes for Tungsten

Mining		Processing/refining	
CN trade code	**title**	**CN trade code**	**title**
26110000	Tungsten ores and concentrates	28418000	Tungstates 'wolframates', containing 70.2% of W
28259040	Tungsten oxides and hydroxide	72028000	Ferro-tungsten and ferro-silico-tungsten, containing 22% of W
810100	Tungsten article and powders	28499030	Tungsten carbides

Import of Tungsten Ores and Concentrates have fallen sharply since 2018 and the decline continued with the pandemic period until 2020 (Figure 5). Since 2021, there has been a stabilisation of import as consumption has started to regain pre-COVID level figures.

Major supplier of Tungsten ore and concentrates to EU has been China, followed by Russia. EU also has significant import from Vietnam (Figure 6). After China and Russia, Vietnam possesses the third largest deposit of tungsten in the world.

Import for Tungsten oxide and hydroxide have recovered stronger than Tungsten ore and concentrates post COVID, mostly due to wider application of the former in industries. Exports from EU have remained insignificant for Tungsten oxide and hydroxide (Figure 7).

China, USA and Vietnam have been the main supplier of Tungsten oxide and hydroxide to EU (Figure 8). Post COVID, USA and Vietnam have emerged as top suppliers as import from China has not recovered yet from the pandemic level. Import and export figures for Tungsten powder has been falling since 2013 and has not seen any recovery yet. It is expected to continue having a falling trend.

Wolframates content are imported primarily from China and Vietnam. Import demand have experienced a fall since 2016 and have stabilised in last few year. Export figures have seen a rise since 2019, signalling an increased domestic production capacity for the raw material (Figure 9 and Figure 10).

Tungsten Carbide has seen a post COVID recovery in the past one year. China, US and South Korea are the major suppliers to EU. Export figures have also seen appreciation in last one year which is an indication of improvement in domestic supply for the raw material (Figure 13 and Figure 14).

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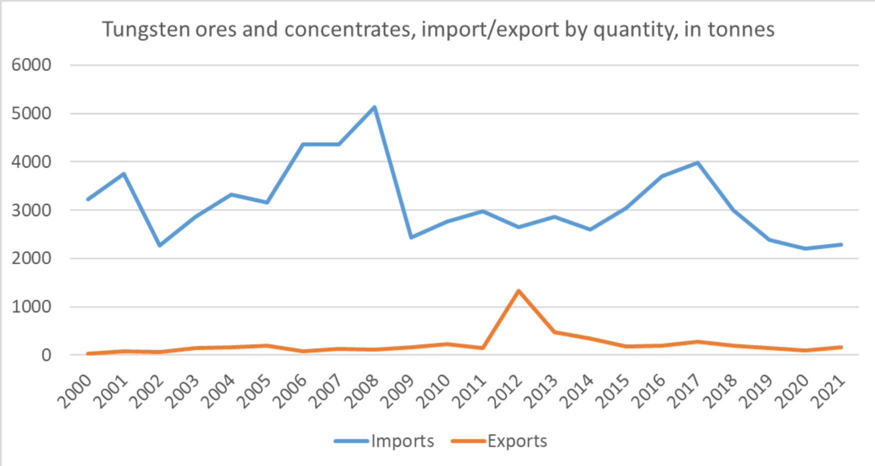

Figure 5. EU trade flows of Tungsten ores and concentrates (CN 26110000) from 2000 to 2021 (Eurostat, 2022)

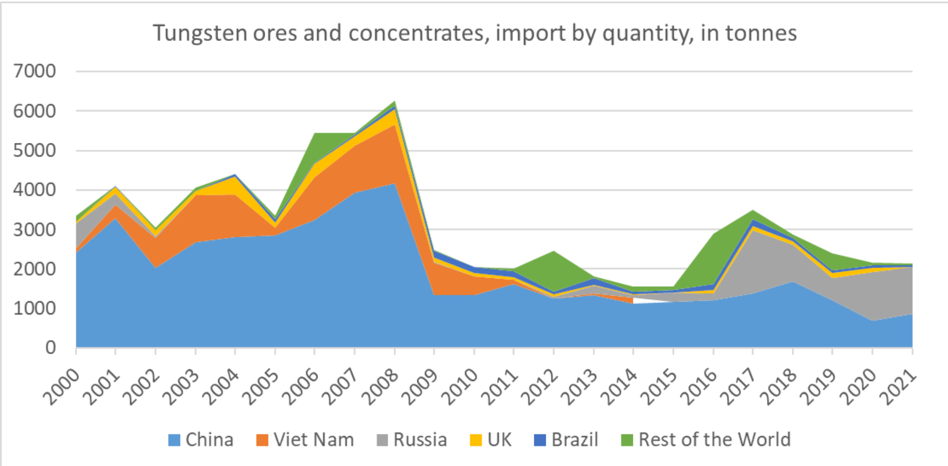

Figure 6. EU imports of Tungsten ores and concentrates (CN 26110000) by country from 2000 to 2021 (Eurostat, 2022)

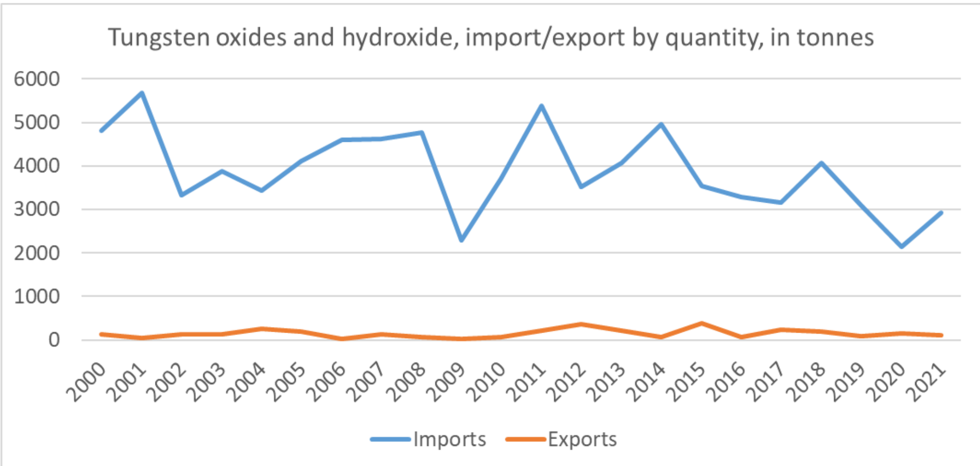

Figure 7. EU trade flows of Tungsten oxides and hydroxide (CN 28259040) from 2000 to 2021 (Eurostat, 2022)

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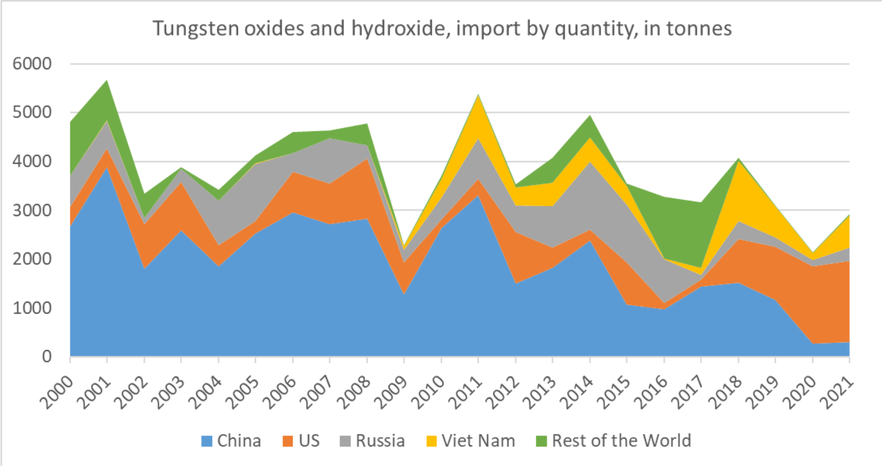

Figure 8. EU imports of Tungsten oxides and hydroxide (CN 28259040) by country from 2000 to 2021 (Eurostat, 2022)

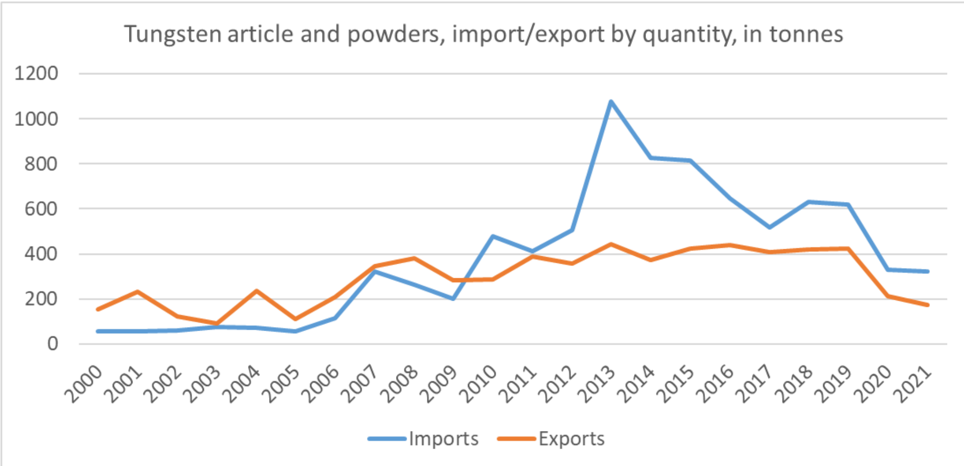

Figure 9. EU trade flows of Tungsten article and powders (CN 26110000) from 2000 to 2021 (Eurostat, 2022)

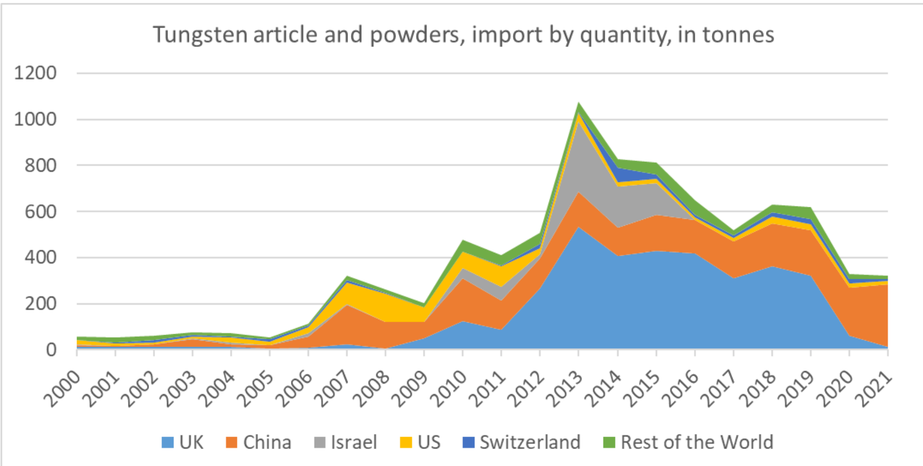

Figure 10. EU imports of Tungsten article and powders (CN 26110000) by country from 2000 to 2021 (Eurostat, 2022)

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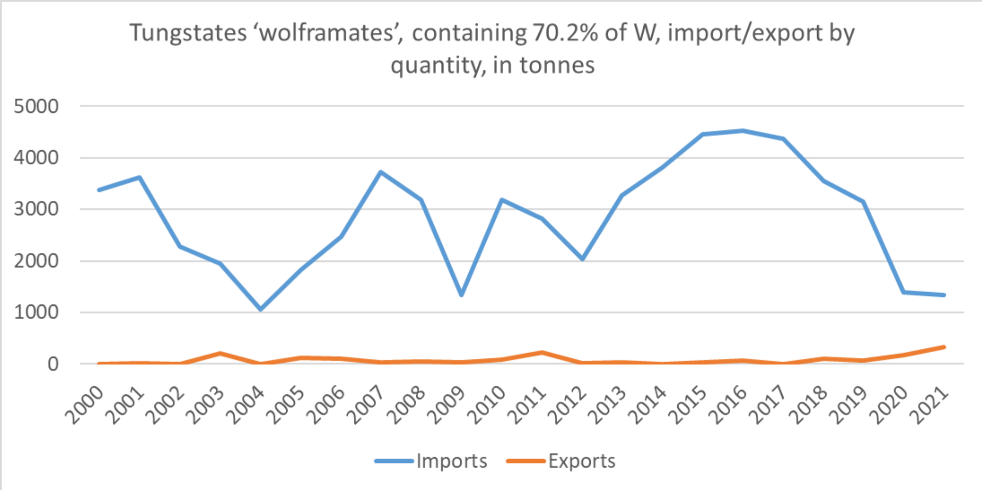

Figure 11. EU trade flows of Tungsten 'wolframates' (CN 28418000 from 2000 to 2021 (Eurostat, 2022)

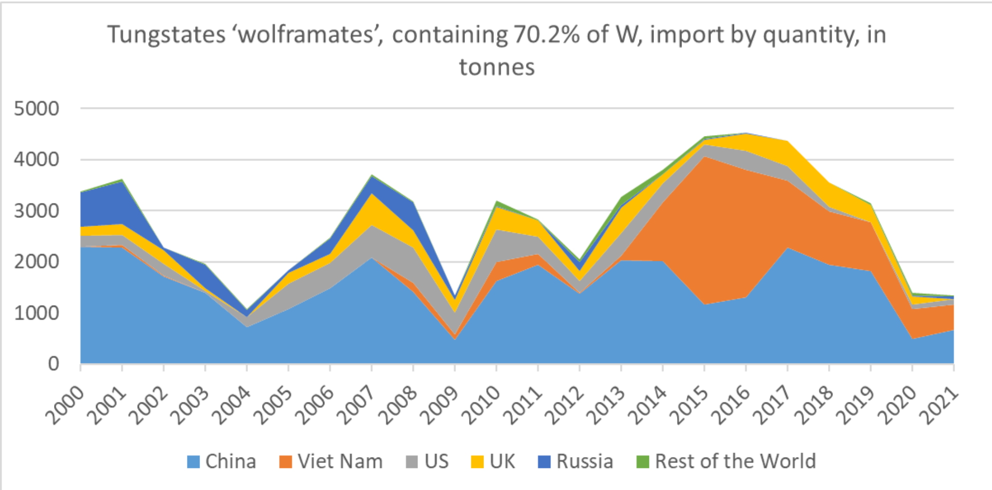

Figure 12. EU imports of Tungsten 'wolframates' (CN 28418000) by country from 2000 to 2021 (Eurostat, 2022)

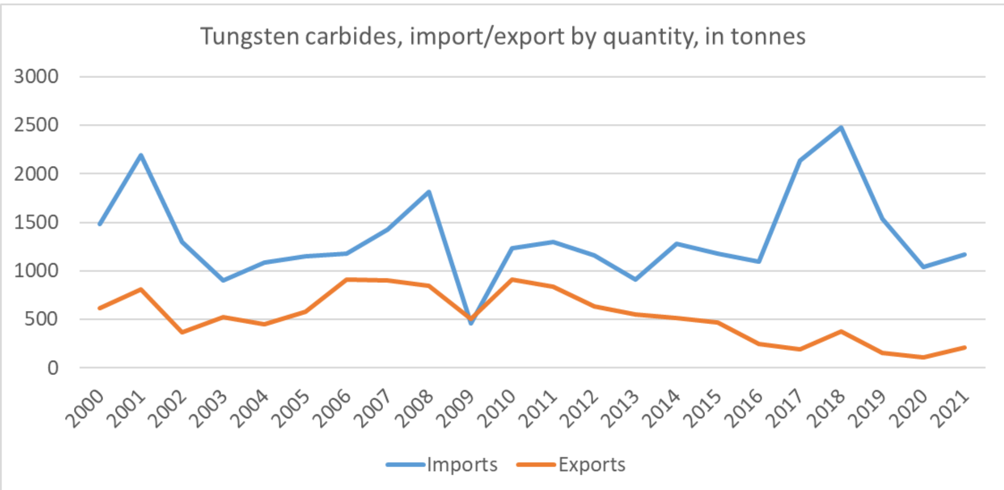

Figure 13. EU trade flows of Tungsten carbide (CN 28499030) from 2000 to 2021 (Eurostat, 2022)

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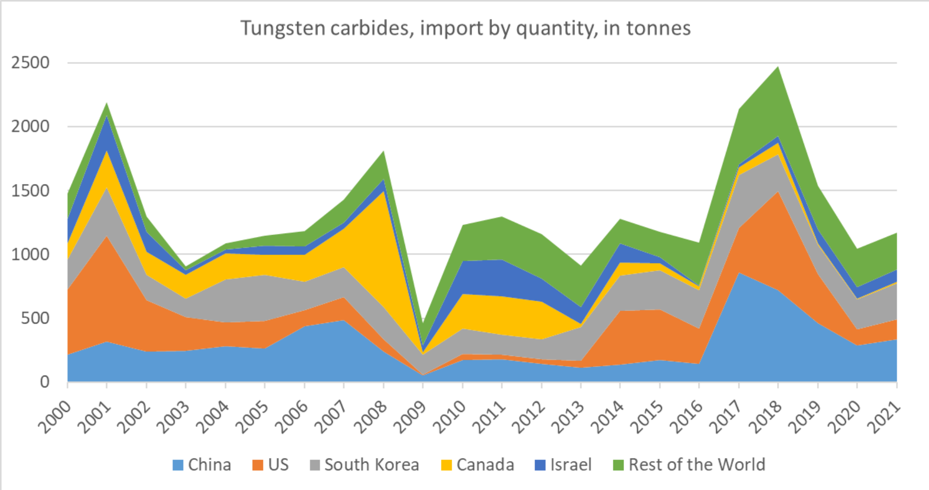

Figure 14. EU trade flows of Tungsten Carbide (CN 28499030) from 2000 to 2021 (Eurostat, 2022)

PRICE AND PRICE VOLATILITY

Average tungsten prices have appreciated consistently since early 2000 till 2011. In the first half of the decade starting from 2010 prices experienced a fall reaching lowest value by 2016. The fall in value around 2015 – 16 was due to economic turmoil in China. Price recovered temporarily after falling again due to COVID (Figure 15). In the future, price is expected to appreciate as its demand outlook remain strong for the upcoming decade.

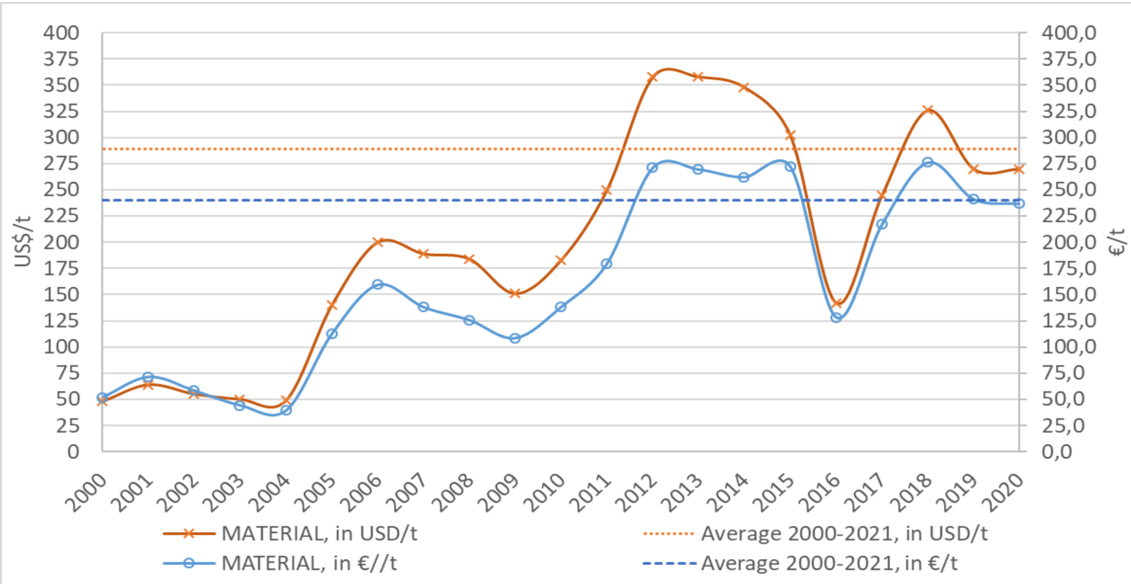

Figure 15. Annual average price of tungsten between 2000 and 2020, in US$/t and €/t[3]. Dash lines indicate average price for 2000-2020 (USGS, 2022b)

[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

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OUTLOOK FOR SUPPLY AND DEMAND

Growing end use industries such as automotive, aerospace and electrical and electronics and increase in the demand of wear resistant materials is expected to drive the global tungsten market. Tungsten is used in electronic and electrical components such as electron emitters, lead-in wires and electrical contacts leading to the increase in the global tungsten market. China, the world second largest economy, is forecast to reach an estimated market size of 67.5 thousand tonnes in the year 2026 trailing a CAGR of 4.7%. Asia Pacific (APAC) is expected to account 71% of the market growth. Within Europe, Germany is forecast to grow at approximately 2.4% CAGR while Rest of European market (as defined in the study) will reach 70.8 thousand tonnes by 2026.

DEMAND

EU DEMAND AND CONSUMPTION

The EU's average annual demand for tungsten (concentrates and all tungsten products) over the period 2016-2020 was estimated at 17,273 tonnes per year (of W content). The EU's demand was higher, at 22000 tonnes in 2017, by far the highest since the global economic crisis in 2009 (ITIA, 2019). In the period of 2016-2020, the EU's demand represents about 20% of the world production, and is the second market after China (that consumes half of the tungsten available worldwide). This went down to 10900 tonnes in 2020 due to COVID pandemic.

Tungsten extraction stage EU consumption is presented by HS code CN 26110000 Tungsten ores and concentrates. Import and export data is extracted from Eurostat Comext (2022), but it is corrected for 2016-2020 by experts with confidential wolfram data. Production data is extracted from Eurostat Prodcom (2022).

Tungsten processing stage EU consumption is presented by HS codes CN 28259040 Tungsten oxides and hydroxides, CN 28418000 Tungstates "wolframates", CN 28499030 Carbides of tungsten, whether or not chemically defined, CN 72028000 Ferro-tungsten and ferro-silico-tungsten and CN 81011000 Tungsten powders. Import and export data is extracted from Eurostat Comext (2022), but it is corrected for 2016-2020 by experts with confidential wolfram data. Production data is extracted from Eurostat Prodcom (2022).

Knowing that the EU production of tungsten is about 2100 tonnes per year and the EU demand about 17300 tonnes, the average import reliance of tungsten is about 88% for 2016-2020.

(https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html)

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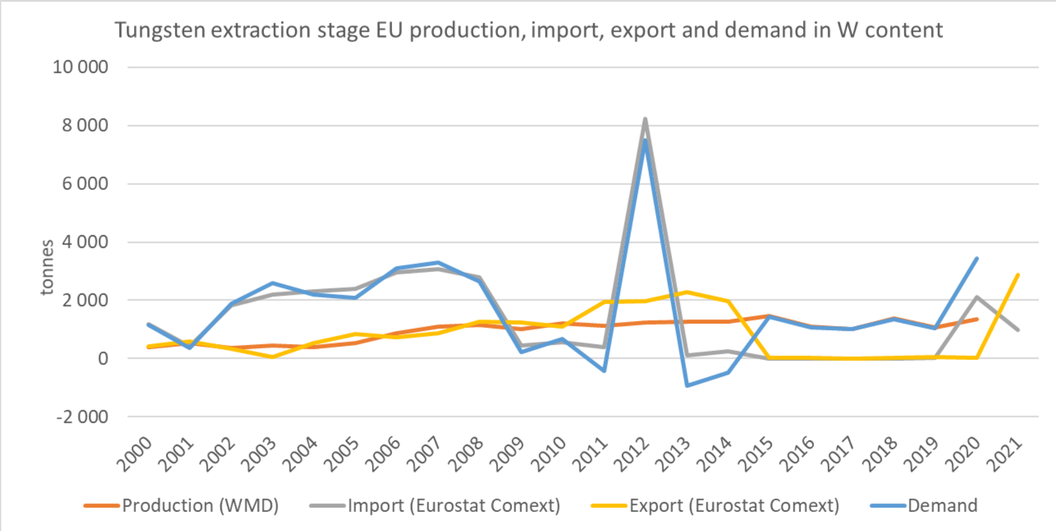

Figure 16. Tungsten (CN 26110000) processing stage apparent EU consumption. Production data is available from WMD (2022). Consumption is calculated in W content (EU production+import-export).

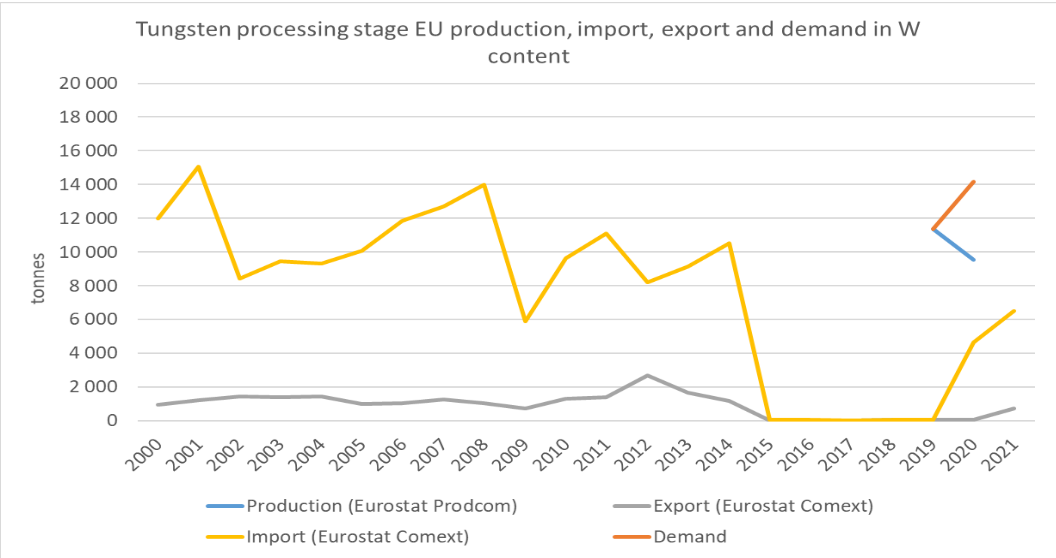

Figure 17. Tungsten (CN 28259040, CN 28418000, CN 28499030, CN 72028000, CN 81011000) processing stage apparent EU consumption. Production data is available from Eurostat Prodcom (2022) for 2008-2020. Consumption is calculated in W content (EU production+import-export).

GLOBAL AND EU USES AND END-USES

- Due to its exceptional physical properties, tungsten is used for a wide range of applications.
- The largest share is used to produce cemented carbides.
- The rest is used for fabricated products, alloy steels, super alloys and tungsten alloys. Most tungsten is used for hard metals, whose main component is tungsten carbide (WC). They are characterized by high wear resistance even at high temperatures. Therefore, hard metals are used for cutting and drilling tools.

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- Similar properties arise from the addition of tungsten to steel. The widest range of applications is represented by tungsten alloys. They are used in lighting technology, electrical and electronic technology, high-temperature technology (e.g. furnaces, power stations), welding, spark erosion, space travel and aircraft devices, armaments and laser technology.

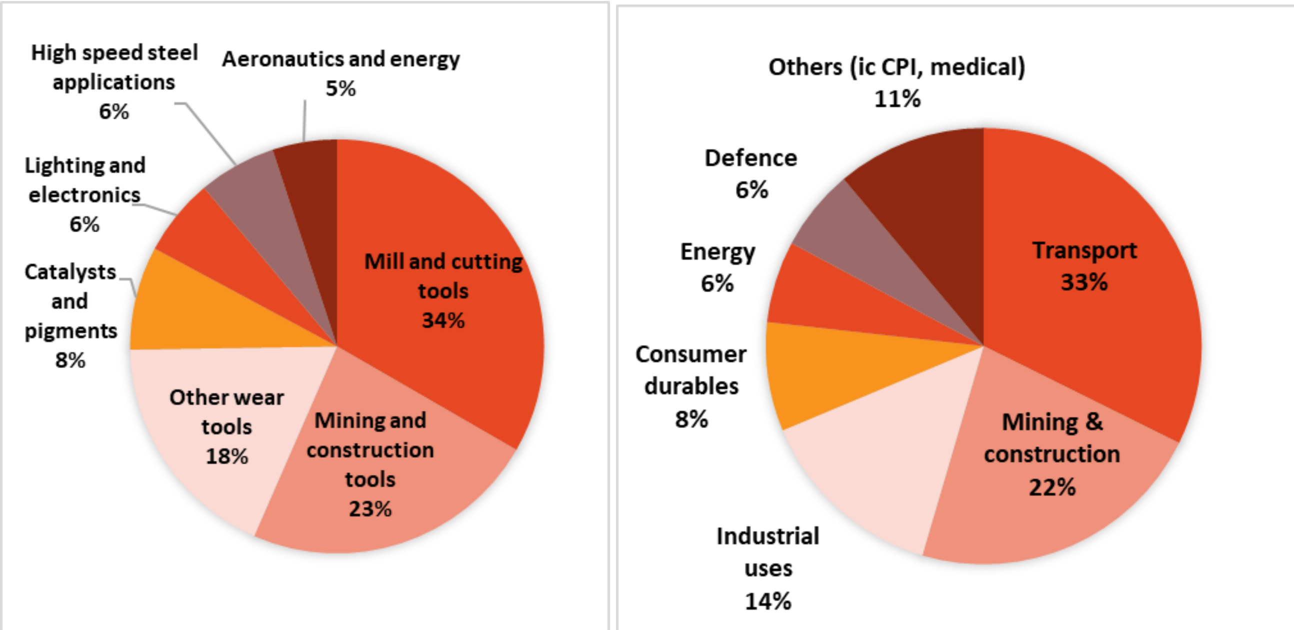

Figure 18: LEFT: End uses of tungsten EU 27, 2012-2016 (SCRREEN, 2019). RIGHT: Global end uses of tungsten, varied date ranges from 2016-2022 (EC CRM Data 2023.

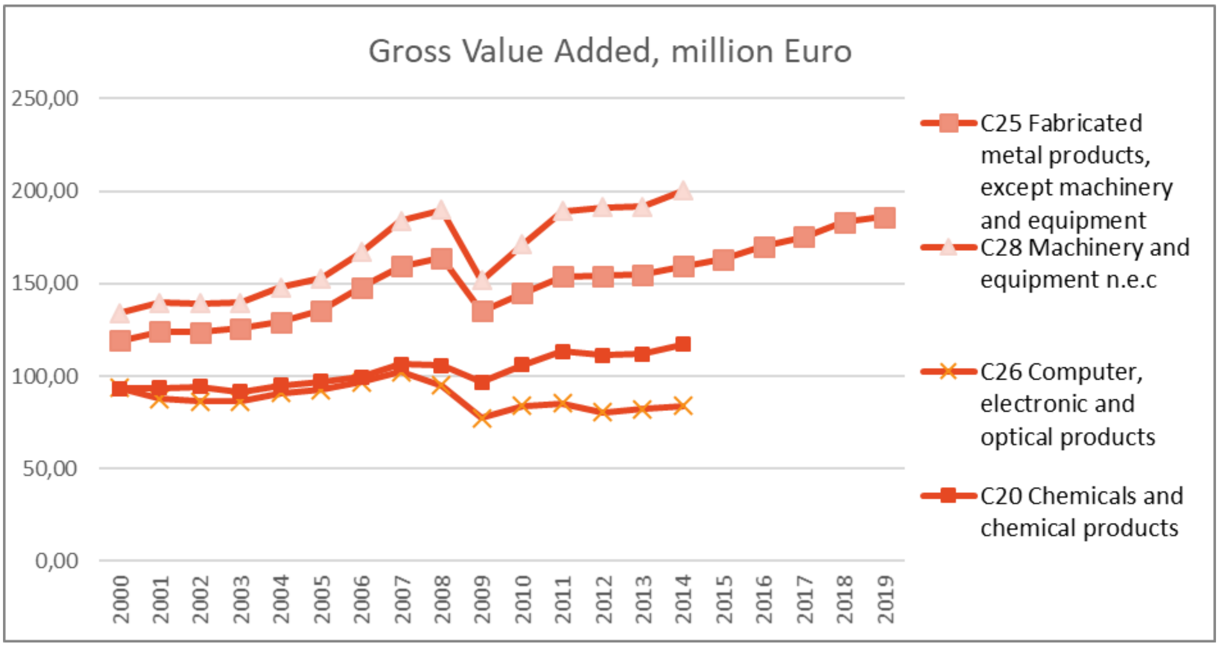

Figure 19: Value added per 2-digit NACE sector over time (Eurostat, 2022)

Relevant industry sectors are described using the NACE sector codes (Eurostat, 2022), presented in Table 4.

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Table 4. Tungsten applications, 2-digit and associated 6-digit NACE sectors, and value added per sector (Eurostat, 2022)

Applications	2-digit NACE sector	Value-added of sector (millions €)	Examples of 4-digit NACE sector
Mill and cutting tools	C28 - Manufacture of machinery and equipment n.e.c	200,138	C2841- Manufacture of metal forming machinery
Mining and construction tools	C28 - Manufacture of machinery and equipment n.e.c	200,138	C2892- Manufacture of machinery for mining, quarrying and construction
Other wear tools	C28 - Manufacture of machinery and equipment n.e.c	200,138	C2849- Manufacture of other machine tools
Catalysts and pigments	C20 - Manufacture of chemicals and chemical products	117,150*	C2012- Manufacture of dyes and pigments; C2059- Manufacture of other chemical products n.e.c.
Lighting and electronic uses	C26 - Manufacture of computer, electronic and optical products	84,074*	C2611- Manufacture of electronic components
High speed steels applications	C25 - Manufacture of fabricated metal products, except machinery and equipment	186,073	C2562- Machining
Aeronautics and energy uses	C28 - Manufacture of machinery and equipment n.e.c.	200,138	C2811- Manufacture of engines and turbines, except aircraft, vehicle and cycle engines; C2812- Manufacture of fluid power equipment; C3030- Manufacture of air and spacecraft and related machinery C2562- Machining

The end-use of tungsten has not changed greatly from the previous assessment. The tungsten consumed in the EU for the manufacture of the following products (Bio Intelligence Service, 2015; SCRREEN, 2019 and 2022)

TOOLS – MILLS & CUTTING, MINING & CONSTRUCTION

- 67% of tungsten consumed in the EU is used for the manufacture of tungsten carbides.
- Tungsten cemented carbides, or hard metals, are materials made by "cementing" very hard tungsten monocarbide grains in a binder matrix of a tough cobalt or nickel alloy by liquid phase sintering. Cemented carbides combine high hardness and strength with toughness and plasticity.
- Tungsten carbide is the most metallic of the carbides, and by far the most important hard phase. Due to those characteristics, tungsten carbides are used in mill and cutting tools, as well as in mining and construction tools.
- Other tools (wear resistance, mirrors, forming tools) are made of tungsten carbides.

LIGHTING AND ELECTRONICS INDUSTRY

- 11% of tungsten consumed in the EU is used for the manufacturing of tungsten metal.
- Tungsten metal is used for the manufacture of fabricated products in the lighting and electronic industry. The lamp industry covers incandescent bulb filament containing tungsten, compact fluorescent lamps, and high intensity discharge lamp (HIDs).

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- In the electronic & electrical industry, tungsten metal is used as an electron emitter in integrated circuits, and in X-ray tubes.

STEEL PRODUCTION

- 8% of tungsten consumed in the EU is used for the manufacturing of tungsten containing steels.
- Tungsten steel refers to any steel alloy that includes tungsten as an alloying element.
- This provides the steel with enhanced hardness, strength, wear resistance, toughness, heat resistance and corrosion resistance.

OTHER USES

- 11% of tungsten consumed in the EU is used for the manufacturing of chemical applications.
- 3% of tungsten consumed in the EU is used for the manufacturing of tungsten alloys.
- Tungsten products are widely used in the automotive industry, particularly in tooling and die cast applications.
- Tungsten's high-thermal conductivity and ability to maintain superior physical properties even at extreme temperatures make it ideal for die casting, extrusion, and other high-temperature tooling applications.

SUBSTITUTION

Substitutes have been identified for the applications of tungsten.

Table 5: Substitution options for tungsten by application (SCRREEN Validation Workshop, 2022; EC Data 2023 files). USGS 2022.

Application	%*	Substitute(s)	SubShare	Cost	Performance
Mill and cutting tools	33%	Molybdenum in molybdenum carbide	15%	Similar or lower costs	Reduced
		Silicon in ceramic-metallic composites (cermets)	10%	Similar or lower costs	Reduced
		Zirconium in ceramics	1%	Similar or lower costs	Reduced
		Aluminium in ceramics	1%	Similar or lower costs	Reduced
		Diamond	1%	Very high costs (more than 2 times)	Similar
		Cubic Boron-nitrate	1%	Similar or lower costs	Reduced
		Gold	1%	Very high costs (more than 2 times)	Similar
		Rhenium	1%	Very high costs (more than 2 times)	Reduced
		Tantalum	1%	Very high costs (more than 2 times)	Reduced
		Titanium carbides (TiC)	0%	Very high costs (more than 2 times)	Similar

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		Niobium Carbide	0%	Similar or lower costs	Reduced
		Vanadium Carbide	0%	Similar or lower costs	Reduced
		Titanium nitride (TiN)	0%	Very high costs (more than 2 times)	Similar
		Titanium carbonitride (TiCN)	0%	Very high costs (more than 2 times)	Similar
Mining and construction tools	23%	Molybdenum in molybdenum carbide	5%	Similar or lower costs	Reduced
		Silicon in ceramic-metallic composites (cermets)	10%	Similar or lower costs	Reduced
		Zirconium in ceramics	1%	Similar or lower costs	Reduced
		Aluminium in ceramics	1%	Similar or lower costs	Reduced
		Diamond	1%	Very high costs (more than 2 times)	Similar
		Cubic Boron-nitrate	1%	Similar or lower costs	Reduced
		Gold	1%	Very high costs (more than 2 times)	Similar
		Rhenium	1%	Very high costs (more than 2 times)	Reduced
		Tantalum	1%	Very high costs (more than 2 times)	Reduced
		Titanium carbides (TiC)	0%	Very high costs (more than 2 times)	Similar
		Niobium Carbide	0%	Similar or lower costs	Reduced
		Vanadium Carbide	0%	Similar or lower costs	Reduced
		Titanium nitride (TiN)	0%	Very high costs (more than 2 times)	Similar
		Titanium carbonitride (TiCN)	0%	Very high costs (more than 2 times)	Similar
Other wear tools	18%	Molybdenum in molybdenum carbide	15%	Similar or lower costs	Reduced
		Silicon in ceramic-metallic composites (cermets)	10%	Similar or lower costs	Reduced
		Zirconium in ceramics	1%	Similar or lower costs	Reduced
		Aluminium in ceramics	1%	Similar or lower costs	Reduced
		Diamond	1%	Very high costs (more than 2 times)	Similar
		Cubic Boron-nitrate	1%	Similar or lower costs	Reduced
		Gold	1%	Very high costs (more than 2 times)	Similar
		Rhenium	1%	Very high costs (more than 2 times)	Reduced
		Tantalum	1%	Very high costs (more than 2 times)	Reduced
		Titanium carbides (TiC)	0%	Very high costs (more than 2 times)	Similar
		Niobium Carbide	0%	Similar or lower costs	Reduced

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		Vanadium Carbide	0%	Similar or lower costs	Reduced
		Titanium nitride (TiN)	0%	Very high costs (more than 2 times)	Similar
		Titanium carbonitride (TiCN)	0%	Very high costs (more than 2 times)	Similar
Catalysts and pigments	8%	Not assessed, below 10%			
Lighting and electronic uses	6%	Not assessed, below 10%			
High speed steels applications	6%	Not assessed, below 10%			
Aeronautics and energy uses	5%	Not assessed, below 10%			

Tungsten is typically the best choice of material. For its selected applications, due to its special performance. Accordingly, very low-performing substitution exists for this material in industry.

Potential substitutes for cemented tungsten carbides include cemented carbides based on molybdenum carbide, niobium carbide, or titanium carbide; ceramics; ceramic-metallic composites (cermets); and tool steels (USGS 2020). For tungsten carbide-based cemented carbides, substitution appears to be technically possible but implies higher costs and a decrease in performance in some cases. Titanium carbides TiC or TiC-M (M=Fe or Ni based alloys) and titanium nitride (TiN) are potential substitute but the technology is not competitive at the moment. Tungsten can be replaced by other refractory metals such as niobium (critical in 2020) or molybdenum in steel products. In other application areas, possible substitution of tungsten is affordable, for example super-alloys substituted by Ceramic Matrix Composites (CMCs) made from a silicon carbide/nitride matrix for gas turbine engines. Substitution with nanostructured n-alloys such as FeTa, could be possible in 10 years since current TRLs are very low (TRL 3-4). Substitution in the lighting sector is based on carbon nanotube filaments (USGS 2022).In power electronics packaging in aerospace applications (thermal management), tungsten from CuW can be substituted using carbon reinforced Metal Matrix Composites (MMC) (Cu, Al) micro/nano-scale powder mixes

FLAT DISPLAY SCREENS

- Indium-thin-oxide (ITO) is substitutable in LCDs by antimony-tin-oxide (ATO). However, antimony is also classified as critical raw material (European Commission 2020).
- For architectural glasses with low emissivity coating, ITO can be replaced by Fluorine-doped-thin-oxide (FTO).
- Smart window applications with double glazing (moisture protected) Aluminium-doped-Zinc-Oxide (AZO) or Zinc Oxide (ZnO) can be used instead of ITO.
- In thin film solar cells and flat panel displays, it is possible to use FTO or AZO as Transparent Conductive Oxide (TCO) instead of ITO, however not without a loss in performance with respect to conductivity and/or transparency.

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- AZO, FTO and ATO might represent together about 15% of the substitutions for ITO at the global level (ass validated at the SCRREEN2 Workshop, 2022).
- There is also competition between indium and "transparent carbon" nanotubes in the manufacture of glasses, and perhaps also in mass production of LCDs (Techniques de l'Ingénieur, 2022). Carbon nanotube coatings have been developed as an alternative to ITO coatings in flexible displays, solar cells, and touch screens.
- Poly(3,4-ethylene dioxythiophene) (PEDOT) has also been developed as a substitute for ITO in flexible displays and organic light-emitting diodes; and copper or silver nanowires have been explored as a substitute for ITO in touch screens.

PV CELLS

- Indium phosphide can be replaced by gallium arsenide in solar panels. However, gallium is also classified as critical raw material (European Commission 2020).
- CdTe or a-Si based thin film solar cells can be used instead of CIGS/CI Si based semiconductors in thin film solar cells (CIGS represents 1% of the installed capacity worldwide).

SOLDERS

- Tin-bismuth alloys can replace tin-indium alloys for low temperature bonding and soldering applications.
- Lead-based alloys can be used instead of indium and indium-tin alloys.
- Lead based solders are not used in the EU (there are a few exemptions) (SCRREEN2 Validation Workshop)

ALKALINE BATTERIES

- Indium is replacing mercury in zinc powders used in alkaline batteries (SCRREEN2 Validation Workshop)

SEMI-CONDUCTORS

- Silicon has largely replaced indium and germanium in transistors.
- No substitute for indium gallium nitride-InGaN in LEDs.
- In diodes, GaAs is possible to replace InP but not used or in some minor applications only. However, gallium is also classified as critical raw material (European Commission 2020).

OTHERS

According to USGS (2022):

- Carbon nanotube coatings have been developed to replace ITO coatings in flexible displays, solar cells, and touch screens;

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- Poly(3,4-ethylene dioxythiophene) (PEDOT) has been developed as an ITO substitute in flexible displays and organic light-emitting diodes.
- Graphene has been developed to replace ITO electrodes in solar cells.
- Hafnium can replace indium in nuclear reactor control rod alloys.

SUPPLY

EU SUPPLY CHAIN

Mining of W ores is performed currently at a small scale, at the range of few kt, in EU in Spain, Portugal and Austria (Eurostat, 2021). At processing stage, the EU also has the capacity to process tungsten ores and concentrates into tungsten-based products. ITIA identified at least two tungsten ores and concentrates processing facilities in the EU, one located in Austria and one located in Germany. While the EU demand for ammonium paratungstate (APT) and tungsten carbides is supplemented by imports, ferrotungsten is entirely supplied from imports. The EU production of tungsten at the refining/intermediates product stage, including ferro-tungsten, ferro-silico-tungsten alloys, carbides of tungsten and tungsten oxides and hydroxides was 18.7 kt in 2019 and 17.8 kt in 2020. The annual average amounts of imported and exported W products by EU during the period 2016-20120 were 23.7 kt and 7.4 kt, respectively. The imported W raw materials include concentrates and ores, oxides and metallic W powder. The recycling rate of W in EU is estimated at 42% (Eurostat, 2021). Recent figures from ITIA mentioned 8,800 tonnes of recycled tungsten generated in the EU in 2018 (ITIA, 2019).

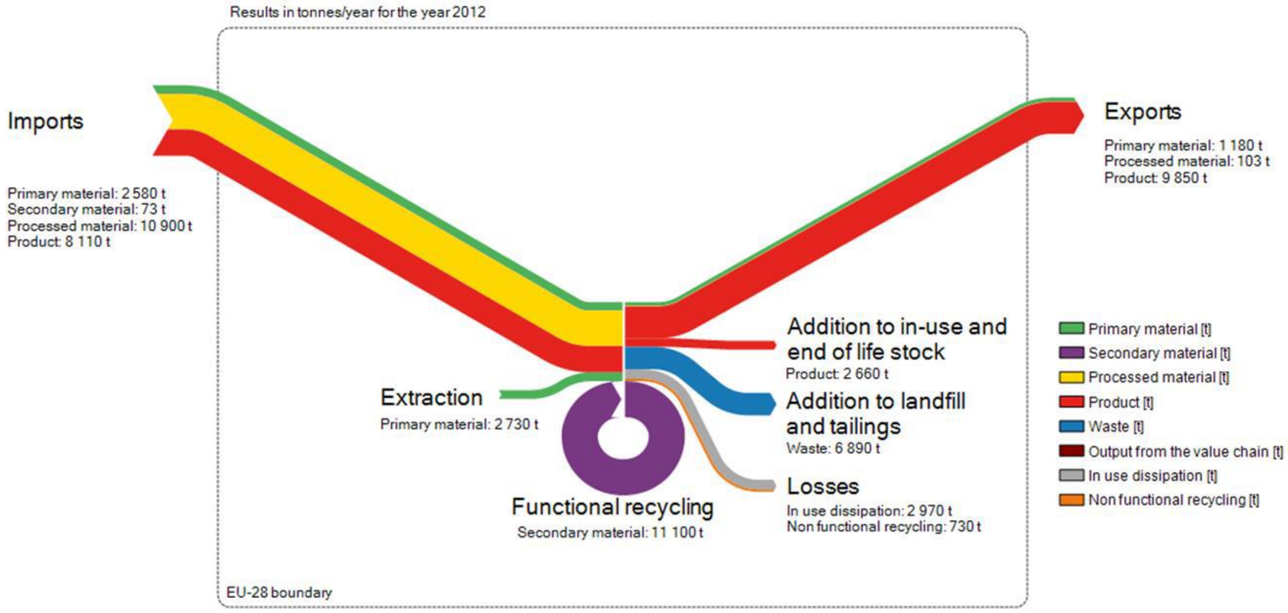

Figure 20: Simplified diagram of material system analysis of tungsten in the EU27+the UK, for the year 2012 (Bio Intelligence Service, 2015)

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SUPPLY FROM PRIMARY MATERIALS

GEOLOGY, RESOURCES AND RESERVES OF TUNGSTEN

GEOLOGICAL OCCURRENCE:

The average abundance of tungsten in the Earth's crust is estimated to be 1.25-1.50 ppm (BGS, 2011), and its concentration in the upper crust is 3.3±1.1 ppm (Rudnick, 2003). In nature, tungsten does not occur as free metal but in 45 different minerals, of which only two, wolframite and scheelite, have any economic importance. Tungsten minerals often occur as monotungstates, such as scheelite (calcium tungstate, $CaWO_4$), stolzite (lead tungstate, $PbWO_4$), and wolframite. Wolframite is a solid solution of ferberite (ferrous tungstate, $FeWO_4$) and hübnerite (manganous tungstate, $MnWO_4$) (BGS, 2011). Scheelite is the most abundant tungsten mineral and is present in approximately two-thirds of known tungsten deposits (BGS, 2011).

GLOBAL RESOURCES AND RESERVES:

World tungsten known resources are estimated at 7 million tonnes of contained tungsten metal (BGS, 2011; USGS, 2019). World tungsten resources are geographically widespread. Major tungsten deposits are located in China, Canada and Russia. Canada, Kazakhstan, Russia, and the United States also have significant resources (USGS, 2022).

According to USGS (2022), world known reserves of tungsten is estimated at 3.7 million tonnes of contained tungsten metal, with more than 51% of these located in China (Table 1).

Table 6: Global reserves of tungsten (Data source: USGS, 2021)

Country	Tungsten Reserves (tonnes of tungsten content)
United States	NA
Austria	10,000
Bolivia	NA
Canada	290,000
China	1,900,000
Portugal	5,100
Russia	400,000
Rwanda	NA
Spain	52,000
United Kingdom	51,000
Vietnam	100,000
North Korea	29,000
Other countries	1,200,000
World total	3,700,00

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EU RESOURCES AND RESERVES:

Resource information for Spain, Portugal, Poland, Slovakia, Czechia are available at Minerals4EU (2019) (see Table 2) but cannot be summed as they are partial and they do not use the same reporting code. About 500,000 tonnes of tungsten are contained in EU known resources according to the MSA study, estimated by contacting several geological survey in EU member states (Bio Intelligence Service, 2015). According to industry experts, there are more deposits known or ready to be developed in Europe, such as Hemerdon deposit (UK) that led to a mine opening in 2016, Barruecopardo (Spain) which has already financing in place, and some work is done at La Parilla (Spain) (Wolfram, 2016).

Table 7: Resource data for the EU compiled in the European Minerals Yearbook of Minerals4EU (Minerals4EU, 2019)

Country	Reporting code	Quantity	Unit	Grade	Code Resource Type
Spain	NI 43-101	615	kt	0.0032% WO_3	Measured
Portugal	NI 43-101	1495	Mt	0.55% WO_3	Indicated
Poland	Nat. rep. code	0.24	Mt	0.04% W	C2+D
Slovakia	none	2846	Mt	0.23% W	-
Czech Republic	Nat. rep. code	70.2	kt	0.8% W	Potentially economic

In the EU, an estimated of 80,000 tonnes of tungsten reserve were identified by several EU geological surveys (Bio Intelligence Service, 2015). Similarly to resource, quantitative information on tungsten reserve for some countries in Europe are available in the Minerals4EU website but cannot be summed as they are partial and they do not use the same reporting code.

To date, there has not been any new information referring to EU resources and reserves of tungsten at Minerals4EU (2019).

In 2018, Lauri et al. (2018) reported tungsten occurrences in the following EU member states:

- Austria: an estimated quantity of 24,000 tonnes of tungsten resources was reported at the Mittersill mine
- Finland: 17 occurrences with tungsten as main commodity and 6 occurrences with tungsten as minor commodity were listed in the FODD database. Four deposits have a non-compliant resource estimate of 2,333 tonnes of tungsten metal
- France: 15 tungsten deposits with an estimated resource quantity of 66,000 tonnes and 100 occurrences without resources data.
- Greece: One medium-sized tungsten deposit with a non-compliant resource of 6,000 tonnes of tungsten.
- Portugal: The resources (including reserves) at Panasqueira mine were estimated to be 27,240 tonnes of tungsten at the end of 2016. At S. Pedro da Águias (Tabuaço), there is an indicated resource of 0.76 Mt with 0.58 % WO_3 and inferred 1.33 Mt at 0.57% WO_3, accounting for a total estimate of 9,500

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tonnes of tungsten content. The ProMine database lists eight closed tungsten mines for Portugal; jointly these are reported to contain resources of nearly 40,000 t W. In addition, there are six tungsten occurrences without resource data in the ProMine database.

- Spain: A total resource of 15,334 tonnes of tungsten metal was estimated at Los Santos and 15,400 tonnes fo Valtreixal in 2015. In addition, an estimated of 21,800 tonnes of tungsten resources, 15 closed mines and other occurrences without resource information were listed for Spain in ProMine database.
- Sweden: Non-compliant resource estimates are available for three W occurrences that have not been exploited. Two of these give information on the tungsten content of the ore, with a total of 2.1 Mt of tungsten-bearing ore at 0.2 % of W.
- Bulgaria, Czechia, Germany, Ireland, Italy: occurrences of tungsten were reported with no available information on the resource quantity.

Taking into account the upper presented resources of tungsten in EU, specific attention should be given to the exploitation of Portuguese resources. Portugal is one of the main tungsten producers in Europe, generating about 121 kt of contained tungsten in mineral concentrates from 1910 to 2020, corresponding to the ≈3.3% of the global production documented for the same time period. According to forecast studies, there is a significant future potential for increasing production in Portugal due to the low (<2%) depletion rates of the remaining known tungsten resources (≈141 kt) globally. Portuguese reserves are currently estimated at 5.4 kt of contained tungsten in wolframite-dominant mineral concentrates, accounting for 0.16% of the world reserves (3.4 Mt) in Panasqueira, Borralha and Vale das Gatas localities. Concerning tungsten resources in Portugal, these are estimated at 141 kt, representing 2% of the tungsten world resources (7 Mt) (Mateus et al. 2021).

WORLD AND EU MINE PRODUCTION

Mining of tungsten is performed through both open-pit mining and underground mining. The ore from mine is crushed and milled, and then upgraded by means of gravity enrichment or flotation. For commercial trading 65-75% WO_3 content is required for further refining (European Commission, 2014). The ore beneficiation allows to increase the tungsten content of the concentrate up to 65-75% WO_3, which can be (BGS, 2011):

- directly used for production of ferrotungsten or steel manufacture, or
- converted by hydrometallurgy into intermediate tungsten compounds (APT or tungsten oxides), or
- further refined by pyrometallurgy into pure tungsten (metal, carbide, alloys, etc.).

Figure 21 and Figure 22 present the global mining production of tungsten ores since 1984 and since 2000 according to WMD and USGS, respectively (WMD, since 1984, USGS, since 2000). China is by far the largest W producer representing over the 79% of the global production for 2020. Vietnam, Russia and Bolivia are notable producers representing cumulatively the 13% of the global production. To provide the domestic industry with a target and to manage the country's natural resources in a way to balance supply and demand, China imposed a tungsten mining quota in 2002. Since the introduction, the amount of the quota has increased from 43,700 t concentrate of 65% WO_3 in 2002 to 100,000 t in 2018 (ITIA, 2019). However, despite the quota, Chinese production has been stable from 2012 to 2016.

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From 2014, Vietnam went from a medium-scale to the world's second largest producer of tungsten concentrates outside China by the opening of the Nui Phao mine in 2013 (about 4000 tonnes in 2014 and more in 2016). In contrast, Canada will be "zero" from 2016 onwards, due to the closure of the Cantung mine in late 2015 (Wolfram, 2016).

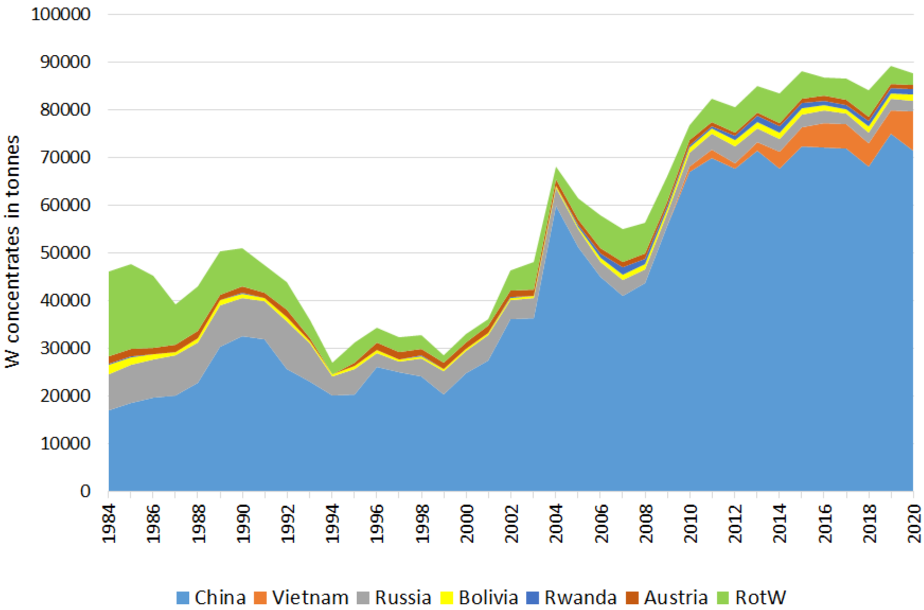

Figure 21: Global primary tungsten production since 1984 according to WMD data (WMS, since 1984).

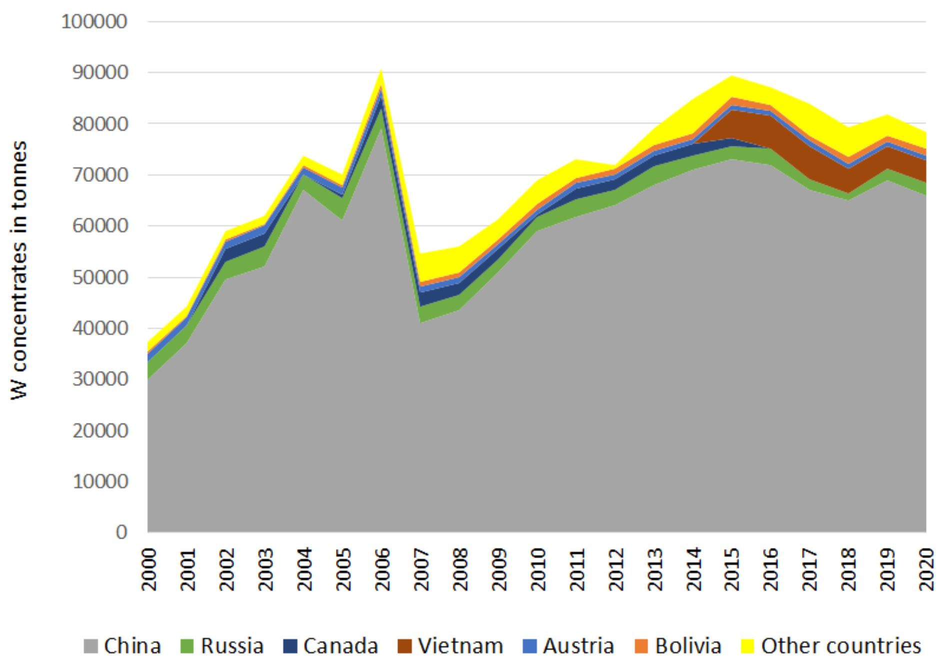

Figure 22: Global primary tungsten production since 2000 according to USGS data (USGS, since 2000).

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Tungsten extraction in the EU is exclusively located in Austria, Portugal and Spain and represents around 2,120 tonnes of tungsten content, i.e 3% of the global extraction (Figure 23).

In 2016, a tungsten mine in England was opened. Due to a combination of technical problems and depressed prices, this mine stopped in late 2018 and will likely not be producing in the foreseeable future. The Los Santos mine in Spain ceased mining in 2019, but minor production is maintained by retreating old tailings. In total, this accounts for a loss of over 4000 t of (planned) production in Europe (Eurometaux, 2019).

The concentrate facility of Barruecopardo mine (Salamanca), Spain, formerly active until 1991, obtained a licence to operate in September 2019. The first WO_3 production is expected to be put on the market in 2019. A new project in Spain, owned by Valtreixal Resources Spain, SL (Almonty Group), has recently obtained a research permit, and currently conducting a Environmental Impact Assesement (Marchan, 2019).

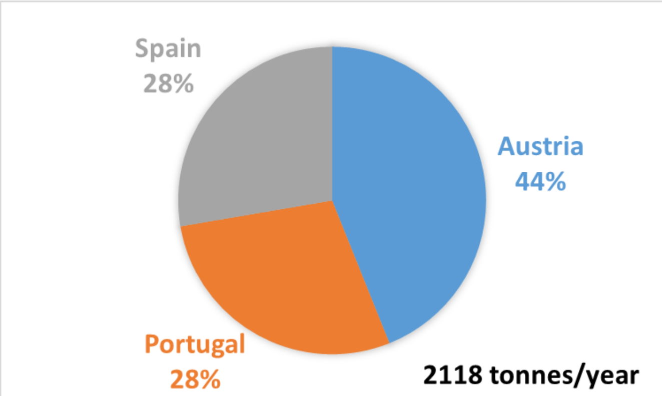

Figure 23: EU mine production of tungsten ores and concentrates in tonnes and percentage. Average for the years 2016-2020. (WMD, 2022)

OUTLOOK FOR SUPPLY

In 2021, prices of tungsten concentrates, scrap, and downstream tungsten materials trended upward in response to strong demand, constrained spot supplies of ammonium paratungstate and concentrates, reduced scrap availability, and low inventory levels (USGS, 2022). Concerns about its supply security have been raised by various studies in literature, mostly due to trade disputes arising from supply concentration and exports restrictions in China and its lack of viable substitutes. More intensive exploitation of W secondary resources is proposed an alternative action for the supply increase. Tungsten metal scrap is the only secondary source for this metal so far. However, reprocessing of tungsten tailings may also become important in the future. Enhanced gravity separation, wet high-intensity magnetic separation, and flotation have been reported to be successful in reprocessing tungsten tailings. In 2020, the world's tungsten mine production exceeded 80 kt of tungsten, with known tungsten reserves of 3400 kt. On the other hand, old tungsten tailings deposits may have great potential for exploration. The incomplete statistics indicate about 96 kt of tungsten content in those deposits, with an average grade of 0.1% WO_3 (in comparison typical grades of 0.3–1% in primary deposits) (Han et al. 2021).

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SUPPLY FROM SECONDARY MATERIALS/RECYCLING

Secondary tungsten can be found in two main types of sources: in waste from processed materials (intermediates as ferrotungsten and APT) as well as in manufacturing residues (W cemented carbide, W metals, ...) and end-of-life products from urban mines (Sundqvist Oeqvist L., SCRREEN 2018). Tungsten scrap, due to its high tungsten content (40–95%) in comparison to ore (around 0.4–0.6%), is a very valuable source.

RECYCLING RATES

Based on studies performed by the International Tungsten Industry Association (ITIA) (Zeiler B., ITIA, 2018), the global input for production of intermediates of tungsten was 108,500 t for the year 2016 from which 37,500 t were scrap (new and old scrap) which results in a recycling input rate (RIR) of 35%. 98,000 t of tungsten were consumed in end-use products and based on the estimate for old scrap generated (29,000 t) an end-of-life recycling rate (EoL-RIR) of 30% can be calculated. Tungsten carbide (WC) products are, by far, the most common forms of tungsten semi-finished products (about 65% of all tungsten products), and the current global rate of tungsten recycling from tungsten carbide products is 46%. For tungsten-containing steels and superalloys, the global recycling rate of tungsten is estimated at 15%, for W-metal products, it is rather low at 22%, and finally, for chemicals and others, a very small global recycling rate of 5% is estimated.

The recycling activities inside EU have considerably increased since the global economic crisis in 2009. Based on the material flow analysis performed in the MSA study, a 42% EoL-RIR has been estimated, mainly from cemented carbide scrap (Ladenberger A., 2018). This is consistent with the estimation that nearly half of the tungsten contained in the total EU production of semi-finished products in Europe is recycled (Bio, 2015).

RECYCLING TECHNOLOGIES

A wide variety of recycling technologies for tungsten exists today and can be divided into three main groups (Figure 24): direct recycling, chemical recycling and melting metallurgy (Zeiler B., 2019 and 2021). Some of them cover a big share of tonnage recycled today, others are more exotic and limited to special fields of applications.

DIRECT RECYCLING

One of the main recovery techniques for secondary tungsten is the “zinc process”. It is mainly used in EU for recovery of tungsten in cemented carbide which comprises 70% of all tungsten used in Europe (Kurylak, 2016). This process involves exposing tungsten carbide scrap to molten zinc and zinc vapour in the presence of argon or nitrogen at furnace temperatures of 800 °C to 1050 °C for a prolonged duration of time. The zinc is then distilled off and what is left behind is a spongy metallic material that can be crushed and milled. The chemical composition of the reclaimed carbide is almost identical to the original. About 30% of hard scrap is recycled through the zinc method in the US and Europe.

Other direct techniques of tungsten recycling exist including mechanical pulverization of the scrap in high pressure and velocity stream of air (up to twice the speed of sound) to cause fracture. This process is known

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as The Coldstream Process (Zeiler B., 2021). Direct recycling can also be performed by oxidation-reduction of cemented carbide scrap and heavy metals turnings (composed of W-NiFe, W-NiCu and W-NiCo), at high temperature (800 °C to 1000 °C).

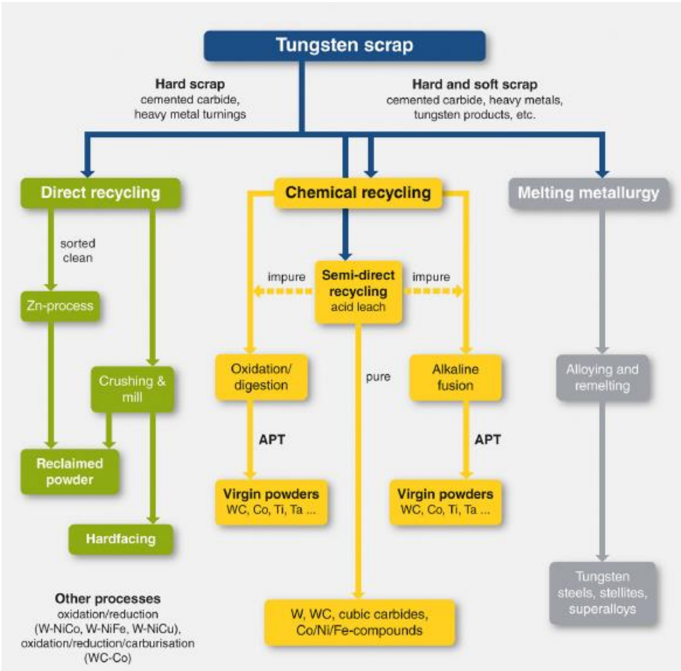

Figure 24: Overview of the most important recycling technologies for secondary tungsten (from Zeiler B., 2021)

CHEMICAL RECYCLING

The majority of tungsten scraps can be chemically recycled to obtain high purity starting materials for the modern powder metallurgical (PM) industry. The recovery processes are based on alkaline fusion or oxidation and alkaline digestion. The alkaline fusion route is carried out at high temperature (commonly between 550 ◦C–800 ◦C) with sodium nitrite or sodium nitrate as oxidising agent and sodium carbonate and/or sodium hydroxide as flux and diluent. Sodium tungstate is the desired reaction product, which is leached in hot water and the solution is filtered. The oxidation and alkaline method consists of two steps: oxidisation in air to form a mixture of tungsten oxide and tungstates, followed by a digestion of the oxidation product in an aqueous solution of sodium hydroxide under controlled conditions of temperature and pressure. The tungsten-bearing solution is filtered and the filter residue contains valuable concentrates of scrap attendants such as Co, Ni, Cu and Ta, which are converted into high-purity materials. Finally, high purity virgin W and WC powders are obtained. Compared to direct recycling, chemical recycling consumes more energy and chemicals but it is suitable for the widest variety of tungsten scrap compositions.

MELTING METALLURGY

Melting metallurgy is the process route for tungsten steels and superalloys. Scrap is added directly to a new steel charge.

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RESEARCH PROJECTS FOR EOL PRODUCTS RECYCLING

Several research projects to recover tungsten from EoL products have been developed in the EU, for example:

- Recovery of tungsten from spent selective catalytic reduction (SCR) catalysts used in chemical industry (Kurylak W., 2016)
- Recovery of tungsten from wastewater of Printed Circuit Boards (PCB). Although used in minor quantities, tungsten can be traced in PCB by emulsion liquid membrane (ELM) commonly used to separate metal ions and also hydrocarbons or biological compounds. The technology is still at early stage of development, but the tests results has shown that the separation of W from wastewater is possible (Sundqvist Oeqvist L., SCRREEN 2018).
- Besides, considerable attempts have been put into the development of the electrodissolution processes to recycle different varieties of WC scraps (Katiyara P.K., 2020).

PROCESSING OF TUNGSTEN

Tungsten extractive metallurgy is based on the synthesis of the intermediate product ammonium paratungstate (APT) [$(NH_4)_{10}(H_2W_{12}O4_2)\cdot 4H_2O$] through leaching, digestion and crystallization of the two main W minerals, wolframite and scheelite (Figure 25). Alternatively, and more widely in the western world, APT is produced through a processes that involves solvent extraction (Figure 26). APT is then calcined to WO3, while finally W metallic powder is produced by the oxide reduction with carbon or hydrogen (Shen et al., 2019).

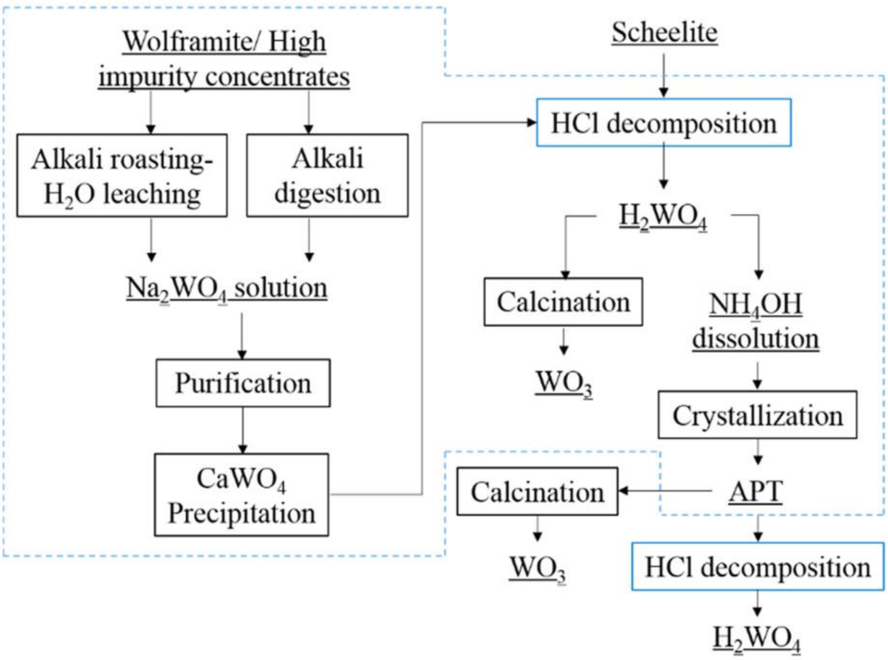

Figure 25: Extractive metallurgy of tungsten: flowsheet of the ammonium paratungstate (APT) production through leaching, digestion and crystallization processes (Shen et al., 2019).

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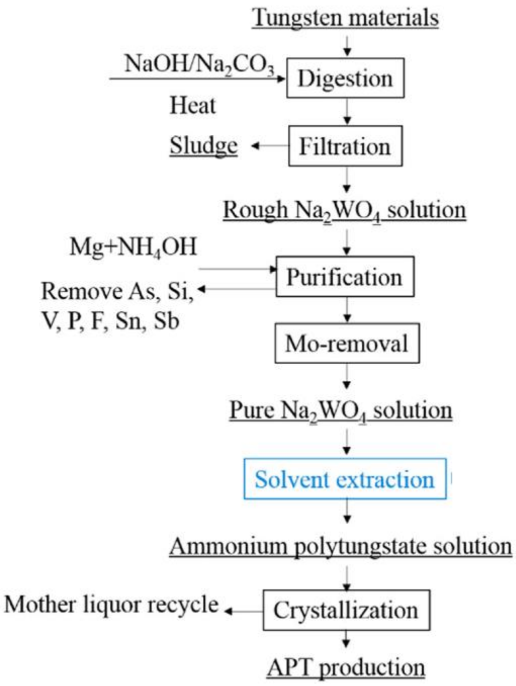

Figure 26: Extractive metallurgy of tungsten: flowsheet of the ammonium paratungstate (APT) production through solvent extraction (Shen et al., 2019).

In the EU, tungsten smelters are located in Austria and Germany, both process tungsten ores and concentrates into mainly ammonium paratungstate. Despite the lack of quantitative data on the production capacity of each country, Figure 8 indicates the domination of China in the mid-downstream of tungsten supply chain (ITA, 2018).

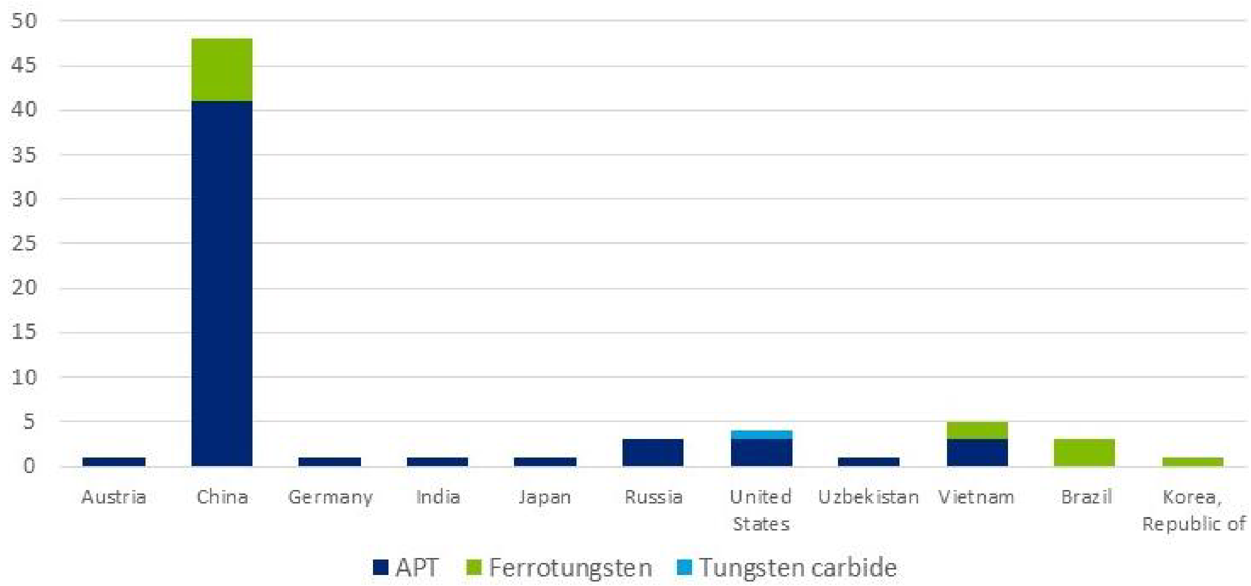

Figure 27: Number of identified global consumers of tungsten concentrates in 2017 (ITA, 2018)

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OTHER CONSIDERATIONS

HEALTH AND SAFETY ISSUES RELATED TO THE TUNGSTEN

According to the classification provided by companies, tungsten is a flammable solid, it is self-heating in large quantities and may catch fire. (ECHA, 2022a) (ECHA, 2022b). Nickel tungstate ($NiWO_4$) is cited as carcinogen in Appendix 1 of Annex XVII (List of restricted substances) as a nickel compound but is not currently being manufactured in and/or imported to the European Economic Area (ECHA 2022c).

During the production and use of tungsten the main route for intake proceeds via the respiratory tract. In 2017 an extensive epidemiological study of hard metal workers was published where the researchers found no evidence that exposure to tungsten, cobalt, or nickel, at levels experienced by the workers examined increases lung cancer mortality risks. (ITIA 2022, Hadrup 2022). However, the United States Environmental Protection Agency (US EPA) did claim tungsten as an emerging toxicant (Wasel 2018).

ENVIRONMENTAL ISSUES

Tungsten is not expected to be hazardous to the environment. (LENNTECH 2022) However, the presence of tungsten in groundwater near background sources and anthropogenic sources suggests that under certain conditions, tungsten dissolves in water and is mobile in the environment. (UE EPA 2017).

NORMATIVE REQUIREMENTS RELATED TO MINING/TUNGSTEN PRODUCTION, USE AND PROCESSING OF THE MATERIAL

Regulation (EU) 2017/821 ("Conflict Minerals Regulation") stipulates for tungsten the alignment of due diligence requirements with the 5-step framework for risk-based due diligence developed by the Organisation for Economic Co-operation and Development (OECD) - 'Due Diligence Guidance for Responsible Supply Chains from Conflict-Affected and High-Risk Areas' (OECD 2016).

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF THE TUNGSTEN FOR EXPORTING COUNTRIES

Table 8 lists the countries for which the economic value of exports of tungsten represents more than 0.1 % in the total value of their exports.

Table 8: Countries with highest economic shares of tungsten exports in their total exports

Country	Export value (USD)	Share in total exports (%)
Rwanda	20 573 826	1.44 %
Burundi	1 047 491	0.65 %
Bolivia (Plurinational State of)	20 588 804	0.29 %

Source: COMTRADE (2022), based on data for 2020

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

For Rwanda, the fourth world producer of tungsten, tungsten exports represent 1.4% of its total exports. Burundi and Bolivia also have an important share of tungsten compared to total exports, whereas for all other exporting countries, this share is below 0.1 %.

SOCIAL AND ETHICAL ASPECTS

Tungsten is one of the four minerals called conflict minerals. These minerals include tungsten, tantalum, tin and gold, also referred to as 3TG (OECD 2016). Tungsten is a conflict mineral because its mining and trade are said to directly finance armed conflicts or contribute to human rights abuse through forced labour in countries that supply the ore. Such countries include Vietnam, China, Rwanda, etc. Section 1502 of U.S. Dodd Frank Act requires U.S. listed companies to disclose whether they use such conflict minerals and whether these minerals originate in the Democratic Republic of the Congo (DRC) or an adjoining country (SEC 2012).

There are attempts globally to regulate the trade of these minerals so that they do not negatively affect the citizens of the countries where they are produced. For example, the European Union enacted in June 2017 new regulations called the Conflict Minerals Regulation (European Union 2017), which came into effect in January 2021. It aims to ensure that importers of 3TG minerals follow due diligence and import these minerals from conflict-free sources only, and that producers follow the guidelines and standards set by the Organisation for Economic Co-operation and Development (OECD) (OECD 2016).

The regulation directly affects up to 1000 importers of these metals located in the EU (European Commission 2023). But it also affects companies elsewhere indirectly as the EU-based companies will only be able to conduct business with foreign companies that follow similar due diligence and share similar values. However, recycled tungsten and tungsten scrap are not subject to the above regulation, as it is logistically impossible to document all their original sources. They are therefore considered "DRC conflict-free"[4] and require no additional due diligence.

Technically, recycling tungsten from tungsten scrap is more favourable from a logistics point of view as it eliminates the cost of compliance (Dynda 2015). Therefore, it is to be expected that if primary sources of tungsten are regulated properly, the secondary sources would also indirectly comply with the regulations.

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- Application of tungsten oxide in the proton exchange membrane fuel cells

Proton exchange membrane fuel cells (PEMFCs) have high energy density. During the last years tungsten oxide has been attracting attention as low-cost candidate for replacing platinum as catalytic material (Tian et al. 2021). Considering the acidic environment in PEMFCs, tungsten trioxide (WO_3) exhibits excellent stability

[4] DRC conflict free: Product does not contain conflict minerals necessary to the functionality or production of that product that directly or indirectly finance or benefit armed groups, in the Democratic Republic of the Congo or an adjoining country.

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properties in acidic electrolytes (Antolini et al. 2010). It seems that WO_3 can effectively accelerate the anodic reaction leading to enhanced anode activity. Thus, WO_3 can play a role as hydrogen reservoir, and even hydrogen supplier at the anode of PEMFCs. In practical fuel cell automotive applications, Tungsten has been employed also to improve fuel cell performance and durability, because of its reduced cost. (Chen et al. 2015, Sun et al. 2015)

- WO_3 employment in heterogeneous photocatalysis technologies

Heterogeneous photocatalysis is a well-tested technology for the purification of wastewater. Polycrystalline WO_3 is one of the principal emerging materials useful to replace titanium for this application (Kumar et al. 2015). Polymorphic n-type WO_3 absorbing nearly 30 % of solar radiation seems to be a potential visible light photocatalytic material with notable features, like non-toxicity and very easy preparation with high purity, durable stability in various electrolytes, intense absorption within the solar spectrum (UV-visible), narrow band gap energy (2.4–2.8 eV), and it has a significant photocurrent conversion efficiency (Chen et al. 2021).

- Noble Metal Loaded Oxygen-deficient Mesoporous Tungsten Trioxide for Green Catalysis under Solar Light - NOMTGCS (EU, 2019-2021)[5]

In this project, the synthesis and solar light driven green catalytic applications of noble metal (Au, Pd, or Au-Pd) loaded oxygen deficient mesoporous tungsten trioxide is proposed for the high selective synthesis of hydrogen peroxide from water and molecular oxygen without the usage of hydrogen gas.

- Multiscaled Smart Metallic and Semiconductor Electrodes for Electrochemical Processing and Devicesm- SMARTELECTRODES (EU, 2018-2022)[6]

The multi- and interdisciplinary project SMARTELECTRODES is proposing elaboration of advanced systems covered under umbrella of “smart” electrodes which will be involved and play significant roles in several important electrochemical/electrophysical applications as catalysis/electrocatalysis, sensoring, thermoelectrics, electrowinning, electrochemical machining and electrospark alloying. Ultrananocrystalline tungsten was applied for electrocatalytic water splitting in order to produce hydrogen from water. Catalysts based on electrodeposited molybdenum disulfide (MoS_2) thin films (acidic media) and W/molybdenium based alloys with iron group metals (alkaline media) with the special emphasis on the alloys having high refractory metal content (≥ 30 at.% of W or molybenium) were evaluated for hydrogen evolution reaction.

- Novel diffusion architectures are a breath of fresh air for fuel cell technology - HydrogenLung (EU, 2021-2024)[7]

Fuel cells have attracted global attention with successful applications in sectors including transportation and stationary power generation. The key reactions at the two electrodes, both relying on catalysts, are hydrogen oxidation (HOR) and oxygen reduction. Herein, we propose tungsten carbide nanoarrays (WC NA) as the skeleton for platinum catalysts and invent a vacuum-control method based on superwetting technology to direct the gas channels.

[5] https://doi.org/10.3030/785794

[6] https://doi.org/10.3030/778357
[7] https://doi.org/10.3030/892856

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

- Mechanics of Nanoporous W under irradiation (Nuclear fusion application) – MeNaWir (EU, 2022-2024) [8]

Fusion reactors demand materials capable of withstanding unprecedented extreme conditions. Refractory-based nanoporous metals offer a combination of mechanical and radiation performance that makes them ideal potential candidates for nuclear applications. The MeNaWir project aims at shedding light into elusive aspects of the mechanical behaviour of nanoporous refractory metals, focusing on nanoporous tungsten (np-W) and the effect of radiation damage on its mechanical properties. MeNaWir could lastingly impact innovation on materials for fusion.

OTHER RESEARCH AND DEVELOPMENT TRENDS

- OptimOre[9]: Increasing yield on tungsten and tantalum ore production by means of advanced and flexible control on crushing, milling and separation process (2014 - 2018, EU)

The OptimOre Project proposes the research and development of modelling and control technologies, using advanced sensing and advanced industrial control by means of artificial intelligence techniques, for the more efficient and flexible Tantalum and Tungsten ores processing from crushing to separation process.

- CARBIDE 2500:[10] The first 2500 °C industrial furnace, for higher efficiency and up to 5 times higher strength materials (2018 - 2020, EU)

One of the most common Carbide powders is the Tungsten Carbide (WC). WC powder is used in many different applications and across multiple large industrial sectors, including automotive and aerospace manufacturing, construction, surface and underground mining, oil & as exploration, as well as in many manufacturing industries (e.g. paper, textiles, electronics). Demand for other carbides, such as tantalum carbide or niobium carbide, is also increasing. Tests have proven that WC powder produced at ,2500°C is 3 to 5 times higher strength than the same material produced at 2,200°C. The problem is that, at industrial scale, there are no such furnaces able to operate at 2,500°C. CARBIDE 2500 is the first industrial furnace capable of operating at 2500 °C, making it possible to produce the highly demanded higher strength carbides. With a potential market estimated at 1.08 billion € in 2020, a yearly turnover of 45.73 million €, in 2024, is expected with CARBIDE2500.

- Flintstone[11] 2020: Next generation of superhard non-CRM materials and solutions in tooling (2016 – 2020, EU)

Flintstone2020 developed innovative alternative solutions for tooling operating under extreme conditions to replace tungsten (W) and cobalt (Co), which are the main constituents for two important classes of hard materials (cemented carbides/WC-Co, and PCD/diamond-Co).

Fundamental knowledge on mechanical properties and wear of different tools, gained in machining tests and dedicated experiments is the base for experiments on small samples with 3-9 mm Ø for testing the

[8] https://doi.org/10.3030/101062254
[9] https://cordis.europa.eu/project/id/642201
[10] https://doi.org/10.3030/811248
[11] CORDIS EU research results, https://cordis.europa.eu/project/id/689279

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fundamental behaviour of new B-X phases and particularly as a feedback for binder matrix improvement. Further samples (12 mm Ø) will be investigated from individual HPHT runs for characterization and testing to guide high pressure sintering process optimization. The HPHT process and the samples produced are then upscaled to the industrial mass production level. Demonstrator cutting tools from full size HPHT synthesis test runs will be prepared via laser cutting and consecutive macro- and microshaping of tool geometry. Aspects of environmental benefits in the total life cycle of the super-hard materials will be investigated, including health and safety aspects.

- Tungsten in electrochemical sensors

Transient Electronic Devices are new bioresorbable medical devices useful to monitor in real-time relevant human vital signals and parameters for the health (Hwang et al. 2012). The components of these devices (electronic circuits, wires, power supply) must be fully reabsorbed in human tissues environment. The interest in these technologies regards, among other things, the request to supply the demand of "zero-waste" consumable electronics and they could have a significant impact in the environmental sector, consumer electronics, and healthcare (Fernandes et al. 2022) (Fu et al. 2016). Transient devices are formed by different parts, each of which is characterized by different materials like polymers Polyglicol Acid), metals and oxides. Within this class of materials, transition metals like tungsten (W) are promising candidates for the fabrication of some specific parts (like interconnects, electrodes, wire) of transient electronic devices, in particular for electrochemical sensors (Fernandes et al. 2022). Several studies have attested the innocuous bio-dissolution of W into non-toxic products as well as controllable dissolution mechanisms in biological fluids, at physiological temperature (Yin et al. 2014) (Chatterjee et al. 2019). The applicability of transient technology in healthcare is still at first steps. Most research remains confined to in-vitro and animal studies (TRL <5). Although examples of remarkable transient implantable sensors can be found in the literature, they suffer from recurring drawbacks (La Mattina et al. 2018).

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