SCRREEN2

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

TITANIUM

AUTHOR(S):

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TITANIUM

OVERVIEW

Titanium (Ti) is a lustrous-white metal of low density (4.51 g/cm^3) with high mechanical strength. The light metal has a high melting point (1,668°C). Its boiling point is 3,500°C. Despite its high melting point, titanium is not suitable for high temperature applications, since its mechanical strength drops sharply when the temperature exceeds 426°C. The range of applications using titanium widened as a result of transport equipment inventions (i.e. titanium alloys used in gas turbines engines) during the 20th century, although the most common compound of titanium is used for pigments. The titanium market can be split into the titanium oxide market and the titanium metal market. The primary products in the titanium industry chain are titanium dioxide (TiO_2) and titanium sponge. More than 95% of the world's titanium ore raw materials are used to produce TiO_2 (Hu et al. 2022). Titanium sponge is the primary metal stage of titanium, an intermediate product between titanium ore and titanium ingot (Georgitzikis et al. 2022). Titanium sponge also allows the production of ferro titanium.

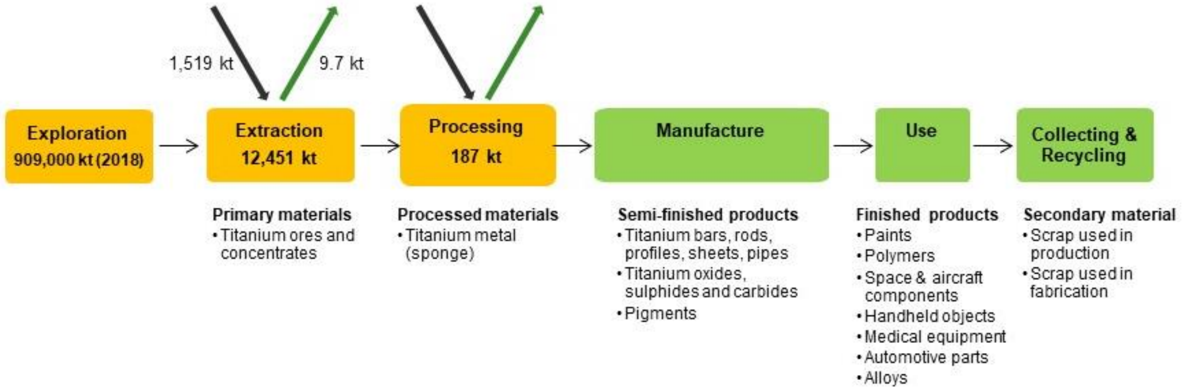

Figure 1. Simplified value chain for titanium in the EU[1]

Table 1. Titanium supply and demand (extraction stage) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers (extra EU)	Import reliance
4,520,677	China 25% South Africa 13% Australia 12% Mozambique 10% Canada 8% Ukraine 6% Kenya 4% Senegal 4%	456,539	10%	Norway 23 South Africa 16% Canada 14% Mozambique 10% Ukraine 9% UK 9% Australia 6% Sierra Leona 6%	100%

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

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Table 2. Titanium supply and demand (processing stage) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
4,497,005	China 32% United States 13% South Africa 12% Canada 11% Germany 4% Japan 4%	425,694	8,9%	Germany 45% Canada 14% Finland 12% Belgium 8% Italy 8% China 4%	18%

Table 3: Titanium metal supply and demand in metric tonnes, in Ti content, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers	Import reliance
194,455	China 43% Japan 26% Russia 20% Kazakhstan 7% Ukraine 4% Saudi Arabia 1%	9,812	5%	Kazakhstan 37% Russia 35% China10% Switzerland 6% Japan 6% Turkey 2%	100%

Prices: Post 2009 prices have seen a declining trend till 2016 reaching an all-time low. The price has picked up since and has been on a rising trend. It is expected that the price will continue to appreciate as the demand strengthens from the aerospace sector and existing stocks are depleted.

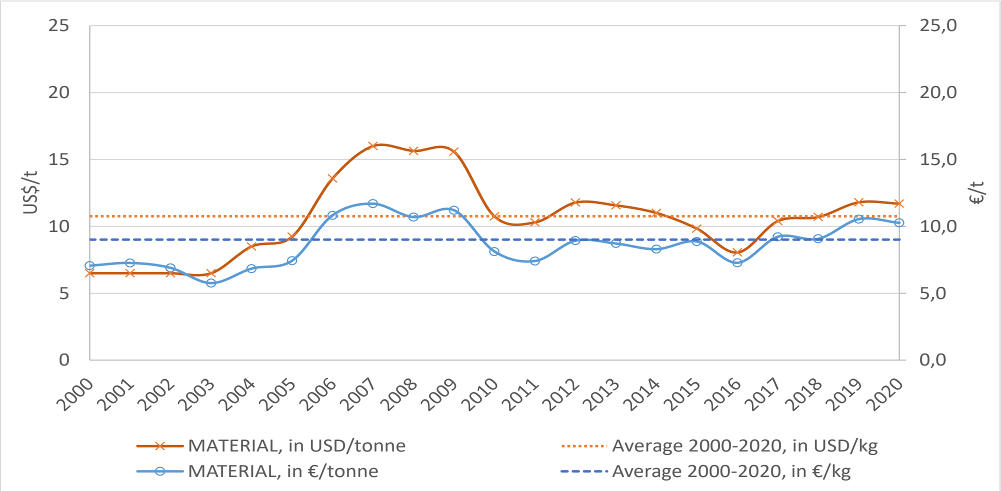

Figure 2. Annual average price of titanium between 2000 and 2020 (USGS, 2021)[2].

Primary supply: Titanium is typically produced form orthomagmatic iron-titanium-oxide (Fe-Ti-oxide) deposit, where it is mostly concentrated in ilmenite. Another important source of titanium is heavy-mineral sand deposits, where it occurs in ilmenite and rutile (Woodruf et al. 2013). A potentially significant hard-rock titanium source is in eclogites, where Ti is hosted by rutile. According to British Geological Survey (Iodine et

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[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)

al. 2022), the annual global production of ilmenite and rutile concentrates in 2020 were 12.2 Mt and 0.6 Mt, respectively. The calculated total amount of TiO_2 based on these production numbers is 7.02 Mt (4.22 Mt Ti).

Secondary supply: The major resource in titanium recycling is in-house scraps generated during smelting and fabrication processes, and the actual recycling rate of titanium, including the in-house cascade recycling rate, is high. The major and problematic impurities contained in the titanium scrap are oxygen and iron. High-grade titanium scraps with low oxygen and iron concentrations are recycled to titanium and its alloy ingots by remelting. Low-grade titanium scraps with high oxygen and iron concentrations are utilized as the raw material of ferro-titanium for the steel industry (Takeda et al. 2020). The end of life recycling input rate for titanium is estimated to be 19%, using the UNEP methodology (UNEP, 2011) (SCRREEN workshops 2019). For the primary material input we take the amount found in this study from (BGS, 2019) of 12,345 kt. The (UNEP, 2011) report offers amounts of scrap of titanium that are used worldwide. A recycled end-of-life material input (old scrap) of 2,716 kt, an amount of scrap used in fabrication (new and old scrap) 1,630 kt and scrap used in production (new and old scrap) of 244 kt.

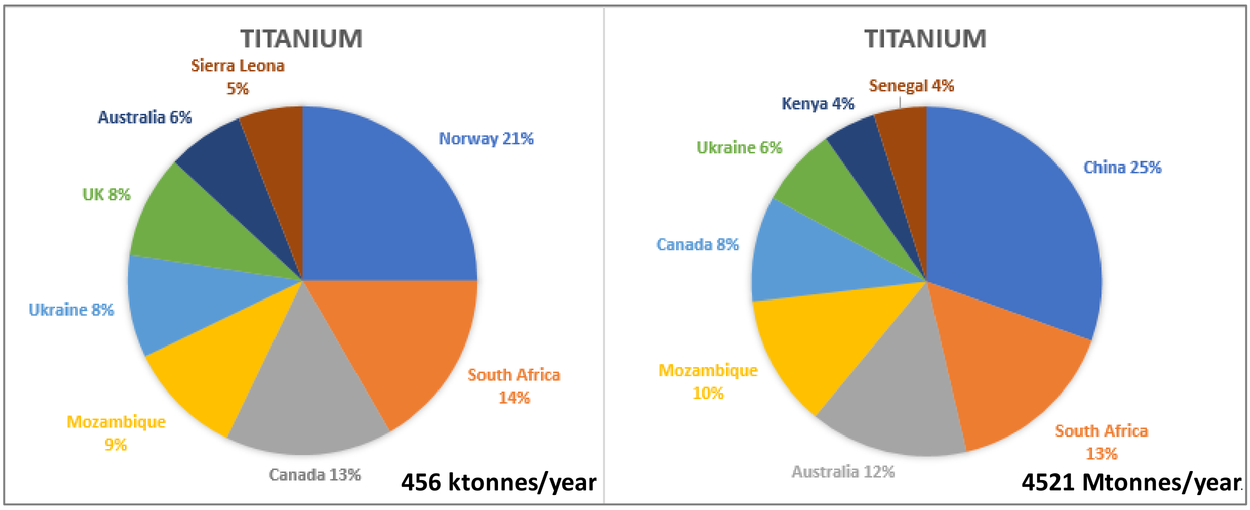

Figure 3. EU sourcing of titanium and global mine production (extraction, Ti content, average 2016-2020)

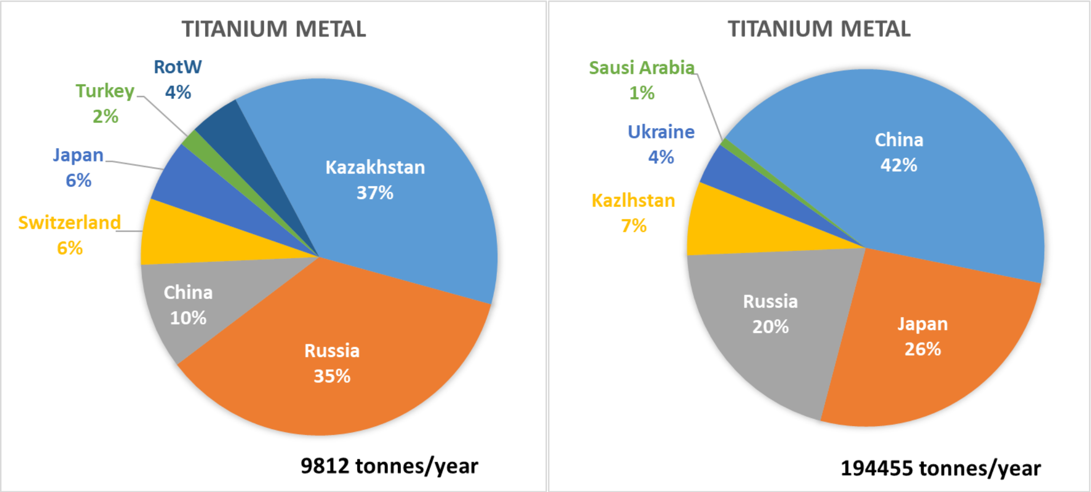

Figure 4. EU sourcing of titanium metal and global sponge production (processing, average 2016-2020)

Uses: Titanium serves a range of industrial markets due to its remarkable properties. Most of the titanium ore is used for the production of pigments, for example paints and the paper industry (Louvigné, 2021). Titanium metal has advantageous characteristics, including being lightweight, having high mechanical strength, a high melting point, and small thermal expansion. These characteristics make titanium and titanium alloys important for many applications such as in the aerospace industry, or for medical purposes. Being lightweight, titanium use results in better performance, with lower fuel consumption when used in transportation, aerospace, sports equipment and other related industries. Titanium metal has a distinct tendency to build a passive film of TiO_2, (titanium dioxide) which leads to a high corrosion resistance for the metal.

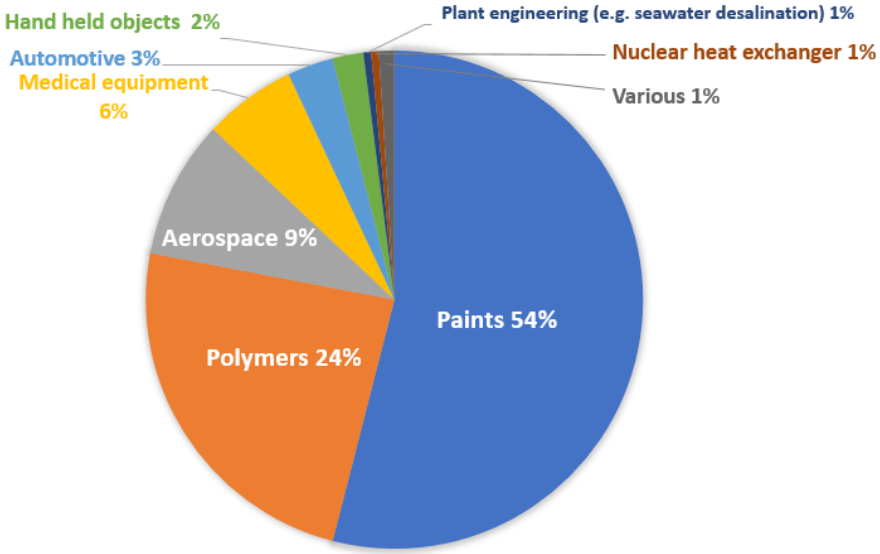

Figure 5: EU uses of titanium (2016)

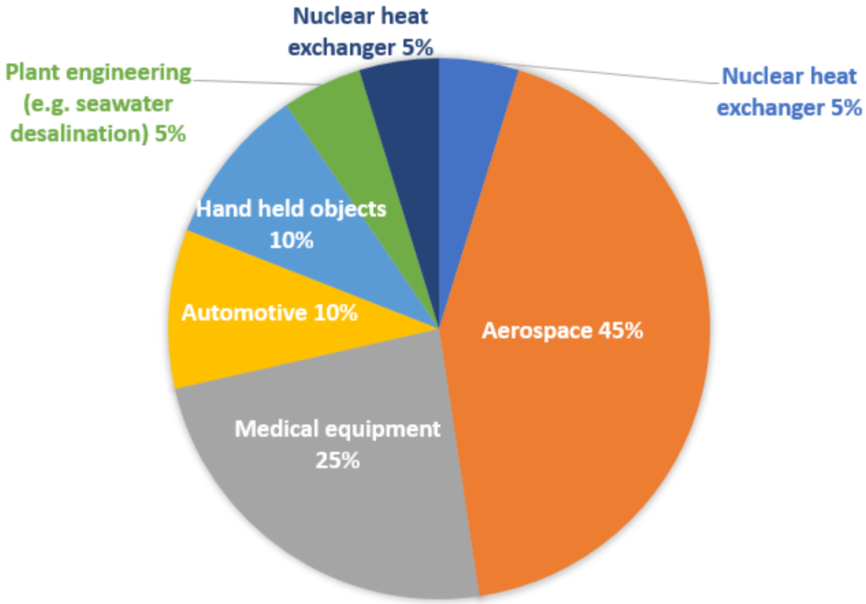

Figure 6: EU uses of titanium metal (2012-2016)

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Substitution: As a white pigment, titanium dioxide can in some cases be replaced by calcium carbonate, kaolin or talc (USGS 2019). For the metallic form, due to the outstanding properties of titanium, only a few materials can compete with its strength-to-weight ratio and corrosion resistance. When a good corrosion resistance is necessary, titanium can be substituted by aluminium, nickel, specialty steels or zirconium alloys (Tercero Espinoza et al, 2015) (USGS 2019). For applications where high strength is required, titanium competes with superalloys, steel, composites, aluminium and intermetallics (USGS 2019). Zirconium and magnesium can serve as substitutes for titanium in medical applications (CRM experts, 2022).

Other issues: Metallic titanium can be found in water streams, and it can bioaccumulate in various animal species. Impacts on the trophic chain are still under study, but the presence of this material in the environment is suspected of causing serious threats to human and non-human animals, vegetation, and bacteria (Markowska-Szczupak et al., 2020). The International Titanium Association (ITA) prepared a set of compliance Guidelines to support companies to comply with relevant antitrust laws. In addition, members of ITA also adopted a special resolution according to which ITA meetings and facilities shall not be used to exchange information on the price of titanium (ITA 2022). In Mozambique, Madagascar, Senegal and Kenya, the share of titanium exports in the total exports is higher than 2 %. In these countries, almost all titanium exports are in the form of ores and concentrates.

Table 4. Uses and possible substitutes of Titanium dioxide and Titanium metal

Material	Use	Share*	Substitutes	SubShare	Cost	Performance
TiO2	Paints	54%	Talc	17%	Similar or lower costs	Similar
TiO2	Paints	54%	Kaolin	17%	Similar or lower costs	Similar
TiO2	Paints	54%	Calcium carbonate	17%	Similar or lower costs	Similar
TiO2	Paints	54%	no substitute	49%	no substitute	
Ti	Aerospace	45%	no substitute	100%	no substitute	
Ti	Medical equipment	25%	no substitute	100%	no substitute	
Ti	Automotive	10%	no substitute	100%	no substitute	
Ti	Hand held objects	10%	not assessed below 10%	100%		
Ti	Nuclear Heat exchanger	5%	not assessed below 10%	100%		
Ti	Plant engineering (e.g. seawater desalination)	5%	not assessed below 10%	100%		

*EC CRM Data 2023

MARKET ANALYSIS, TRADE AND PRICES

GLOBAL MARKET

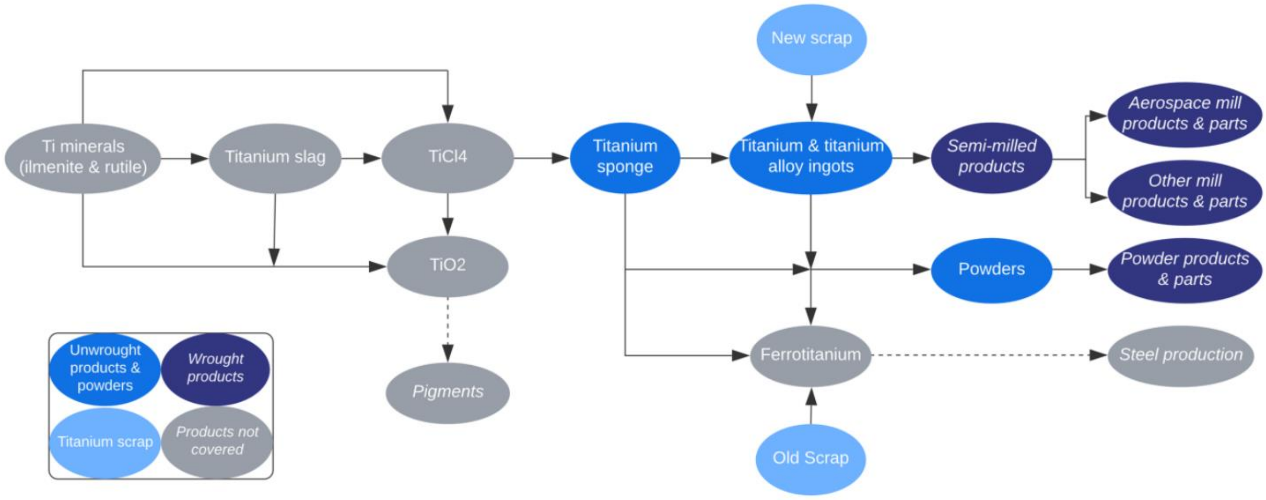

Figure 7. Titanium value chain and scope (JRC 2022)

Figure 7 describes very well the titanium market, which can be split into the titanium oxide market and the titanium metal market. Indeed, the primary products in the titanium industry chain are titanium dioxide (TiO_2) and titanium sponge. More than 95% of the world's titanium ore raw materials are used to produce TiO_2 (Hu, X., Luo, F., Lin, J., Wang, M., Li, X., 2022). Titanium sponge is the primary metal stage of titanium, an intermediate product between titanium ore and titanium ingot (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). Titanium sponge also allows the production of ferro titanium.

Table 5. Titanium supply and demand (extraction stage) in metric tonnes, 2016-2020 average

Global production	Global Producers	EU consumption	EU Share	EU Suppliers (extra EU)	Import reliance
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The global market of titanium can be classified based on the following major applications: aerospace and marine sector, industrial, medical, energy, pigments, additives and coatings, papers and plastics and others (European Commission, 2020). The consumption of titanium dioxide in 2020 was estimated to sit at 6.45 million tonnes. With 56 % of this volume, 3.6 million tonnes, the paint and coatings industry are the main consumer of the white pigment, a market worth more than EUR 17.82 billion (Gagro, D., 2022).

Table 6. Titanium supply and demand (processing stage) in metric tonnes, 2016-2020 average

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The world's consumption of Titanium metal goes to civil aerospace se!ctor (45%), followed by industrial equipment (40%), defence (9%) and consumer goods (6%) (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). In 2020, the global output of titanium sponge is estimated to be 245 kt with China accounting for more than half (56%) followed by Japan (20%) (Entirely produced from imported titanium minerals), Russia, Kazakhstan, Ukraine (each with 13%, 6% and 2% of share, respectively) (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). On the 2016-2020 period, the global production is around 204 ktonnes in average, with a regular increase from 2016 to 2020. The Chinese titanium sponge is qualified only for common applications (metallurgical quality) and not for aerospace (Georgitzikis, K., D`elia, E. and Eynard, U., 2022).

In 2020, the sponge production capacity of an aeronautical quality accounted for about 40% of global titanium sponge production while the qualified melting capacity for aerospace alloys accounts for 54% of the total processing capacity, with approximately 100 kt/year of output (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). After the closure of the US plant, the only qualified producers of aviation-grade titanium sponge are Japanese, Russian and Kazakh. Russia is a substantial source country of titanium for the aerospace industry globally, (especially to the US and European aerospace industries) making supply chains vulnerable to disruption (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). For instance, the Russian company VSMPO-Avisma used to supply about one-third of the titanium used by the aviation sector globally and more than 45% of the world's aerospace titanium parts output (Georgitzikis, K., D`elia, E. and Eynard, U., 2022).

3.2 EU TRADE

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

Table 8. Relevant Eurostat CN trade codes for Titanium

Mining		Processing/refining	
CN trade code	**title**	**CN trade code**	**title**
26140000	Titanium ores and concentrates	28230000	Titanium oxides
		26209960	Slag, ash and residues containing mainly titanium
		81082000	unwrought titanium; titanium powders
		81083000	Titanium waste and scrap (excl. ash and residues)
		72029100	Ferro-titanium and Ferro-silico titanium

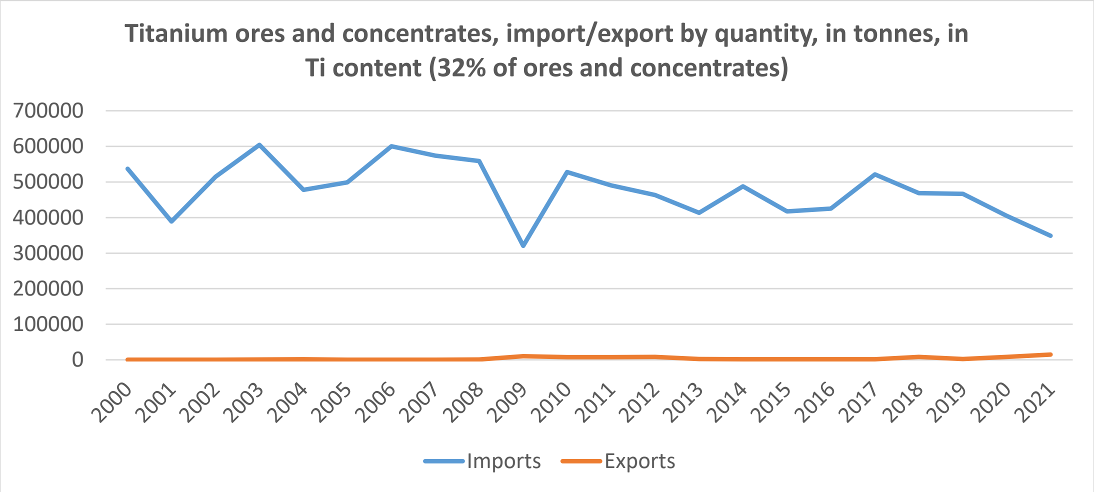

Figure 8. EU trade flows of Titanium ores and concentrates (CN 26140000) (Eurostat, 2022)

The EU is a net importer of Titanium ores and concentrates (about 450 ktonnes/year in Ti content (assuming 32% of Ti in ores and concentrates) in average along the last 10 years. The annual export quantity is insignificant compared to imports. Post-COVID import numbers have fallen sharply and do not appear to have recovered yet from the demand shock. Apart from Norway, the top suppliers of Titanium concentrates are Canada, South Africa, Australia, and Ukraine.

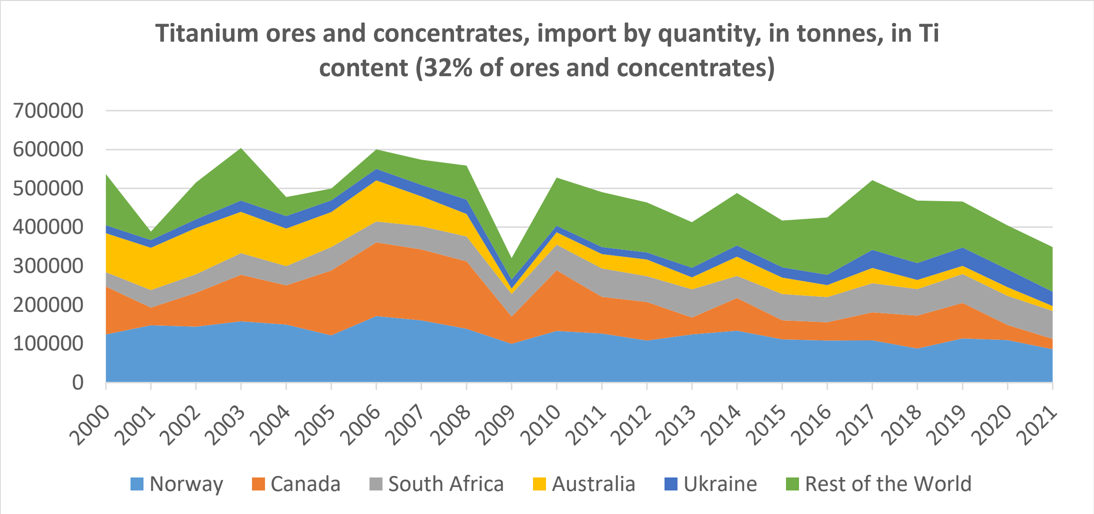

Figure 9. EU imports of Titanium ores and concentrates (CN 26140000) (Eurostat, 2022)

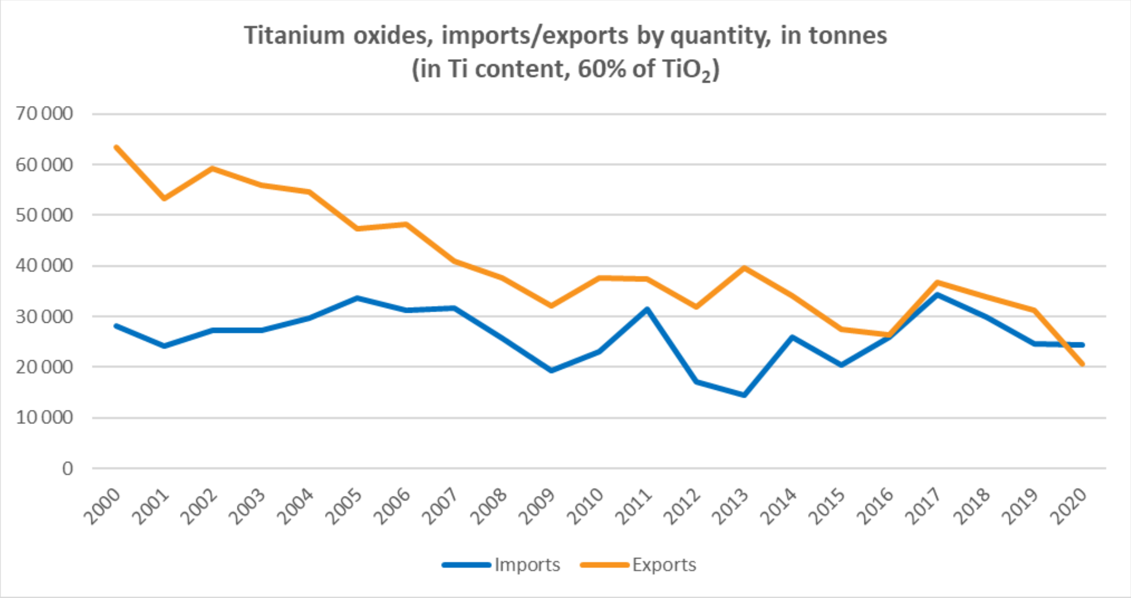

Figure 10. EU trade flows of Titanium oxides (CN 28230000), in Ti content (60%) (Eurostat, 2022)

The EU remained a net exporter of Titanium oxide for the period 2000 – 2016. Annual export quantity has consistently declined in the past 2 decades while the import quantity has mostly remained stable and gradually grown over time. China remains the most important supplier of Titanium oxide to EU. It is expected that China will continue to increase capacity over time, according to Hunan 2022 titanium dioxide industry innovation conference and high-tech exchange there are at least four titanium dioxide projects under construction now, with a design capacity of 660,000 tons/year or more, to be completed in 2022-2023. Thus, by 2023, the total production capacity of titanium dioxide in China will reach at least 5.7 million tons / year.

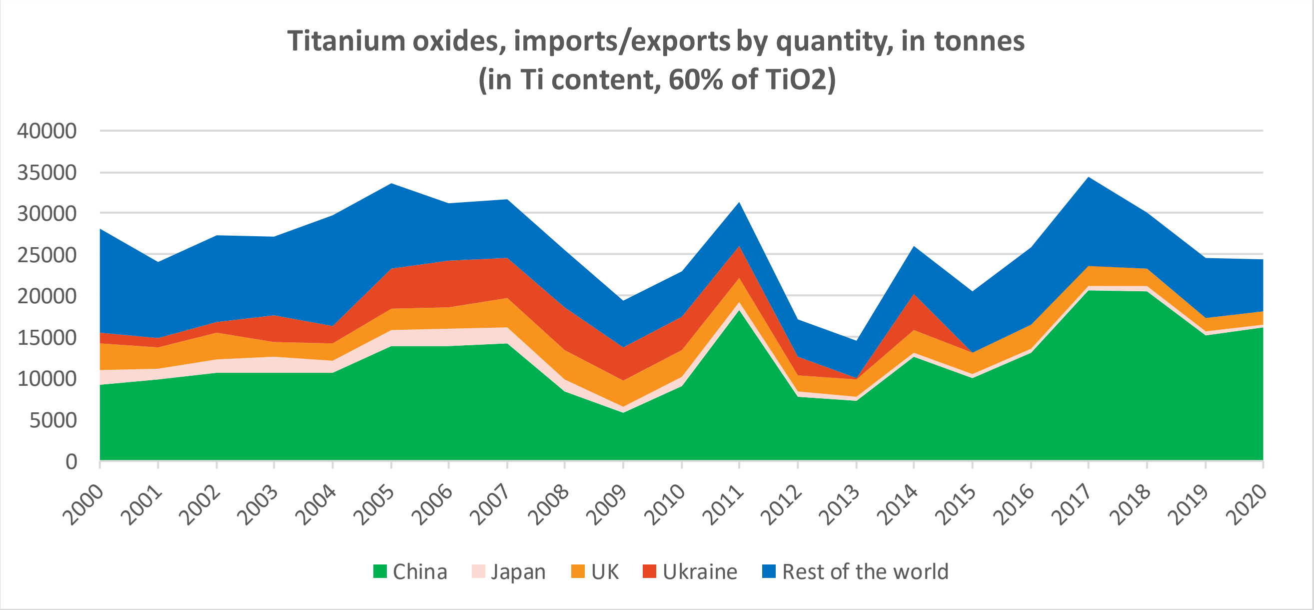

Figure 11. EU imports of Titanium oxides (CN 28230000) by country, in Ti content (60%) (Eurostat, 2022)

While concentrates imports decreased along the years, slag imports highly increased from 3 ktonnes in 2009 to almost 90 ktonnes in 2020, slags being today a precursor for TiO_2 synthesis. If Norway was the main supplier from 2009 to 2015, the slags are now almost exclusively imported from Canada (90%). There is no export of slag.

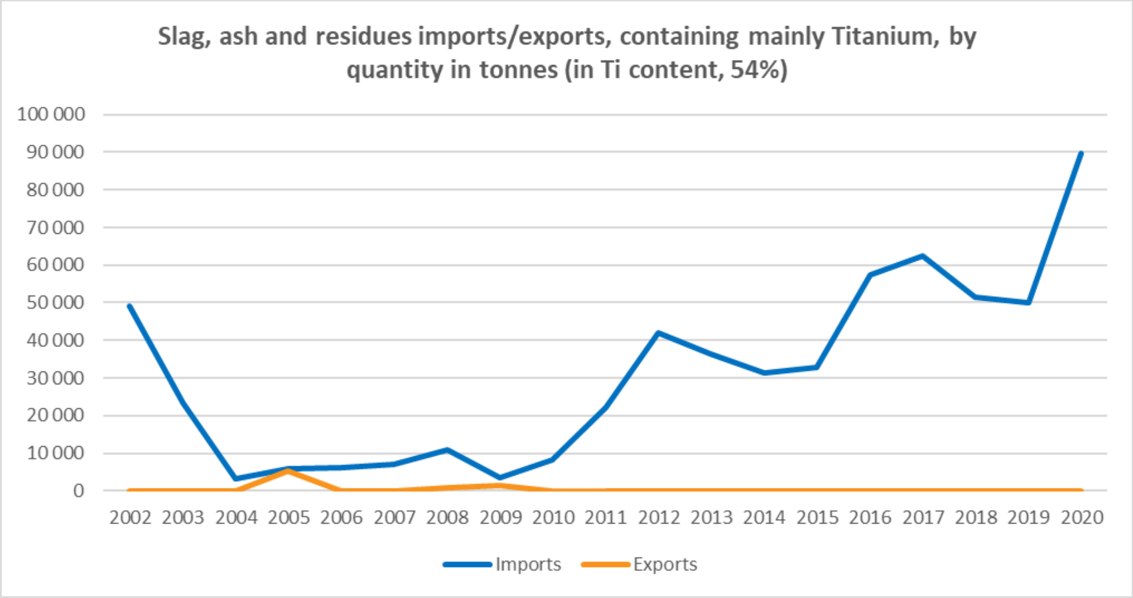

Figure 12. EU trade flows of slag, ash and residues containing mainly titanium (CN 26209960) in Ti content (54%) (Eurostat, 2022)

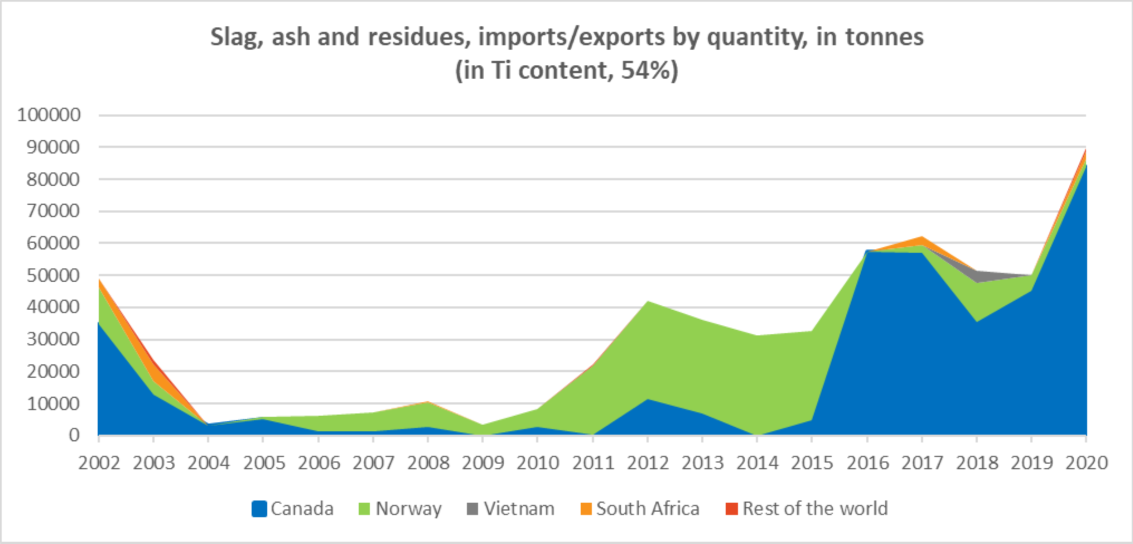

Figure 13. EU imports of slag, ash and residues containing mainly titanium (CN 26209960), in Ti content (54%) (Eurostat, 2022)

EU is a net importer of titanium metal under the unwrought and powders forms, knowing that there is no production of titanium metal in the EU. After 8 year of plateau around 17000 tonnes per year from 2011 to 2019, the Covid pandemic had huge negative impact of titanium metal import, with only about 10000 tonnes imported per year in 2020 and 2021, down to the level of 2002-2003. Titanium metal is mainly imported from

Kazhastan, USA, and Russia (about 20% each on the 2016-2020 period) and then Ukraine and UK (12% each), followed by China and Japan (about 5% each).

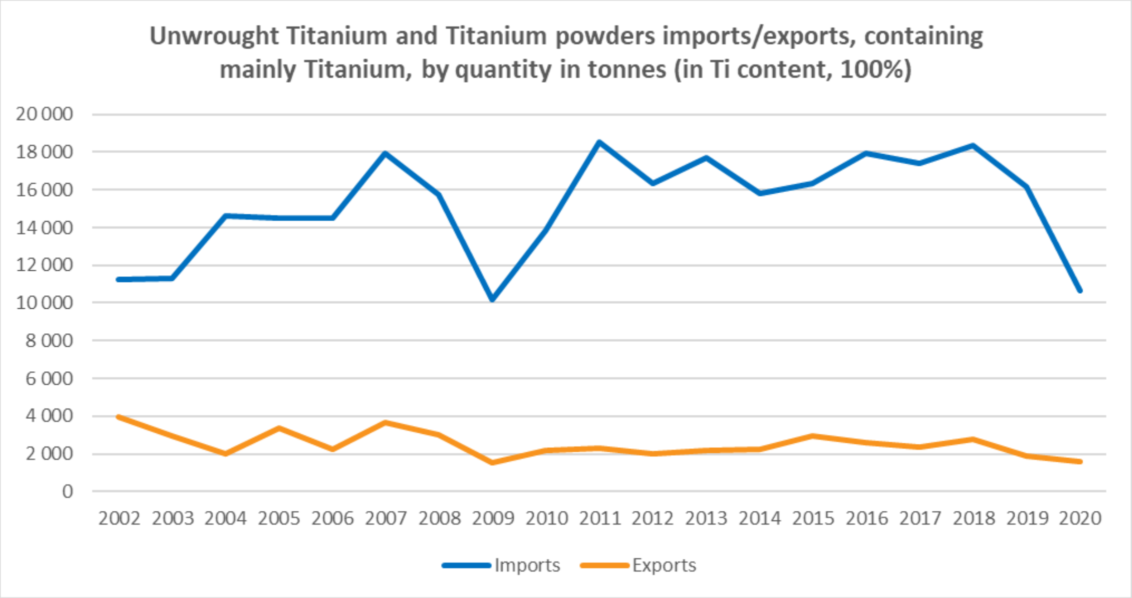

Figure 14. EU trade flows of unwrought titanium; titanium powders (CN 81082000) in Ti content (100%) (Eurostat, 2022)

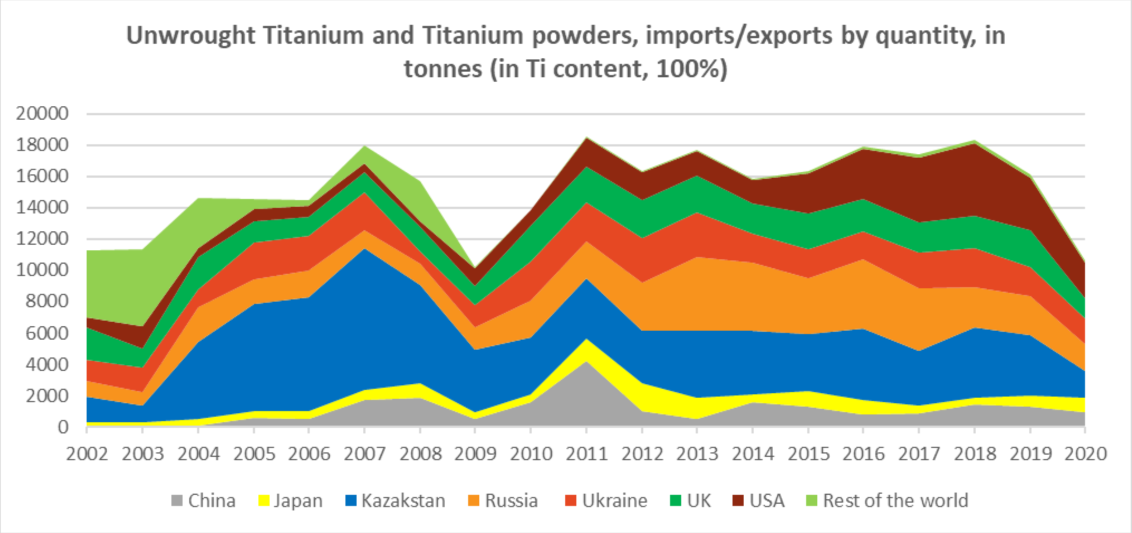

Figure 15. EU trade flows of unwrought titanium; titanium powders (CN 81082000) in Ti content (100%) (Eurostat, 2022)

In return, the EU is a net exporter of titanium scraps, with about 15000 tonnes in average on the 2016-2020 period against 5000 tonnes of import. The imports are mainly from Russia, USA, Switzerland and UK, with a strong decrease from Russia in 2019 and 2020.

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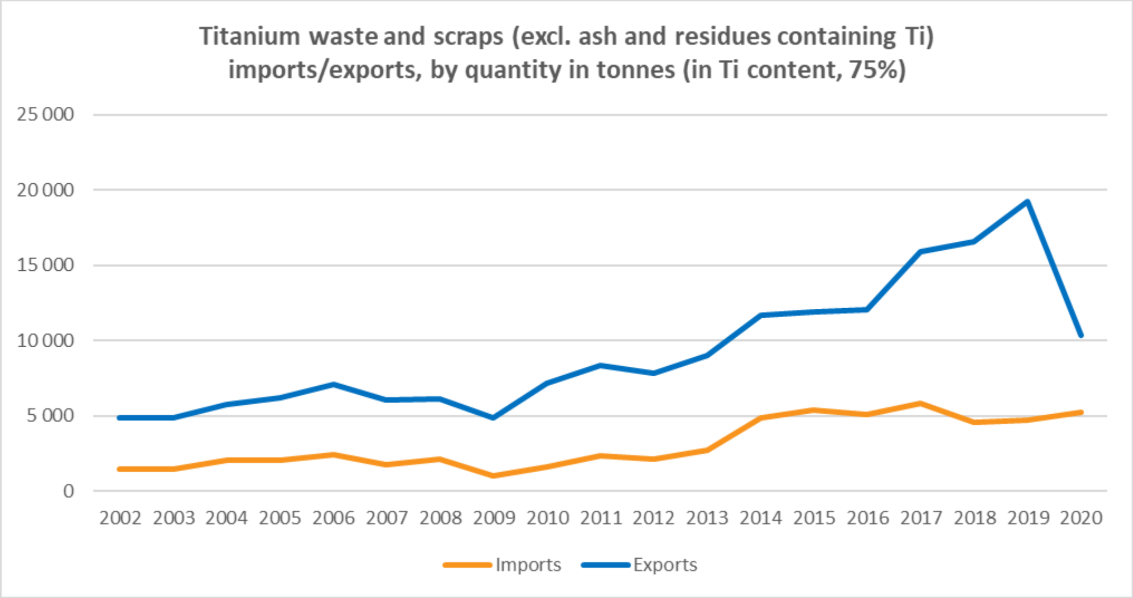

Figure 16. EU trade flow of Titanium waste and scraps (CN 81083000) in Ti content (75%) (Eurostat, 2022)

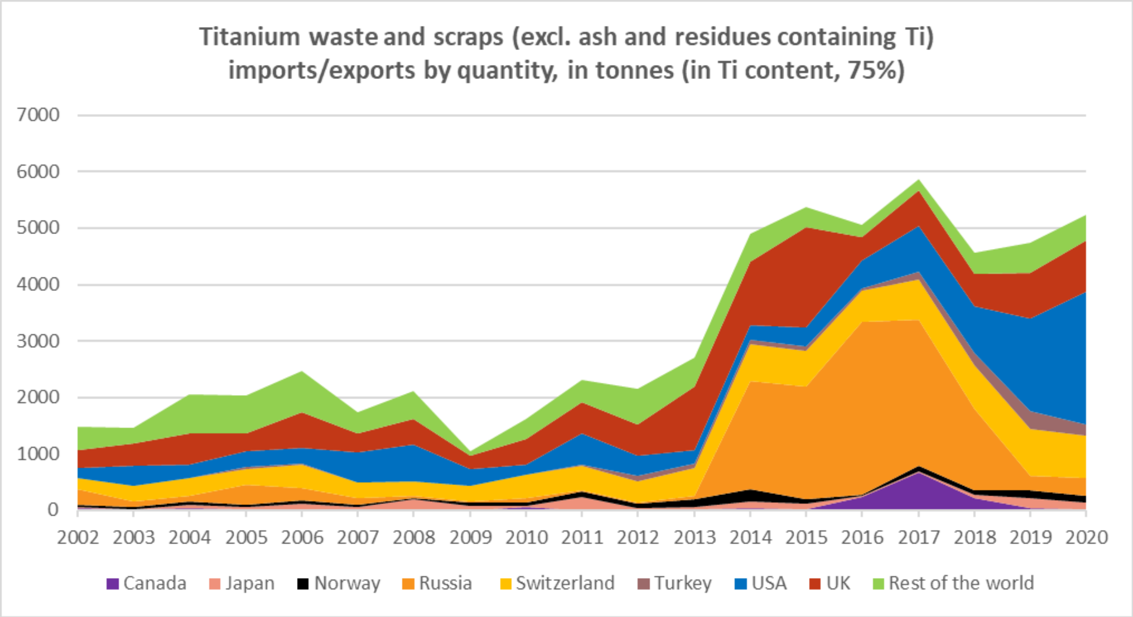

Figure 17. EU imports of Titanium waste and scraps (CN 81083000) in Ti content (75%) (Eurostat, 2022)

The EU is a net importer of Ferro Titanium. UK and Russia remain top suppliers to EU. Annual import quantity has rebounded sharply after the post COVID decline indicating that demand for Ferro Titanium for EU industries is immediate and growing stronger.

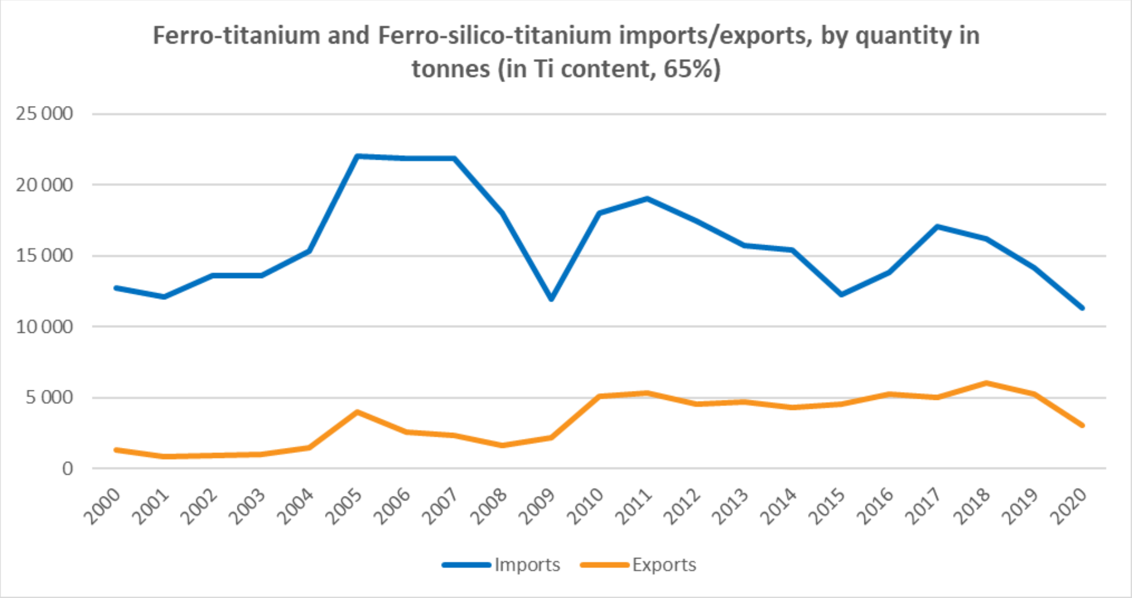

Figure 18. EU trade flows of Ferro-titanium and Ferro-silico-titanium (CN 72029100) in Ti content (65%) (Eurostat, 2022)

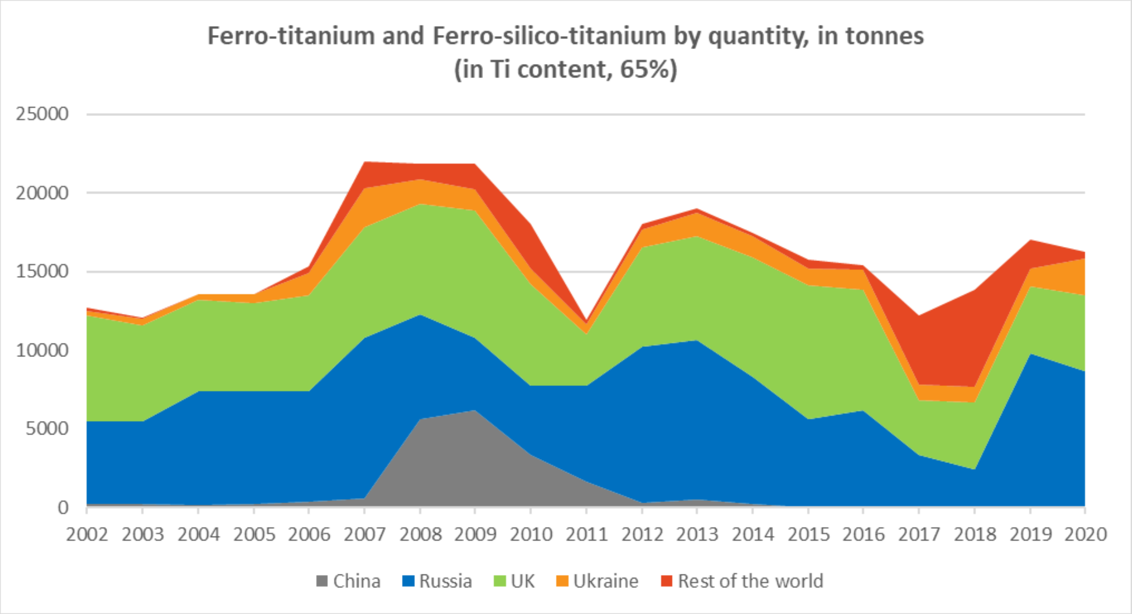

Figure 19. EU imports of Ferro-titanium and Ferro-silico-titanium (CN 72029100) in Ti content (65%) (Eurostat, 2022)

3.3. PRICE AND PRICE VOLATILITY

Post 2009 prices have seen a declining trend till 2016 reaching an all-time low. The price has picked up since and has been on a rising trend. It is expected that the price will continue to appreciate as the demand strengthens from the aerospace sector and existing stocks are depleted.

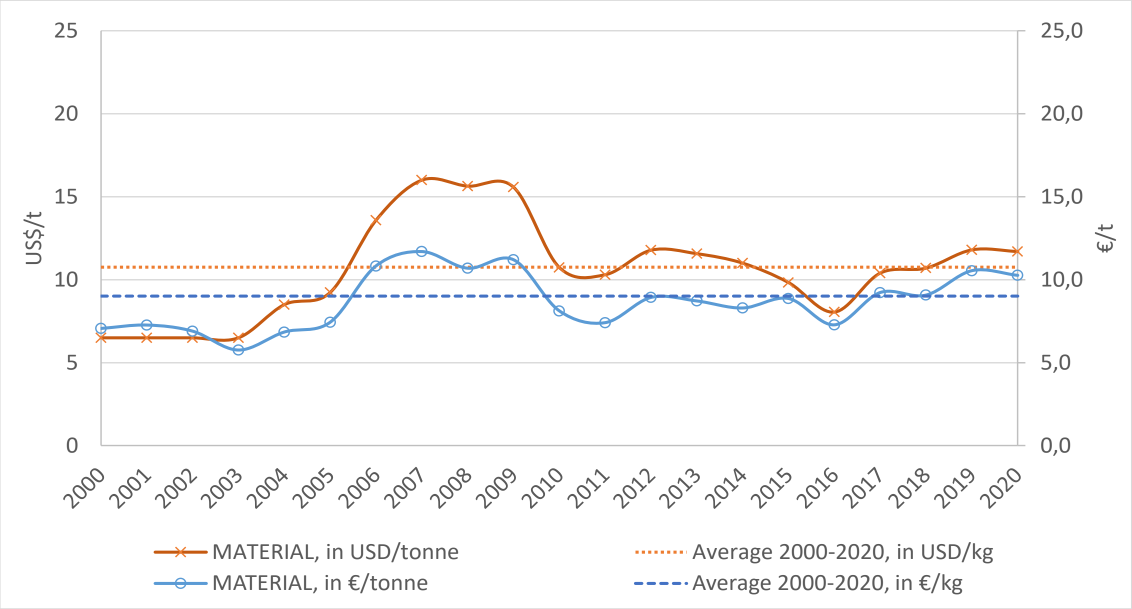

Figure 20. Annual average price of Titanium between 2000 and 2020, in US$/t and €/t[3]. Dash lines indicate average price for 2000-2020 (USGS, 2021)

OUTLOOK FOR SUPPLY AND DEMAND

Titanium's demand is heavily dependent on industrial activity (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). Prior to the Covid-19 crisis, titanium demand reached a record high in 2019, with more than 160 kt tonnes of titanium consumed all over the world, primarily driven by the aerospace sector (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). With the collapse of aviation activity in 2020 following Covid- 19 pandemic, the demand of titanium dropped by 30% in 2020 to 113 kt and, further, to 90 kt in 2021 (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). Beyond 2021, the annual growth rate of demand is anticipated at about 12% until 2026, and the level of consumption of 2019 is expected to be seen after 2026. Nevertheless, increased defence budgets over the coming years in the aftermath of Russia's conflict with Ukraine may increase the future demand (Georgitzikis, K., D`elia, E. and Eynard, U., 2022).

On the supply side, western aerospace companies have reportedly been creating stocks or looking to diversify their supply base to get ahead of any supply disruption before the conflict between Russian and Ukraine (Georgitzikis, K., D`elia, E. and Eynard, U., 2022). The global supply of titanium sponge may be in favour to Japan due to the sanctions against Russia. In April 2022, the Japanese company Toho Titanium Co. has reportedly increased its output of the aerospace-grade titanium as U.S. aviation industry customers are looking for alternatives to Russian supply (Suga, M., 2022).

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

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DEMAND

GLOBAL AND EU DEMAND AND CONSUMPTION

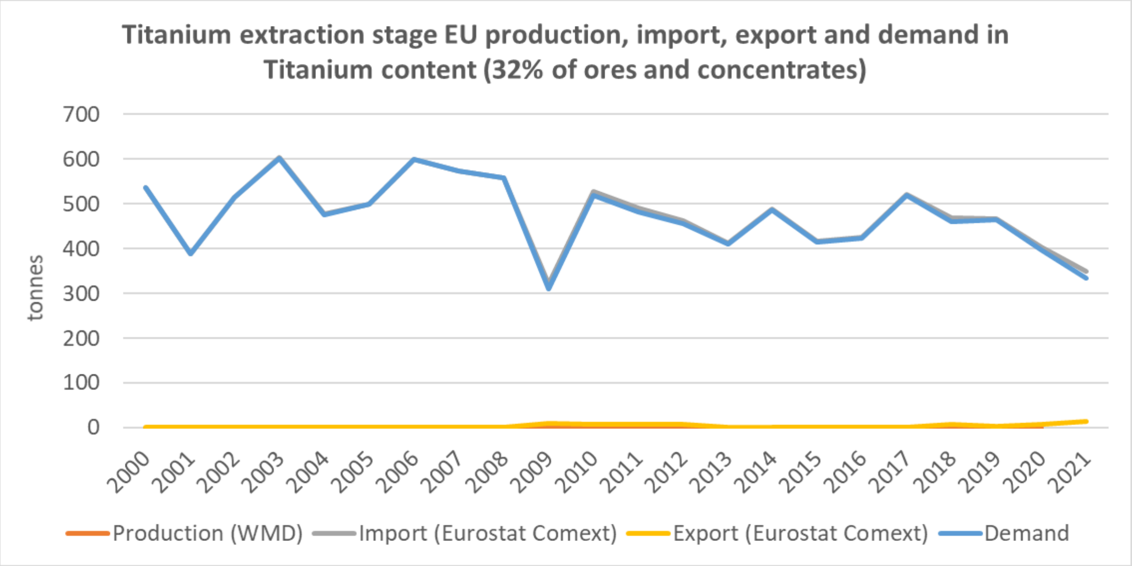

Figure 21. Titanium (CN 26140000) processing stage apparent EU consumption. Production data is available from WMD (2022). Consumption is calculated in titanium content (32 % of CN 26140000) (EU production+import-export).

Titanium extraction stage EU consumption is represented by HS code CN 26140000 Titanium ores and concentrates. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from WMD (2022).

There is no ores and concentrates production in the EU. Most of this materials will be processed to produce titanium oxides. So, EU is a titanium oxides producer (PRODCOM code 20121150)

Titanium processing stage EU consumption is presented by HS codes CN 26209960 Slag, ash and residues containing mainly titanium (which a precursor for TiO_2, CN 28230000 Titanium oxides, CN 72029100 Ferro-titanium and ferro-silico-titanium, CN 81081010 + CN 81082000 Unwrought titanium; titanium powders and CN 8108300 Titanium waste and scrap (excl. ash and residues containing titanium). Import and export data is extracted from Eurostat Comext (2022).

To analyse titanium at the processing stage, it is impossible to merge all these materials according to their Ti content, the titanium metal market being very different than the titanium oxide market. For titanium metal (unwrought, powders and Ferro Titanium), knowing that there is no EU production, the demand is calculated on imports – exports. Oxides and ashes are managed together.

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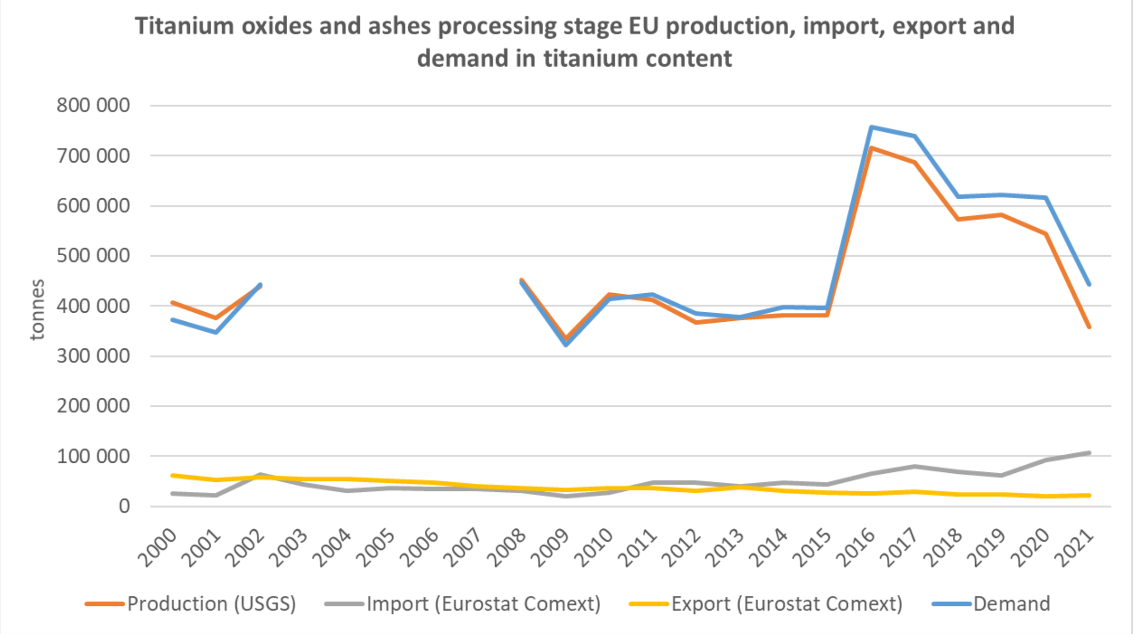

Figure 22. Titanium oxides and ashes (CN 28230000 and CN 26209960) processing stage apparent EU consumption. Production data is available from PRODCOM code 20121150 (PRODCOM 2022, no data for years 2003 to 2007). Consumption is calculated in titanium content (EU production+import-export).

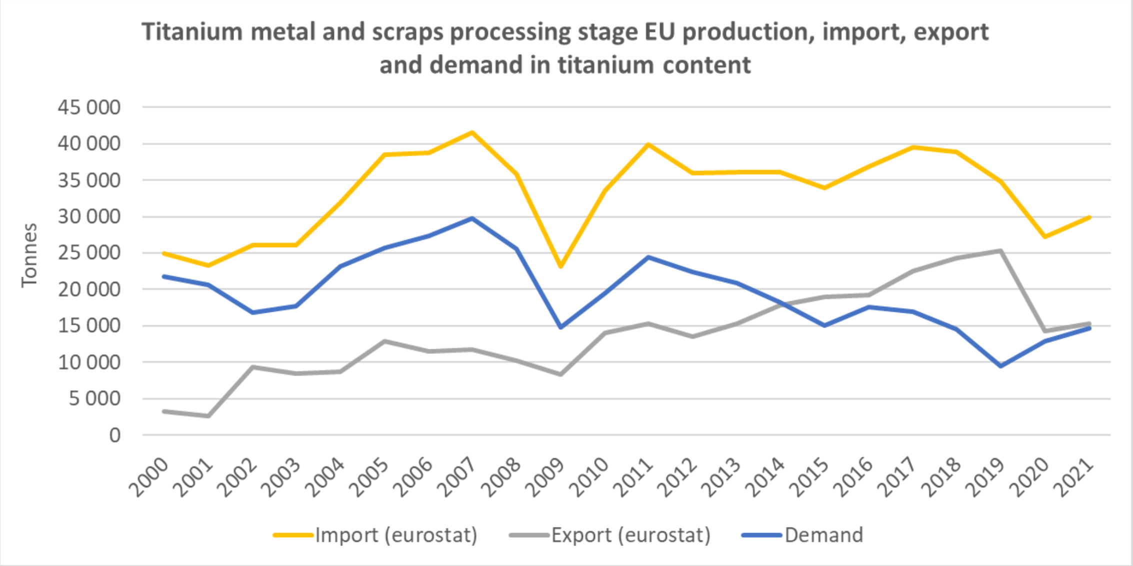

Figure 23. Titanium metal and scraps (CN 81082000 + 81081010, CN 72029100 and CN 81083000) processing stage apparent EU consumption. Consumption is calculated in titanium content (EU production+import-export).

Based on Eurostat Comext (2022), WMD (2022) and USGS (2022) average import reliance of titanium for 2016-2020 is 100% at extraction stage, 18% at oxides processing stage and 100% at metal sponge processing stage.

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GLOBAL AND EU USES AND END-USES

Titanium serves a range of industrial markets due to its remarkable properties.

Most of the titanium ore is used for the production of pigments, for example paints and the paper industry (Louvigné, 2021).

Titanium metal has advantageous characteristics, including being lightweight, having high mechanical strength, a high melting point, and small thermal expansion.

These characteristics make titanium and titanium alloys important for many applications such as in the aerospace industry, or for medical purposes.

Being lightweight, titanium use results in better performance, with lower fuel consumption when used in transportation, aerospace, sports equipment and other related industries.

Titanium metal has a distinct tendency to build a passive film of TiO_2, (titanium dioxide) which leads to a high corrosion resistance for the metal.

The end uses of titanium and titanium metal are presented in Figures 24 and 25 for Europe and in Figure 266 globally. Civil aerospace is the major demand sector for titanium metal demand, which also increased globally and particularly in Europe within the past decade.

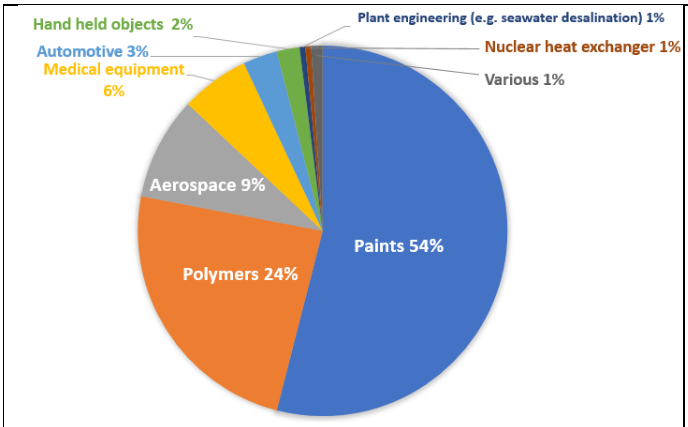

Figure 24: Estimated European end uses of titanium (all forms) (2012-2016)

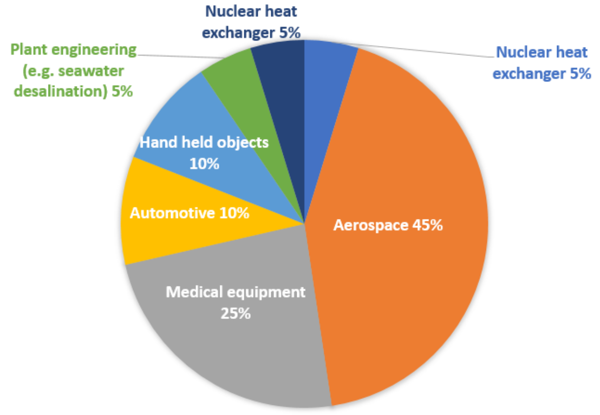

Figure 25: Estimated European end uses of titanium metal (2012-2016)

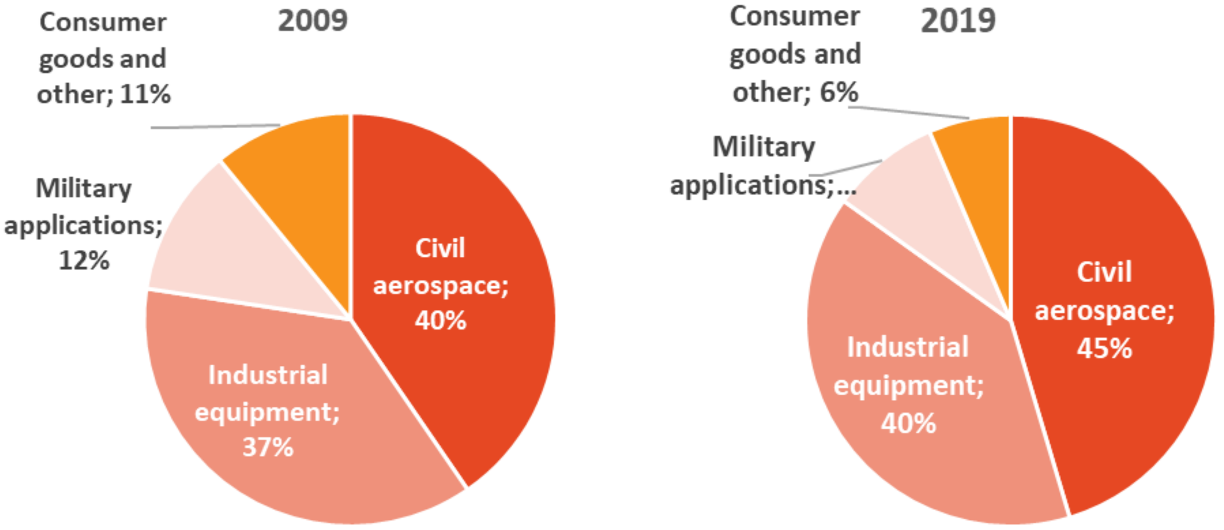

Figure 26: Estimated global end uses of titanium metal for 2009 and 2019 (Louvigné, 2021)

The relevant industry sectors and their 2 and 4-digit NACE codes are summarised in Table 9 and visualized in Figure 27.

Table 9: Titanium applications, 2-digit and examples of associated 4-digit NACE sectors, and value-added per sector for 2018 (*for 2014) (Eurostat, 2021).

Applications	2-digit NACE sector	Value added of NACE 2 sector (M€)	4-digit CPA
Paints	C20 - Manufacture of chemicals and chemical products	117,093*	C20.30 - Manufacture of paints, varnishes and similar coatings, printing ink and mastics
Polymers	C22 - Manufacture of rubber and plastic products	92,674	C22.22 - Manufacture of plastic packing goods
Aerospace	C30 - Manufacture of other transport equipment	49,098*	C3030 - Manufacture of air and spacecraft and related machinery
Medical equipment	C28 - Manufacture of machinery and equipment n.e.c.	200,030*	C28.99 - Manufacture of other special-purpose machinery n.e.c.
Automotive	C29 - Manufacture of motor vehicles, trailers and semi-trailers	23,4941	C29.32 - Manufacture of other parts and accessories for motor vehicles
Hand held objects	C25 - Manufacture of fabricated metal products, except machinery and equipment	183,016	C25.73 - Manufacture of tools
Alloys	C24 - Manufacture of basic metals	71,391	C24.45 - Other non-ferrous metal production
Various	C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	94,338*	C21.10 -Manufacture of basic pharmaceutical products

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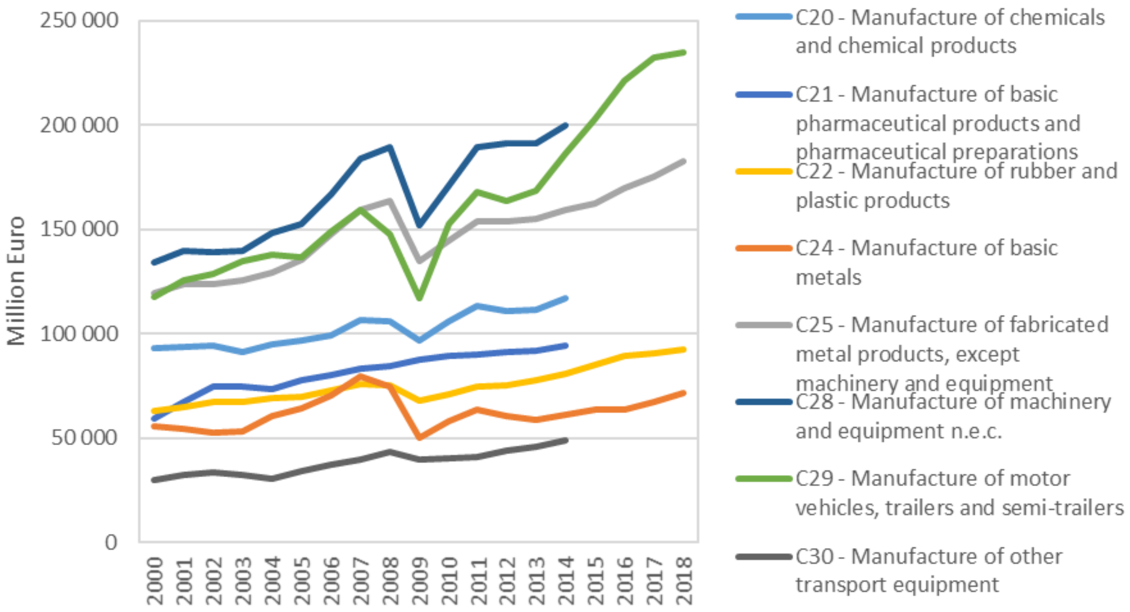

Figure 27. Value added per 2-digit NACE sector over time (Eurostat, 2021).

APPLICATIONS OF TITANIUM

PAINTS

The major market for titanium dioxide is inorganic pigments, so-called ‘titanium white’ which uses approximately 54% of all titanium.

AEROSPACE

The aeronautics sector largely dominates demand of titanium metal in Europe, followed by industrial applications and, more marginally, military applications and consumer goods (Louvigné, 2021).

Some titanium alloys can be used at working temperatures up to 600°C.

Titanium is lighter than steel, and titanium alloys are stronger than aluminium alloys at elevated temperatures.

Due to their high tensile strength to density ratio, high corrosion resistance, and ability to withstand moderately high temperatures without creeping, titanium alloys are used in several parts of aircrafts like engine, airframe structures and other components (JRC, 2022). Around two thirds of all titanium metal produced is used in aircraft engines and frames (Reade 2019).

INDUSTRIAL EQUIPMENT

Due to its corrosion resistance, titanium and its alloys are used in chemical industry as well as petrochemical and nuclear plants (JRC, 2022).

Titanium's passive layer leads to a good toleration of titanium by human tissue, and due to its non-toxic nature, titanium is used for implants, pins for fixing broken bones and heart pacemaker capsules (Enghag, 2004)(Reade 2019).

Furthermore, titanium is used as a tool material. Titanium nitride and titanium carbide are used to improve the wear characteristics and to prolong the tool life. These materials, also known as 'hardmetals' are used for the manufacturing of cutting tools (Uhlmann 2001) (TNO 2015).

MILITARY APPLICATIONS

Within military applications, titanium is used for aircrafts, armour plating, naval ships, spacecraft, submarines, and missiles (Louvigné, 2021).

Titanium alloyed with aluminium, vanadium, and other elements is used for a variety of components including critical structural parts, fire walls, landing gear, exhaust ducts (helicopters), and hydraulic systems.

4.3 SUBSTITUTION

The substitution options for titanium are summed up in Table 10 and described in the subsections below.

Table 10: Substitution options for titanium by application.

Material	Use	Share*	Substitutes	SubShare	Cost	Performance
TiO2	Paints	54%	Talc	17%	Similar or lower costs	Similar
TiO2	Paints	54%	Kaolin	17%	Similar or lower costs	Similar
TiO2	Paints	54%	Calcium carbonate	17%	Similar or lower costs	Similar
TiO2	Paints	54%	no substitute	49%	no substitute	
Ti	Aerospace	45%	no substitute	100%	no substitute	
Ti	Medical equipment	25%	no substitute	100%	no substitute	
Ti	Automotive	10%	no substitute	100%	no substitute	
Ti	Hand held objects	10%	not assessed below 10%	100%		
Ti	Nuclear Heat exchanger	5%	not assessed below 10%	100%		
Ti	Plant engineering (e.g. seawater desalination)	5%	not assessed below 10%	100%		

*EC CRM Data 2023

PIGMENTS

As a white pigment, titanium dioxide can in some cases be replaced by calcium carbonate, kaolin or talc (USGS 2019).

Studies have been undertaken to replace TiO_2 pigment by various percentages of calcined clays in two latex paint formulations.

Properties such as thixotropy ("becoming liquid when being put under stress, being shaken), film brightness, scrub resistance, and weather resistance are important to be substituted (Narayan and Raju, 1999).

METALLIC APPLICATIONS

Due to the outstanding properties of titanium, only a few materials can compete with its strength-to-weight ratio and corrosion resistance.

When a good corrosion resistance is necessary, titanium can be substituted by aluminium, nickel, specialty steels or zirconium alloys (Tercero Espinoza et al, 2015) (USGS 2019).

For applications where high strength is required, titanium competes with superalloys, steel, composites, aluminium and intermetallics (USGS 2019).

Zirconium and magnesium can serve as substitutes for titanium in medical applications (CRM experts, 2022).

SUPPLY

EU SUPPLY CHAIN

There is no current primary titanium ore mining nor titanium sponge (metal) production within the EU (Idoine et al. 2022, JRC 2022, Reichl & Schatz 2022). An average annual production of 571 kt of titanium compounds (pigments, oxides etc.) at the processing stage, during the period 2016-2020 is reported by Eurostat (Eurostat, 2021). The production of Ti compounds is taking place mainly in Germany and Finland. 1.6 million tonnes of metallic titanium and titanium compounds were imported by EU annually between 2016-2020. The estimation of the exact amount of each product is difficult since there is lack of data in the Eurostat database. Metallic titanium is mainly by China, while titanium compounds (with a Ti content between 41 and 65 wt.%) is imported by a wide number of countries including: Norway, South Africa, and United Kingdom. Around 93 ktonnes of metallic titanium and titanium compounds were annually exported to third countries during the same period. Mexico, India and Taiwan are the main trade partners concerning the exportation (Eurostat, 2021).

SUPPLY FROM PRIMARY MATERIALS

Titanium is typically produced form orthomagmatic iron-titanium-oxide (Fe-Ti-oxide) deposit, where it is mostly concentrated in ilmenite. Another important source of titanium is heavy-mineral sand deposits, where it occurs in ilmenite and rutile (Woodruf et al. 2013). A potentially significant hard-rock titanium source is in eclogites, where Ti is hosted by rutile. Only a small fraction of mined titanium minerals worldwide ends up as its use in metallic form. The main uses of titanium are TiO_2 in inorganic pigments for paints, plastics, and polymers. The metallic titanium is used mostly in aerospace industry.

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

GEOLOGY, RESOURCES AND RESERVES OF TITANIUM

GEOLOGY OCCURRENCE

The economically important sources for titanium metal and dioxide are ilmenite, titanite, anatase, leucoxene, rutile, and synthetic rutile. Since the ionic radius of titanium is similar to some other common elements, titanium is present in most minerals, rocks, and soils. However, there are few titanium minerals with more than 1% titanium content. Another relevant source of titanium is titaniferous slag, which can contain up to 95% titanium dioxide (Enghag 2004).

Heavy-mineral exploration and mining projects were underway in Australia, Madagascar, Mozambique, Tanzania, and Sri Lanka (USGS, since 2000). According to Minerals4EU (2019), some exploration is done for titanium in Spain, Sweden, Poland, Ukraine and Romania but with no further details.

GLOBAL RESOURCES AND RESERVES:

The resources and reserves for most of the Ti deposits are estimated by the amounts and compositions of mineral concentrates. This is especially important with the case of orthomagmatic iron-titanium-oxide deposits, where ilmenite is the major economic Ti-rich mineral. In these deposits, the economic value of titanium is typically estimated by the recovery of ilmenite by processing the ore. This is because ilmenite in these deposits may occur in different textures, i.e., it may occur as discrete grains, but also as lamellae in grains composed of magnetite and ilmenite (these composite grains are referred to ilmenomagnetite or titanomagnetite).

Table 11. Ilmenite reserves by country (USGS, 2022).

Country	Reserves for ilmenite (Mt)	Country	Reserves for ilmenite (Mt)
China	230	Mozambique	26
Australia	160	Madagascar	22
India	85	Ukraine	5.9
Brazil	43	United States	2.0
Norway	37	Vietnam	1.6
Canada	31	Kenya	0.4
South Africa	30	Other countries	26
Total, rounded	**700**		

NA = Not available.
The 'ilmenite' data of United States also includes domestic reserves of rutile.
Correction factor to estimate the Ti content of stoichiometric ilmenite ($FeTiO_3$) = 0.316.

USGS (2022) has estimated that the world resources of titanium are about 2000 Mt of titanium-bearing minerals including ilmenite, rutile and anatase of which ilmenite accounts for about 90 %, whereas the global reserves are about 700 Mt of ilmenite and 50 Mt of rutile. By using stoichiometric formula of ilmenite and rutile, it is here estimated from the values given by USGS (2022) that the global Ti resources and reserves are 688 Mt and 251 Mt, respectively (in TiO_2 content, the ilmenite resources are 419 Mt). The world reserves of ilmenite and rutile can be seen in Table 12 and Table 13.

Table 12. Rutile reserves by country (USGS, 2022).

Country	Reserves for rutile (Mt)
Australia	31
India	7.4
South Africa	6.5
Ukraine	2.5
Mozambique	0.89
Sierra Leone	0.49
Madagascar	0.40
Kenya	0.17
United States	NA
Other countries	NA
Total, rounded	49

NA = Not available.
Correction factor to estimate the Ti content of stoichiometric rutile (TiO_2) = 0.6.

One third of the global reported ilmenite reserves are in China (33 %), but also Australia (23 %) and India 12 %) have significant reserves. In Europe, 5 % of the ilmenite reserves are in Norway, and 1 % in Ukraine (Table 1). With rutile, most of the reserves are in Australia (63 %), India (15 %), and South Africa (13 %). In Europe, Ukraine contains 5 % of the global rutile reserves (Table 2). In Europe, the Ukrainian and Norwegian ilmenite and rutile reserves contain altogether 15 Mt of Ti metal, which is accounts for about 6 % of the global reserves.

EU RESOURCES AND RESERVES

According to European Minerals Yearbook (Minerals4EU 2022) the titanium resources of EU are in France, Slovakia, Portugal, Sweden, and Finland. Most of these resources are in Finland and Sweden which altogether amount to 42.2 Mt of Ti (70.4 Mt TiO_2).Table 13 presents titanium resources in the EU (For Finland, only the largest deposits are shown).

Table 13: Titanium resources data in the EU. Data collected from databases of the European Minerals Yearbook (Minerals4EU 2022) and Fennoscandian Ore Deposit Database (Eilu et al. 2022).

Country	Classification	Quantity (Mt of ore)	Grade (%)	Reporting code	Reporting date	Deposit, Source
France	?	0.84 (Ti-content)	?	Historic	?	?
Slovakia	?	0.068	16 % Ti or TiO2	Historic	?	?
	?	1.782	18.28% Ti or TiO_2	Historic	?	?
Portugal	?	0.69	21.12% Ti or TiO_2	Historic	?	?
Sweden	Not exploited	230	2.69 % Ti	Historic	?	Akkavare

	Closed mine	150	3 % Ti	Historic	?	Smålands Taberg
	Resources	140	5.7 % Ti	JORC	?	Routivare malmfält
	Not exploited	12.7	0.12 % Ti	Historic	?	Nakerivaara
	Not exploited	6	3 % Ti	Historic	?	Jerfojaure
	Not exploited	2.5	2.2 % Ti	Historic	?	Simesvallen
Finland	Not exploited	230	2.8 % Ti	Non-compliant	10/2006	Lumikangas
	Not exploited	200	3.2 %Ti	Non-compliant	10/1984	Perämaa
	Measured + indicated	103.7	0.563 % Ti	NI 43-101	10/2020	Mustavaara
	Indicated	38.60	4.9 % Ti	JORC	09/2006	Koivusaarenneva
	Inferred	30.09	4.0 % Ti			
	Indicated + inferred	14	7.6 % Ti	Non-compliant	2015	Otanmäki
	Closed mine	26.35	0.09 % Ti	Non-compliant	?	Jussarö
	Not exploited	20	2.14 % Ti	Non-compliant	?	Akanvaara gabbro
	Closed mine	19.6	2.84 % Ti	Non-compliant	05/2016	Riuttamaa

GLOBAL AND EU MINE PRODUCTION

According to British Geological Survey (Iodine et al. 2022), the annual global production of ilmenite and rutile concentrates in 2020 were 12.2 Mt and 0.6 Mt, respectively. The calculated total amount of TiO_2 based on these production numbers is 7.02 Mt (4.22 Mt Ti). In addition, USGS (2022) has estimated that in 2021, the global production was 8.40 Mt ilmenite and 0.63 Mt rutile which converted to TiO_2 is 5.05 Mt (3.03 Mt Ti). Another estimate of the global production, given by Reichl & Schatz (2022) for 2020 is 8.42 Mt TiO_2. It appears that these estimates differ slightly from each other. It is anticipated here that the estimate of Reichl & Schatz (2022) contains error in that it was made based on the amount of concentrate rather than the amount of titanium oxide.

Figure 28 and Figure 29 present the global mine production of TiO_2 since 1984 and 2000 according to WMD and (WMD, since 1984; USGS, since 2000). In the past, the main global producing countries have been Australia, South Africa, and Canada. For example, in 2000 these countries accounted for 70 % of global 2.64 Mt production of TiO_2 during the last decade new producers have appeared with increasing total global production. The new major producing countries are China and Mozambique. During 2020, for example, China, South Africa, Mozambique, and Australia accounted altogether 65 % of the global production. Starting from 2009, the African countries Kenya, Senegal and Madagascar have started producing ilmenite and rutile concentrates, and presently, these countries produce 10 % of global titanium. In Europe, Ukraine has been producing up to 0.3 Mt TiO_2 annually and presently the country accounts 7 % of the global TiO_2 production. Norway is another European country producing TiO_2 and presently it accounts for about 5 % of global production.

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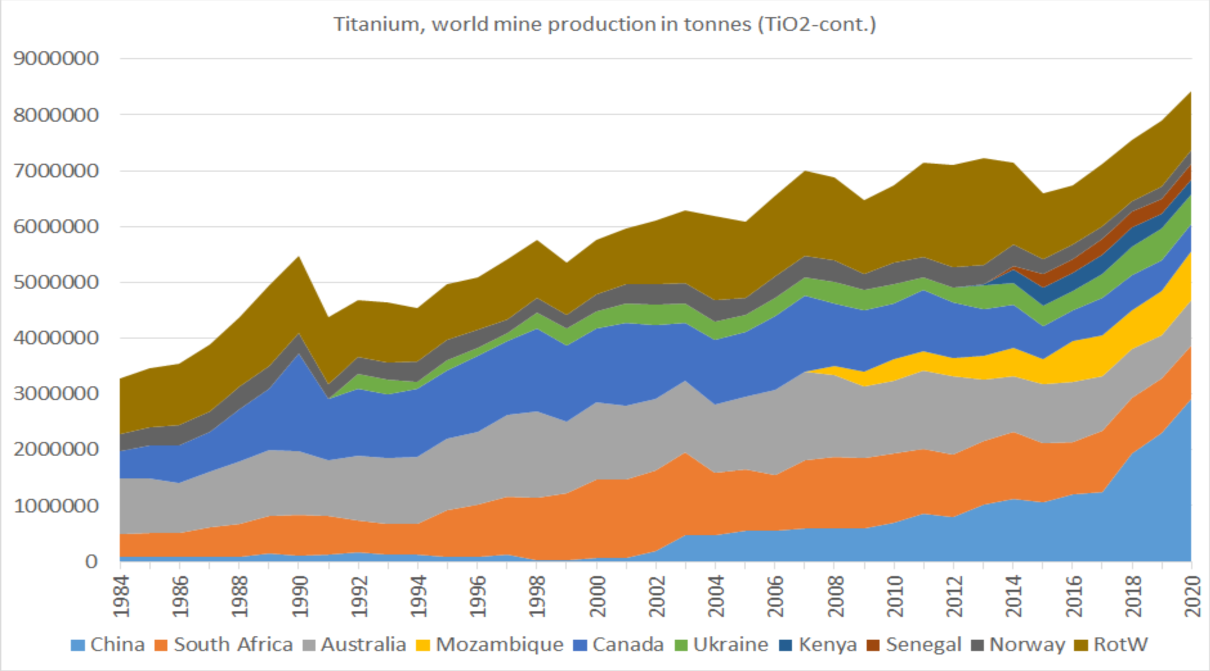

Figure 28: Global mine production of Ti (shown as TiO2) in tonnes since 1984 (WMD, since 1984).

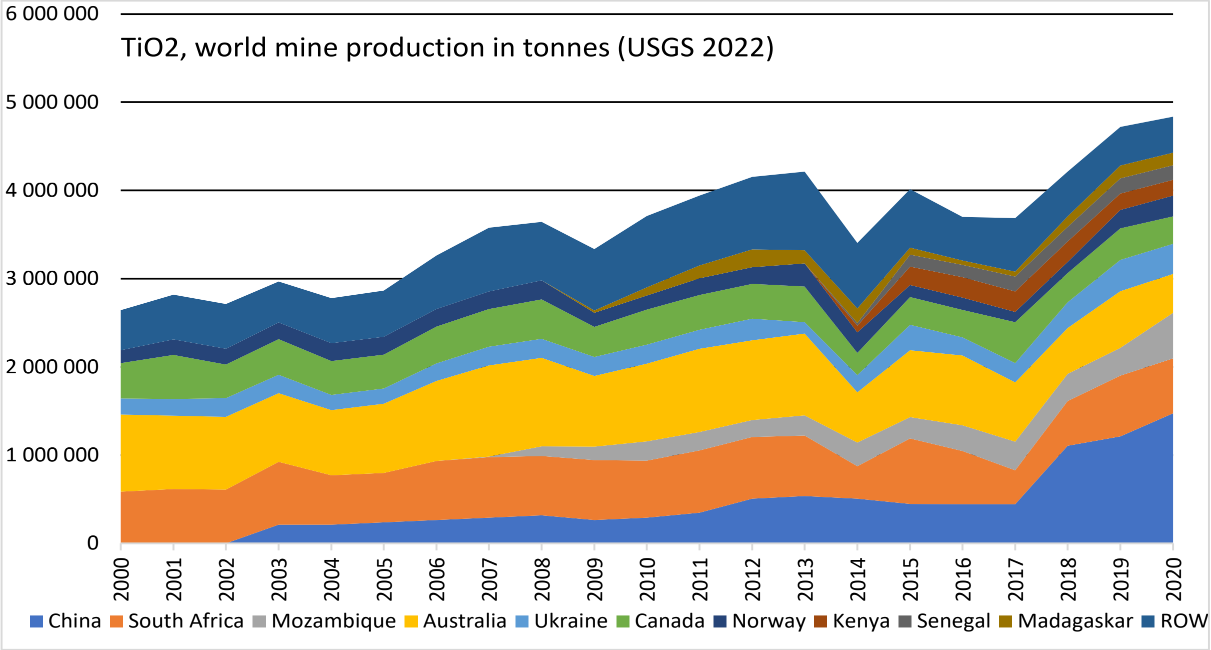

Figure 29: Global mine production of Ti (shown as TiO2) in tonnes since 2000 (USGS, since 2000).

OUTLOOK FOR SUPPLY

At present, around 25 companies predominantly are involved in the titanium industry worldwide. However, the market is highly uncertain in supply and demand. The titanium market is driven by the increase in aerospace and aircraft productions, the enormously expanding construction sector, and the development of lightweight and energy-efficient vehicles. Accordingly, various new ways of TiO_2 application have presently emerged, which would aid the titanium industry to remain on track. The compound annual growth rate (CAGR) s for the production of ilmenite and rutile are 1.73% and 1.40%, respectively during the period of the forecast until 2025 (Subasinghe and Ratnayake, 2022).

SUPPLY FROM SECONDARY MATERIALS/RECYCLING

POST-CONSUMER RECYCLING (OLD SCRAP)

The major resource in titanium recycling is in-house scraps generated during smelting and fabrication processes, and the actual recycling rate of titanium, including the in-house cascade recycling rate, is high. The major and problematic impurities contained in the titanium scrap are oxygen and iron. High-grade titanium scraps with low oxygen and iron concentrations are recycled to titanium and its alloy ingots by remelting. Low-grade titanium scraps with high oxygen and iron concentrations are utilized as the raw material of ferro-titanium for the steel industry (Takeda et al. 2020).

In 2012, about 35,000 t of new scrap and 1,000 t of old scrap were recycled. Whereas the steel industry used about 10,000 t of recycled titanium and ferrotitanium, 1,000 t were used by the super-alloy industry and further 1,000 t by other industries. Today, recycled content from old scrap accounts for 6% of the entire use. In the future, recycled titanium will only cover a small share of the demand, due to a fast rising consumption (UNEP, 2011).

Processing and consequently using titanium scrap is a longstanding practice with patens dating back to the 1950s. The cold hearth melting process contributed to a greater input of secondary titanium starting from the 1980s. (Newman, 2015)

The end of life recycling input rate for titanium is estimated to be 19%, using the UNEP methodology (UNEP, 2011) (SCRREEN workshops 2019). For the primary material input we take the amount found in this study from (BGS, 2019) of 12,345 kt. The (UNEP, 2011) report offers amounts of scrap of titanium that are used worldwide. A recycled end-of-life material input (old scrap) of 2,716 kt, an amount of scrap used in fabrication (new and old scrap) 1,630 kt and scrap used in production (new and old scrap) of 244 kt.

The recovery of titanium by red mud residue has been described in several laboratory and pilot scale studies in the past, however it is not implemented in the industry so far. Ti recovery by red mud, simultaneously with other metallic values such as alumina and scandium, is generally performed through high-pressure acid (usually hydrochloric) leaching followed by successive steps of precipitation and solvent extraction. Finally, a titanium oxide-rich concentrate (with Ti content >20%) is obtained (Grudinsky et al. 2022).

PROCESSING

TITANIUM MINING

Titanium chiefly is obtained from the minerals rutile, ilmenite and rarely from anatase (beta-titanium dioxide). Other titanium-bearing minerals include perovskite, sphene and titanite. Titanium can be mined from intrusive crystalline rocks, weathered rock and unconsolidated sediments. Half of all Titanium mined comes from

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unconsolidated sediments known as shoreline placer deposits. Placers are alluvial deposits formed by rivers as they reach the sea. Suspended sediments have different densities known as specific gravities. A river will deposit different sediments as its speed fluctuates, forming separate layers of sediment. Titanium's ores, ilmenite and rutile are both found in placers worldwide. Placer deposit mining is either done as a wet dredge or dry mining operation. The presence and height of the water table where the deposit is found dictates which method is the most suitable to be applied. In wet dredge mining, an artificial pond is created by digging below the water table. In some cases mining ponds are filled using water pumps. A suction bucket wheel attached to a floating dredge is used to remove heavy mineral sediment from the ground, which is then concentrated by passing it through a set of inclined cylindrical trommel screens. While these are rotating the material that is too small for processing falls through the screens. The particles that make it this far are then sorted by a spiral concentrator where a chute sorts particles suspended in water based on their size and density. The high-density particles stay closest to the inside of the spiral chutes cross-section with the lower density particles on the outside edge. Hence, the sorted sediments are collected in separate containers. On the other hand, dry mining of ilmenite and rutile is carried out with conventional mechanical excavation including excavators, scrapers, loaders and bulldozers. Like wet dredging, the sediments from dry mining also need to be concentrated, following the aforementioned process but without water in the spiral concentrator. After the minerals have been concentrated they are put through the feed preparation plant where they are cleaned with attrition scrubbers and subjected to additional gravity concentration before undergoing froth flotation which can remove sulphides or other local unwanted sediment. The last step is the dry mill, where a combination of magnetic and electrostatic separation is used to improve the quality of the ore. Titanium's ores ilmenite and rutile are conductive because of their iron content and can be easily separated from zircon and unwanted silicates. After the dry mill, the ore is ready for further processing.

PRODUCTION OF TITANIUM DIOXIDE AND METAL

Table 14. World production of titanium sponge (USGS 2022)

Country	2016	2017	2018	2019	2020
China	60000	72000	75000	85000	123000
Japan	54000	51000	49000	49000	49200
Russia	38000	40000	44000	44000	31000
Kazakhstan	9000	9000	16000	16000	15000
USA*	9825	9825	9825	9825	9825
Ukraine	8000	8000	8000	8000	5000
South Arabia				100	2800
India	500	500	250	250	250
Total	179325	190325	202075	212175	236075

* data for USA not available on USGS, estimated at 75% of the production capacity

Titanium was first isolated as a pure metal in 1910, but it wasn't until 1948 that metal was produced commercially using the Kroll process (named after its developer, William Kroll) to reduce titanium tetrachloride with magnesium to produce titanium metal (Zheng and Okabe, 2010; Bordbar, Yousefi and Abedini, 2017). The steps involved include extraction, purification, sponge production, alloy creation, and

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forming and shaping (Figure 30). The production of titanium metal accounts for only 5% of annual titanium mineral consumption.

In Europe and the United States (European and North American markets respectively), many manufacturers specialize in different phases of this production. For example, there are manufacturers that just make the sponge, others that only melt and create the alloy, and still others that produce the final products (ITA 2019).

Titanium dioxide is produced from raw materials mainly through the sulphate process or the more environmentally acceptable carbo-chlorination process that converts TiO_2 into $TiCl_4$ (Zheng and Okabe, 2010; Bordbar, Yousefi and Abedini, 2017). The choice for a process at this stage depends on for instance the titanium material content of the ore, the desired resulting pigments and the allowable amount of waste (ECI, 2016). The latter process also supplies the $TiCl_4$ necessary for the production of titanium metal.

Environmental and economic constraints dictate that the ore feed stocks converted by carbo-chlorination processes now in use contain greater than 90% titanium dioxide. Nevertheless, only natural rutile meets this requirement, while ilmenite can be upgraded through combinations of pyrometallurgical and hydrometallurgical techniques to produce a synthetic rutile of 90% to 93% TiO_2. In addition, titaniferous magnetite ores can be smelted to produce pig iron and titanium-rich slags. Rutile, leucoxene, synthetic rutile, and slag can then be mixed to provide a feed stock of more than 90% TiO_2 for the chlorination process (Zhang 2011).

The extracted materials undergo several chemical reactions resulting in the creation of impure titanium tetrachloride ($TiCl_4$) and carbon monoxide. Impurities are a result of the fact that pure titanium dioxide is not used at the start. Therefore the various unwanted metal chlorides that are produced must be removed (Zheng and Okabe, 2010; Roskill, 2019).

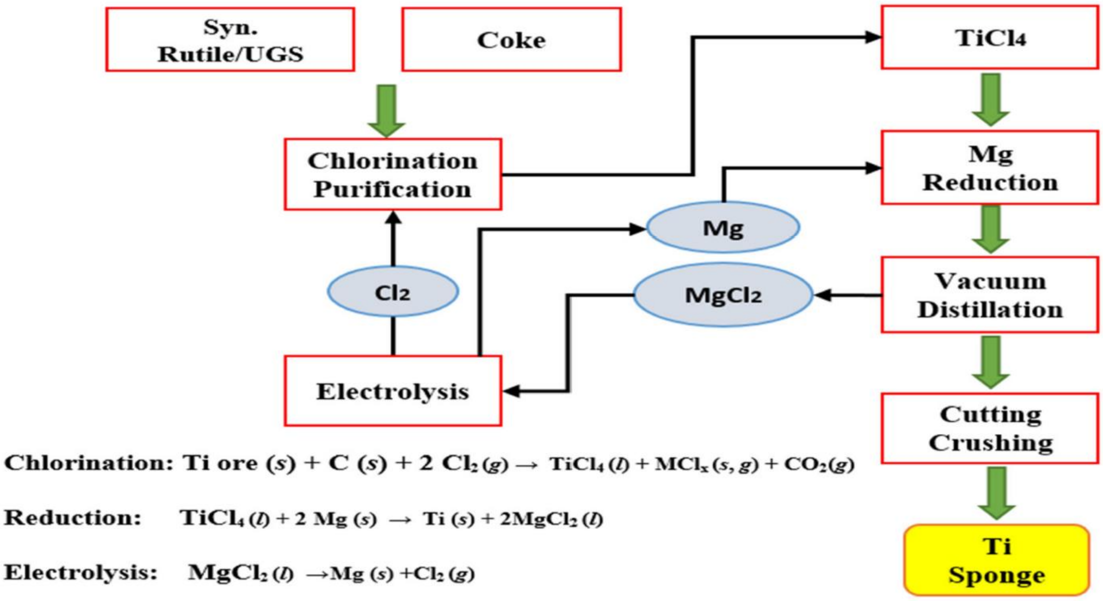

Figure 30: Scheme and reactions of the Kroll process of titanium sponge production (El Khalloufi et al. 2021).

The reacted metal is purified by distillation and precipitation and treated with magnesium. The titanium solid is removed from the reactor by boring and then it is treated with water and hydrochloric acid to remove excess magnesium and magnesium chloride. The resulting solid is a porous metal called a sponge. The pure titanium sponge can then be converted into a usable alloy via a consumable-electrode arc furnace. At this point, the sponge is mixed with the various alloy additions and scrap metal. The exact proportion of sponge to alloy material is formulated in a lab prior to production. This mass is then pressed into compacts and welded together, forming a sponge electrode (Bhushan Ishwar 2016).

OTHER CONSIDERATIONS

ACRONYMS AND DEFINITIONS

CLP	Regulation (EC) No 1272/2008 on the classification, labelling and packaging of substances and mixtures (CLP Regulation)
ECHA	European Chemicals Agency
EEA	European Economic Area (EU + Norway, Liechtenstein and Iceland)
IARC	International Agency for Research on Cancer
LCA	Life cycle assessment
LCGT	Low carbon and/or green technologies
Normative requirements	Legislation and standards other than company-specific ones
REACH	Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)

COMPOUDS AT ANY STAGE OF THE LIFE CYCLE

The CPL regulation categorises the titanium dioxide (TiO_2) powder with aerodynamic diameter smaller than 10 µm as carcinogenic level 2, *suspected of causing cancer*, given the scientifically confirmed evidence of its hazard to health when inhaled (CPL, 2008). According to (IARC, 2022), TiO_2 carcinogenicity is classified as 2B, *possibly carcinogenic*, while titanium alloys carcinogenicity is classified as 3, *not classifiable as to its carcinogenicity to humans*. TiO_2 is also contained in the food additive E171, used to provide white colour and opacity to foodstuff, and is suspected by scientists of being carcinogenic. Thus, following the precautionary principle, the Commission Regulation (EU) 2022/63 amended Annexes II and III to Regulation (EC) No 1333/2008, stating that TiO_2 shall no longer be used as a food additive in the European market, except for medicines and drugs. Moreover, the regulation defines a period of three years during which the Commission shall consult the European Medicines Agency about the necessity to maintain or remove E171 from the list of food additives allowed in the EU (Food additive titanium dioxide, 2022).

Finally, Kyeong et al. (2020) studied dental titanium bio-implants and showed that corrosion could lead to deposits of particles of Ti and Ti-alloys in the bones. This could cause inflammatory reactions and eventually to failing osseointegration of the implant.

ENVIRONMENTAL ISSUES

Metallic titanium can be found in water streams, and it can bioaccumulate in various animal species. Impacts on the trophic chain are still under study, but the presence of this material in the environment is suspected of causing serious threats to human and non-human animals, vegetation, and bacteria (Markowska-Szczupak et al., 2020).

An LCA study of novel and sustainable lubrication methods for machining pure titanium and titanium alloys shows that optimized fluidification systems allow for reducing energy consumption and, in general, impact on the natural environment and human health (Gupta et al., 2018; Khanna et al., 2021).

An LCA study on titanium oxide nanorods used as electron transport layers for perovskite solar cells, with a lifetime of three years, demonstrated that the lifecycle greenhouse gas emissions are 182 g of CO2eq/kWh, which is slightly higher than the established solar technologies. On the other side, the energy payback time is about one year, which is lower than competitor technologies. Thus, the study demonstrates that TiO2 nanorods are a promising technology for solar energy production but that their efficiency rate must be incremented to be competitive with alternative technologies (Harshadeep et al., 2021).

On the other hand, the assessment of production methods of TiO2 nanoparticles show that the routes with the lowest environmental impacts in terms of global warming potential and energy consumption are those based on the use of chemicals, like the sol-gel process. Physical methods have higher energy demand but facilitate a wider spectrum of industrial applications (Fan et al., 2019).

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

The International Titanium Association (ITA) prepared a set of compliance Guidelines to support companies to comply with relevant antitrust laws. In addition, members of ITA also adopted a special resolution according to which ITA meetings and facilities shall not be used to exchange information on the price of titanium (ITA 2022).

The ITA also provide information on the NFPA Standard of Combustible Metals, published back in 2012, where chapter 12 is specifically dedicated to safety guidelines for handling titanium (NFPA 2012).

Specifically regarding the use of titanium in the dentistry sector, the GermanS3 guideline on titanium hypersensitivity in implant dentistry was developed (Muller-Heupt 2022).

SOCIO-ECONOMIC AND ETHICAL ISSUES

ECONOMIC IMPORTANCE OF THE TITANIUM FOR EXPORTING COUNTRIES

Table 15 lists the countries for which the economic value of titanium product exports represents more than 0.1 % of the total value of their exports.

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Table 15: Countries with the highest economic shares of titanium exports in their total exports.

Country	Export value (USD)	Share in total exports (%)
Mozambique	180,499,504	5.2
Madagascar	96,693,862	4.9
Senegal	108,089,816	2.8
Kenya	156,956,350	2.6
South Africa	487,044,439	0.6
Ukraine	171,959,810	0.3
Kazakhstan	123,535,856	0.3

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

In Mozambique, Madagascar, Senegal and Kenya, the share of titanium exports in the total exports is higher than 2 %. In these countries, almost all titanium exports are in the form of ores and concentrates. On the other side, Kazakhstan exports titanium only as unwrought, powders. Finally, Ukraine has a mixed export portfolio, with 82 % of ores and concentrates, and 18 % of unwrought, powders.

SOCIAL AND ETHICAL ASPECTS

In 2001 the company Tiomin (K) started operations to build a new titanium mine in the Kwale region, in Kenya. For this reason, between 2001 and 2007 at least 7,000 people were displaced from their homeland and forced to move to other villages or cities. The Kenyan government provided the displaced population with economic compensation, but for most this was insufficient and not able to replace the loss, since their land played a central role in people's life and was considered sacred (Abuya, W., 2017; Abuya, W., 2016).

Since 2013, the Australian company Base Titanium Limited has been extracting the mineral in the KWALE region. The company constituted an Environment and Community Affairs department to create community awareness by providing project information to stakeholders through discussion, drama, formal presentations and display events in schools and village centres. The company aspires to help developing the local community by providing social infrastructure and educational opportunities, promoting livelihood upliftment and enhancement programmes, and improving community health. Mining operations thus have led to enhanced education, health, and nutrition levels. But excavations resulted in the displacement of people, animals and farming areas and caused conflicts on land ownership, land use and land value on top of increasing dust, noise, and water pollution. Furthermore, the company's efforts involuntarily created a dependency culture among the local community of Kwale County. It is foreseen that the closure of the mine, expected by late 2023, will cause a reduction of the employment and thus migration of inhabitants formerly employed by Base Titanium. (Evers, B., 2020)

Quebec Iron and Titanium Madagascar Minerals (QMM) is currently exploiting titanium in Taolagnaro, Southeast Madagascar. Since the start of the operations in 2013, the local population has strongly opposed the project through strikes, road blockage and trapping of about 200 QMM workers. The soil excavations and the construction of a dam have reduced access to water and the livelihood of the area, in addition to diminishing fishing stocks and access to fishing sites. As for environmental impacts, titanium mining has highly altered the biodiversity and habitat of the area, which is fundamental for the local economy as it guarantees to farm and graze, and it is becoming a growing source of income for its potential to attract ecological tourism (Climate Diplomacy, 2023; EJOLT, 2013).

In the Ninh Thuan province, Vietnam, the company Quang Thuan started operations in August 2012. In December 2012, the provincial government ordered a temporary suspension of the business, on top of requesting an Environmental Impact Assessment and the establishment of clean water facilities for the local populations. In 2013 the company obtained permission to restart the operations in part of the mining area, regardless of not having provided a water treatment facility to the local villagers. In 2014, when Quang Thuan was able to get back to full activity, the local population went on strike, blocking Vietnam National Highway 1 and setting fire to one of the company's factories (EJA, 2015; Dan Bao Lam, 2014; VIR, 2014). According to recent news, the mine is still operating, and a landslide caused the death of four workers in October 2022 (VNExpress, 2022).

RESEARCH AND DEVELOPMENT TRENDS

RESEARCH AND DEVELOPMENT TRENDS FOR LOW-CARBON AND GREEN TECHNOLOGIES

- HyCat[4] project: In-situ fabricated hydrogen evolution catalysts for alkaline water electrolysis - (EU 2020-2022)

The project aimed at developing an innovative TiO_2 nanostructure for hydrogen energy production, with the objective of reducing production costs. This should be achieved by minimizing the content of platinum, the most used material in the catalyst industry, in spite of its scarcity and high cost. To produce the electrocatalyst, metallic copper is coated over TiO_2 current collectors. Later, a solution containing platinum salt is added to the structure, providing the catalyst with a coating of dispersed platinum nanoparticles, increasing the efficiency of water hydrolysis. Results from a small pilot project show that a 2.5 kW electrolyser can produce around 1 kg of hydrogen per day, which is enough to power a house.

- MMTec [5] project: New aerospace advanced cost-effective materials and rapid manufacturing technologies- (EU, 2015-2019)

MMTec focused on the development of technologies and methodologies with the potential of minimizing the cost and time of aircraft production. A 45 % price and time reduction were expected for manufacturing titanium-aluminium alloy components. A new machining architecture was defined to reliably deposit TiO_2 nanoparticles on the alloy. The novel manufacturing technology was tested on three products: an aerospace blade, an automotive exhaust flange and a turbine impellor for an electric aircraft range extender. Results showed a component weight reduction of 45 %, which did positively affect fuel consumption. Moreover, the cost of the devices was reduced by 45 %, and production time by 10 %.

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[4] https://cordis.europa.eu/project/id/899412

[5] https://cordis.europa.eu/project/id/633776/reporting

OTHER RESEARCH AND DEVELOPMENT TRENDS

There is a high number of research around titanium in alloys and in various other contexts, from which the below represents a selection.

- TiPlate[6]: Industrial Titanium-Plating Process for the Manufacturing of Light-Weight Composite Parts (2020 – 2023, EU)

There is a wide range of industrial activities that require cost-efficient and lightweight composite parts. Israeli company Polymertal has created a surface etching method that can produce hybrid metal-polymer components of complex geometries using innovative 3D printing technology and metal post-treatment industrial processes. The company envisages using titanium-based parts because of titanium's strength-to-density ratio, resistance to corrosion and biocompatibility. However, the final costs of titanium-based parts are high. The EU-funded TiPlate project is supporting the development of an innovative titanium-plating process that permits the manufacturing of lightweight, high performance, corrosion-resistant, biocompatible titanium-plated polymer components and final parts. The project is working towards process development and optimisation, aiming to offer the medical and aerospace industries a cost-effective alternative

- TiCoAJo[7]: TItanium COmposite Adhesive Joints (2017 – 2019, EU)

Future aircraft will have to be more fuel efficient in order to accomplish sustainable air transport growth. One of the key enablers to achieve this fuel efficiency is drag reduction by improved aerodynamic efficiency. On its turn, a key enabler within this aerodynamic efficiency is air foil drag reduction by laminar flow control. The relevant technologies involve a hybrid joining of titanium and carbon fibre reinforced polymer for the leading edge design. For a successful implementation of this concept the fracture properties (i.e. strain energy release rates) of this joint must be reliably determined experimentally to pave the way towards more precise numerical tools development for the critical design of such joints. A full experimental characterization of the mode I, II and mixed mode fracture properties of three different joining technologies under quasi-static, fatigue and high strain rate loading in ambient, hot/wet and low-temperature conditions is thus required and targeted in this project.

- GOTA[8]: Greater Operating Temperature Alloy (2012 – 2016, EU)

GOTA selected a titanium alloy capable of being fabricated into intermediate compressor casings, and enduring operating temperatures of at least 500 deg C in this service. Industrial manufacture of the selected alloy was be demonstrated, by the production of rolled rings; gravity cast and centrifugally cast samples; sheets, welding wire, and welded samples.

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[6] CORDIS: https://cordis.europa.eu/project/id/960140
[7] CORDIS: https://cordis.europa.eu/project/id/737785
[8] CORDIS: https://cordis.europa.eu/project/id/323378

- DefTiMOFs[9]: A systematic approach to controlling defect chemistry in titanium–organic frameworks

Metal organic frameworks (MOFs) porous materials with very high chemical and structural diversity are highly promising materials that are widely used in applications such as gas storage and separation, electrochemical energy storage, catalysis and sensing. Structural defects play an important role in material behaviour and can be used as a tool to modify MOFs' porosity, chemical reactivity and electronic conductivity. Funded by the Marie Skłodowska-Curie Actions programme, the DefTiMOFs project will develop a high-throughput synthetic methodology for controlling the defect chemistry, particle size and porosity of titanium MOFs. This class of compounds has hitherto received little attention. The project will also employ synchrotron-based methods to characterise the defects on an atomic and a molecular level.

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[9] CORDIS: https://cordis.europa.eu/project/id/837804

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