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GOVERNMENT OF BRAZIL MINING SECTOR TECHNICAL SUPPORT AND COOPERATION

Titanium – Market Analysis and Competitiveness Report

Prepared for:
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Prepared by:
Deloitte & Touche LLP
1919 N. Lynn Street
Arlington, VA 22209

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DISCLAIMER

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Acronyms

ANM	Agência Nacional de Mineração
CAGR	Compound Annual Growth Rate
CPRM	Geological Survey of Brazil
DERA	German Mineral Resources Agency
DFS	Definitive Feasibility Study
DOS	Department of State
EMGP	Energy and Mineral Governance Program
ENR	Bureau of Energy Resources
EV	Electric Vehicles
$FeTiO_3$	Ilmenite
FID	Final Investment Decision
GDP	Gross Domestic Product
HMS	Heavy Mineral Sands
MME	Ministry of Mines and Energy
PEA	Preliminary Economic Assessment
PFS	Pre-feasibility Study
REE	Rare Earth Elements
TiO_2	Titanium Dioxide
TZMI	TZ Minerals International
USGS	U.S. Geological Survey
UV	Ultraviolet

EXECUTIVE SUMMARY

Deloitte is implementing the *Government of Brazil Mining Sector Technical Support and Cooperation* Task Order (the Project) under Deloitte's Blanket Purchase Agreement (BPA) with the U.S. Department of State (DOS) in support of the Bureau of Energy Resources' (ENR) Energy and Minerals Governance Program (EMGP). The Deloitte team is providing technical assistance to support the Government of Brazil's Ministry of Mines and Energy (MME) and the Geological Survey of Brazil (CPRM) as they seek to improve their ability to:

- Develop safe, sustainable, and effective mine closure procedures and use of tailings, including methods of tailings sampling and characterization, based on international leading practices, to protect and improve the legacy of ongoing and future projects, thereby realizing sustainable benefits from the extractives industry;
- Manage a growing mineral sector and compete effectively in the global market, given a growing market and accelerated demand for critical minerals that are essential to the development of innovative technologies to advance the global clean energy transition (electric vehicles [EVs], batteries, and battery storage systems, etc.); and
- Streamline the structure of Brazil's nickel-cobalt data inventory, so Brazil can improve its understanding and increase development of critical minerals.

Under *Task 2A: Economic Viability and Global Market Competitiveness of Specific Minerals*, the Deloitte team is developing a series of reports focused on nine minerals including, graphite, lithium, nickel, cobalt, rare earth elements (REEs), titanium, vanadium, tantalum, and copper. The purpose of these reports is to provide recommendations to the Government of Brazil on where and how Brazil could compete most effectively and inform their long-term strategic planning for commercialization of minerals based on global market trends and challenges to mineral resource development that may inhibit Brazil's overall market competitiveness. The Deloitte team's recommendations will also inform the National Plan for the Brazilian Mineral Sector 2050 and future policy actions for the Government of Brazil. This report focuses on titanium.

Key Findings

- **Brazil is a relatively small producer of titanium.** In 2021, Brazil produced 66 thousand tonnes (kt) of titanium dioxide (TiO_2), which accounted for 0.7 percent of global TiO_2 production.[1] The largest global producers of TiO_2 are China (33 percent), South Africa (12 percent), Mozambique (11 percent), and Australia (8 percent). In Brazil, there are currently two producers of TiO_2: Tronox Pigmentos do Brasil (operating the Paraíba mine), and Indústrias Nucleares do Brasil (operating the Bueno mine). The Paraíba mine is scheduled to close at the end of 2023 due to resource depletion.[2]

[1] United States Geological Survey (USGS).

[2] The main use of titanium feedstock is to produce titanium pigments (90 percent of global TiO2 demand) for use in paints and plastics, principally as an opacifier. Some 6 percent of global output is used to make titanium metal for use in aerospace and defense, and in chemical processing plants. The balance is used for direct use in products, principally as a flux.

- **Brazil has unexploited titanium resources.** Brazil holds 90.7 million tonnes, or about 3.7 percent, of global titanium reserves and resources, as reported by S&P Global Intelligence. World titanium reserves and resources are concentrated in Australia (23 percent), Paraguay (16 percent), and South Africa (13 percent). Mozambique, Russia, Canada, and the United States also hold significant resources (See Table 2 for more details). Titanium reserves in Brazil are mainly located on the northeast coast of Paraíba.[3] Other important ilmenite deposits[4] have not yet been fully evaluated and occur along the Brazilian coastline in the form of beach placer deposits or marine terraces.
- **Two companies are seeking to expand titanium production in Brazil.** New titanium capacity is expected sometime in 2023 from Largo Resources [TSX: LGO], which is planning to construct an ilmenite concentration plant at its existing Maracás Menchen vanadium mine and a TiO_2 pigment processing plant in Camaçari. In addition, Jangada Mines [LSE: JAN] completed a feasibility study of the Pitombeiras project in Ceará in April 2022. The planned Pitombeiras mining operation is expected to focus on the direct extraction/export of a high vanadium-content iron ore, although Jangada Mines are also assessing the potential to extract TiO_2 from the tailings (*See* pg. 9 for more details).
- **Currently, there are limited opportunities for Brazil to expand titanium production.** As noted above, Brazil has significant titanium prospectivity, but there appears to be insufficient activity to bring the majority of those potential resources through the exploration process towards commercial viability. The only recent report of titanium exploration in Brazil was in May 2022, when U.S.- based Energy Fuels [NYSE: UUUU] announced an agreement to acquire the Bahia heavy mineral sands project, located on the coast in the State of Bahia. Energy Fuels stated that it planned to perform exploration work during 2022, and a preliminary economic assessment (PEA) is anticipated to be developed in the first half of 2023.[5]

Key Recommendations

The titanium market is not large in size or value (compared with other major commodities), but it is a commodity important to consumer markets, as a pigment in paints, plastics, enamels and paper. The Government of Brazil should continue to allow the development of existing titanium assets and should encourage the development of further titanium resources in the longer term - either on a stand-alone basis or as a by-product in association with another commodity, such as vanadium. Given titanium's importance to consumer markets, local consumption of TiO_2 pigment is likely to continue rising as Brazil's gross domestic product (GDP) per person rises, the use of TiO_2-related products expands, and the per capita consumption of TiO_2 correspondingly increases. Brazil should be able to meet this new demand domestically, rather than rely on imports.

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[3] S&P Global Intelligence

[4] Titanium minerals are found in hard rock deposits and in mineral sands deposits. Mineral sands are the most abundant class of economic titanium deposits and contain heavy minerals including titanium minerals. The most important, naturally occurring minerals that are mined to produce TiO_2 feedstock are ilmenite and rutile. Ilmenite is the most common titanium-rich mineral in the Earth's crust and accounts for 92 percent of the world's titanium mineral production.

[5] Energy Fuels has not released any publicly available information on the status of the Bahia project since May 2022.

Indeed, if higher living standards raise Brazil's titanium consumption closer to U.S. levels, it will require over 400 kt/y more of TiO2; an increase of over 500% above current levels of domestic production.

Brazil should consider enhancing titanium-related investment in the longer term by:

- **Examining the potential of Largo Resources upgrading its planned TiO_2 pigment plant from a sulfate plant to a chloride plant.[6]** While the choice of plant is partly dependent on the quality of ilmenite and the TiO_2 pigment demands of the end-market, it may be possible to install a titanium slag upgrading plant and a chloride pigment operation, instead of a sulfate pigment plant. The sulfate process is older, less efficient, and produces a number of waste products that are difficult to treat, while the chloride process uses high grade feedstock to produce high quality TiO_2 pigment. The chloride process offers waste disposal, energy, and quality advantages over the sulfate process. Switching to a chloride plant may result in higher capital costs and additional technology requirements, but the benefits include significantly lower environmental footprint and a higher quality TiO_2 pigment, which is in strong global demand.[7]
- **Increasing access to, and circulation of, up to date titanium resource data to domestic and international exploration to promote titanium development in Brazil.** Increasing access to data may require gathering and distributing more extensive information from those regions (*e.g.,* Paraiba) that are considered to have significant titanium potential. Legacy CPRM geological data, reports, and studies should be made more broadly available online in a range of languages. Brazil should also undertake appropriate marketing of these documents to expand their circulation and increase their impact.

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[6] The Largo Resources TiO_2 pigment plant has not yet been built.

[7] Titanium dioxide pigments are produced from two chemical processes: the sulfate and the chloride process. China, the main producer of sulphate pigment, is recently building predominantly new chloride plants.

1. INTRODUCTION

1.1. Purpose of this Report

This Report provides a detailed analysis of the global titanium market, the current and future dynamics of the industry, plus potential opportunities and possible risks associated with titanium development. The Report analyzes global titanium resources, supply and demand dynamics, technological and industrial drivers, current and future mineral producers and processors, and titanium market economics. The Report also examines Brazil's position within the current titanium market, and its potential positioning in the future, thereby enabling MME and CPRM to make informed decisions about future policy actions in the sector.

2.1. Organization of this Report

This Report is organized into nine main sections and three annexes:

- **Section 1: Introduction** – Presents the purpose of this Report, background and context on titanium, and a summary of market trends and outlook for titanium.
- **Section 2: Titanium Characteristics** – Provides background information on titanium's physical characteristics and applications.
- **Section 3: Titanium Resources** – Provides information on global titanium reserves and resources.
- **Section 4: Titanium Supply** – Gives an overview of the global production of titanium ores and titanium products, recent supply trends, and the supply outlook.
- **Section 5: Titanium Demand** – Explains global titanium demand trends based on end-user markets and examines the demand outlook.
- **Section 6: Titanium Trade and Prices** – Provides information on the main features of global titanium trade and presents historical pricing data.
- **Section 7: Market Balance –** Outlines the key factors in considering the outlook for titanium.
- **Section 8: Economic Competitiveness –** Looks at the available information to consider economic competitiveness within the titanium industry.
- **Section 9: Conclusions and Key Recommendations** – Summarizes the Deloitte team's analysis of the titanium market and presents key recommendations for the Government of Brazil to inform future policy actions.
- **Annex 1** – Provides a description of titanium ores and resources.
- **Annex 2** – Provides a description of mining and processing of titanium ores.
- **Annex 3** – Summarizes the recent consolidation within the titanium industry.

1.2. Background and Context

Brazil is a producer of titanium, accounting for 0.7 percent of global TiO_2 production. Brazil also has about 6.1 percent of titanium reserves[8]. Titanium is a relatively small commodity market in both volume and value. The industry is somewhat opaque and data on production and processing is limited.

[8] USGS.

Titanium is a critical and strategic mineral for the United States, Europe, and many other economies because of the unique properties of both titanium metal (and its alloys) and TiO_2 pigment (90 percent of global TiO_2 demand is for use in paints and plastics). There are no completely satisfactory substitutes for titanium, especially titanium metal, which is used in aerospace and defense. Furthermore, both the titanium feedstock and pigment industries are dominated by just 4 – 5 companies in each market, with China playing a significant role in both markets.

The Deloitte team drafted this Report following the Russian invasion of Ukraine. Ukraine is a producer of titanium minerals and pigments, and in 2021 it accounted for 5.8 percent of global TiO_2 production. Ukraine's TiO_2 operations are located in the Southwest and the North of the country. Russia is also a significant producer of finished aerospace-grade titanium through the company VSMPO-AVISMA, and is reported to be the main supplier to western original-equipment manufacturers (OEMs) and engines manufacturers. Russia is estimated to produce approximately 13 percent of global titanium sponge[9]. TiO_2 feedstock for Russian titanium production is imported from a number of companies, and before the invasion, it also included Ukraine. While Russia's war on Ukraine, may have disrupted the supply chains and put more pressure on global titanium mineral supplies, there have been no sanctions on titanium production from Russia, including production from VSMPO-AVISMA. This Report does not analyze the possible consequences of future sanctions on Russian production or the reduction in supply from Ukraine due to the war.[10]

1.3. Summary of Market Trends and Outlook for Titanium

1.3.1. Titanium Resources

Titanium, in its metallic form, cannot be easily found in nature and most of the titanium produced by mining and processing companies is in the form of TiO_2. Economic concentrations of titanium are mainly comprised of two minerals; ilmenite and rutile. Ilmenite is the most common titanium mineral in the Earth's crust and accounts for 92 percent of the world's titanium mineral production. These titanium minerals are mainly sourced from heavy mineral sands (alluvial deposits) but are also mined from hard rock deposits. World titanium reserves and resources are concentrated in Australia (23 percent), Paraguay (13 percent), and South Africa (13 percent), with Mozambique, Russia, Canada, and the United States also holding significant resources.

Brazil holds about *6.1 percent of global titanium reserves* as reported by the USGS, and *3.7 percent of global titanium reserves and resources* as reported by S&P Global Intelligence. These are mainly located on the northeast coast of Paraíba. Other important ilmenite deposits not yet properly evaluated occur along the Brazilian coastline, in the form of deposits of beach placers or in marine terraces, on the northeast, southeast, and south coast of the country. In February 2023, U.S.-based Energy Fuels [NYSE: UUUU] completed the acquisition of the Bahia project, located on the coast in the State of Bahia, and an exploration drilling program is underway with the aim of identifying and reporting an initial mineral resource.

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[9] EFESO Consulting - https://www.efeso.com/men-news/point-of-view/the-impact-of-the-russia-ukraine-conflict-on-the-aerospace-supply-chain-which-are-the-options-to-replace-russian-titanium

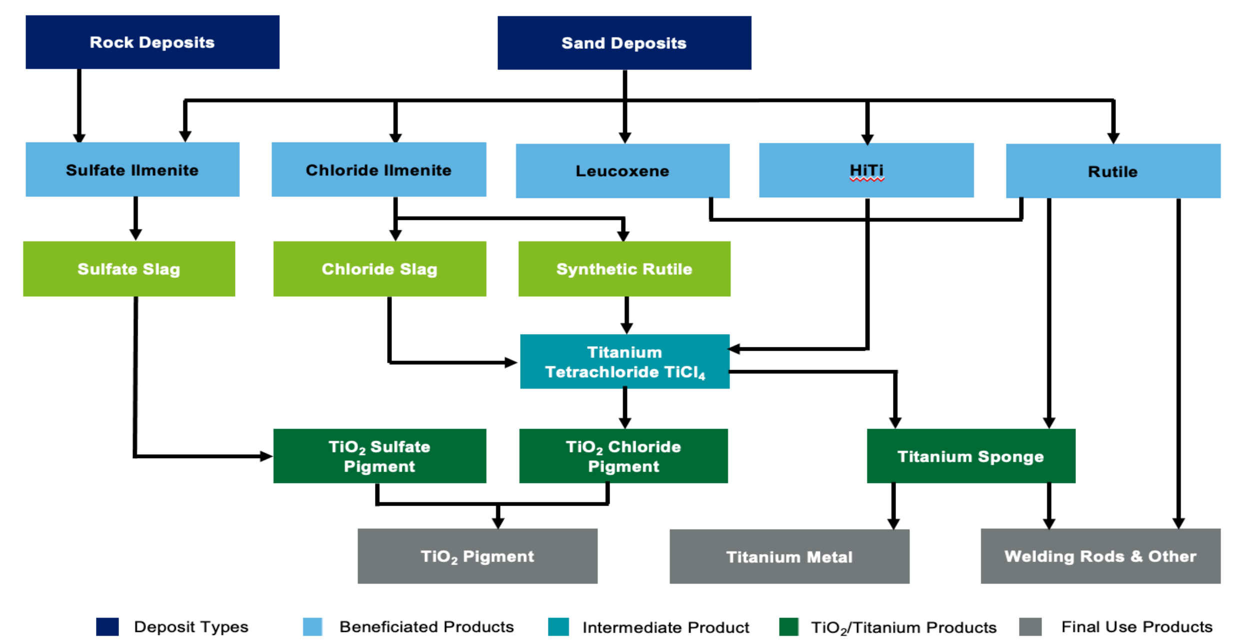
[10] In developing this Report, the Deloitte team extracted data from publicly available sources including: (i) company reports; (ii) industry sources such as TZMI; (iii) government and other public institutions, including the USGS, International Titanium Association (ITA), Titanium Dioxide Manufacturers Association (TDMA), Deutsche Rohstoffagentur (DERA), and the European Union (EU); and (iv) industry conferences and webinars.

1.3.2. Titanium Supply and Demand

TZ Minerals International (TZMI)[11], based in Australia, reports that global titanium feedstock production totaled 8.28 million tonnes (Mt) of TiO_2 in 2021. This includes the mined production of ilmenite and rutile as well as some lower grade mined ilmenite that is upgraded to titanium slag and synthetic rutile as feedstock to intermediate markets. Feedstock production has grown at a compound annual growth rate (CAGR) of 3.6 percent since 2013.

The main source of ilmenite and rutile are heavy mineral sands, but ilmenite and rutile are also found within hard rock deposits. China accounts for a combined 33 percent of global TiO_2 production, South Africa 12 percent, Mozambique 11 percent, and Australia 8 percent. Brazil accounts for 0.7 percent of global TiO_2 production. Figure 1 shows the titanium supply chain.

Figure 1: Titanium Supply Chain



Source: Deloitte

The main use of titanium feedstock is to produce titanium pigments (90 percent of global TiO_2 demand) for use in paints and plastics principally as an opacifier. Some 6 percent of global output is used to make titanium metal for use in aerospace and defense, and in chemical processing plants. The balance is used for direct use in products, principally as a flux.[12] Demand for TiO_2 totaled 8.58 Mt in 2021 according to data from Eramet (and TZMI). This comprised demand for TiO_2 pigments, titanium metal, and other minor uses. Demand grew by a CAGR of 3.0 percent from 2013 to 2021.[13]

[11] TZMI is the main consultant that publishes reports on both titanium feedstock, pigment, and titanium metal supply and demand.

[12] A substance mixed with a solid to lower its melting point.

[13] The market was in surplus during most of this period.

Titanium dioxide pigments are produced from two chemical processes: the sulfate and the chloride process. The chloride process produces TiO_2 products by reacting titanium feedstock with chlorine gas, and the sulfate process produces TiO_2 products by reacting titanium feedstock with sulfuric acid. Supply of chloride quality raw materials accounts for around 46 percent of global supply compared with 54 percent for sulfate quality raw materials.

The sulfate process is older, less efficient, and produces a lower quality product, as well as a number of waste products that are difficult to treat (*See Annex 2 on mining and processing*). The sulfate process is dominant in countries such as China, Vietnam, Russia, and Ukraine. The chloride process uses high grade feedstock to produce high quality TiO_2 pigment. The chloride process is the main process used in western countries, is technologically more difficult than the sulfate process, and is protected by proprietary knowledge (the process is patented). The segmentation on grade of feedstock and pigments causes different supply and demand dynamics and pricing, although some crossover of products can occur.

Recycling for titanium is low because there is no recycling of TiO_2 pigments. In titanium dioxide pigments, TiO_2 can be partially substituted by talc, kaolin, and calcium carbonate, although not in large quantities. Zinc oxide can also be added for white pigments in paints, as it is a cheaper solution, but this process produces an inferior product. Recycling of titanium metal takes place, but it is only 5 percent of the titanium metal market. Due to the outstanding properties of titanium metal, only few materials can compete with its strength-to-weight ratio and corrosion resistance.

The titanium feedstock and TiO_2 pigment markets are controlled by a relatively small number of companies in both extraction and processing (*See* Figure 6). This partly reflects the scarcity of economic deposits, and the relative difficulty in processing the products. In addition, in recent years (from 2013 to 2017 and 2019 into 2020), the industry has had periods of relatively low profitability, and consolidation has taken place to help improve industry economics (*See Annex 3 for details on the recent M&As and the consolidations in the titanium industry*). Brazil produced 66 kt of TiO_2 in 2021, from two TiO_2 producers: Tronox Pigmentos do Brasil (operating the Paraíba mine) and Indústrias Nucleares do Brasil (operating the Bueno mine). The Paraíba mine is scheduled to close at the end of 2023 due to resource depletion.

The current major producers are mainly focused on maintaining existing production levels through the development of satellite mineral sands deposits. The only new project owned by a major producer that is close to a final investment decision (FID) is the Toliara project in Madagascar owned by Base Resources, but it is currently delayed due to negotiations of fiscal terms with the government. Elsewhere, there are a number of active late-stage development projects and projects at feasibility study (*See Section 4.7.3*), although zircon[14] often accounts for the largest proportion of revenue and with some projects, titanium is a secondary product (to niobium and vanadium). Details on the projects are limited in many cases and the level of planned titanium production is sometimes not reported. This makes it difficult to analyze the supply outlook for titanium based on publicly available data.

In Brazil, new titanium capacity is expected from Largo [TSX: LGO], which is planning to construct an ilmenite concentration plant at its existing Maracás Menchen vanadium mine as well as a TiO_2 pigment processing plant in Camaçari. In addition, Jangada Mines [LSE: JAN] completed a feasibility study at Pitombeiras in Ceará in April 2022. The mining operation will focus on the extraction of a direct shipping ore comprised of iron ore with a high vanadium content, but the company is also assessing the possible extraction of TiO_2 from the tailings.

[14] Zircon is an important co-product and is used predominantly in the manufacture of ceramics-based products including tiles, sanitary-ware, and tableware, as an opacifier in the surface glazes and pigments.

1.3.3. Titanium Trade and Prices

Titanium dioxide and titanium metal are not exchange traded commodities and do not have benchmark prices. Companies usually agree on pricing based on a combination of spot trades and short and long-term contracts. The ilmenite and rutile prices have more than doubled over the past five years with prices increasing strongly in 2021 and into 2022 due to robust demand from all major regions and end-use markets, and with global inventories being well below normal levels. The market consensus currently expects a modest 10 percent decline in the price of ilmenite from current 2022 price levels out to 2027, but a continued appreciation in the price of rutile due to the more limited number of new rutile projects expected to come on stream.

1.3.4. Market Balance

Titanium dioxide demand is forecast to grow at a CAGR of 3.3 percent from 2020 to 2027, while TiO_2 supply is forecast to increase by a CAGR of 3.2 percent over the same period.[15] This will leave the market in slight deficit over the period. In 2021 and into 2022, the feedstock market has been unable to meet strong demand growth from the pigments industry, however, higher prices are now incentivizing additional supply from lower quality ilmenite and ilmenite concentrates. The increasing feedstock is expected to balance the market in 2023 and 2024, but the fundamentals are expected to remain supportive of prices. The market is then expected to move back into deficit from 2024 to 2027. The supply deficit appears more acute in the high-grade feedstock market, which supplies the chloride market, and where demand is the strongest.

1.3.5. Economic Competitiveness

A lack of available reported data about industry costs and revenues, the limited current and new production of titanium in Brazil, and the lack of significant new industry projects elsewhere, makes the analysis of both the industry's and Brazil's relative market competitiveness difficult. Furthermore, the value stream of minerals produced and the cost structure from any specific deposit can vary considerably because of the differing grades and assemblage characteristics of each titanium deposit. As a result, within the mineral sands sector, focusing on grade can be misleading and margins are a more important indicator of financial returns. Consequently, the industry tends to use a margin curve or revenue to cash cost ratio curve to assess the relative attractiveness of mineral sands deposits (*See* Section 8 for more details).

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[15] Kenmare Resources

2. TITANIUM CHARACTERISTICS

Titanium (chemical element symbol Ti) is a lustrous-white metal of low density with high mechanical strength and high corrosion resistance. Titanium in its metallic form cannot be easily found in nature and most of the titanium produced is in the form of TiO_2 (Figure 2 and Table 1). TiO_2 feedstock is principally used to produce a white a pigment, which has a high refractive index, ultraviolet (UV) protection, non-toxicity, and inertness, allowing it to impart a durable white color to products. The most common use of the pigment is in coatings (paints and sun creams), plastics, and paper (90 percent). The remaining 10 percent of mined titanium concentrate production is used to produce titanium metal and titanium metal alloys that are used in the aerospace industry due to its high weight-to-strength ratio and high melting point, and for welding rod coatings, chemical processing plants, biological implants, and some consumer goods due to its strength and corrosion resistance.

Figure 2: Titanium Dioxide Feedstock

Source: Kenmare Resources

Titanium minerals are found in hard rock deposits and in mineral sands deposits. Mineral sands are the most abundant class of economic titanium deposits and contain heavy minerals including titanium minerals (*See* Figure 5). The most important, naturally occurring minerals that are mined to produce TiO_2 feedstock are ilmenite and rutile (and small amounts of leucoxene), and the deposits also often contain zircon and sometimes REE. Other minor titanium minerals include brookite and anatase (a common accessory mineral in some Brazilian carbonatites). The mined titanium minerals are either used as feedstock in their natural form or in an upgraded form. China, South Africa, Mozambique, Canada, and Australia are the world's main sources of mineral sands. Hard rock titanium deposits also occur with the largest being in Canada and Norway.

Approximately 50 percent of the ilmenite production is upgraded to synthetic rutile or titanium slag, which are produced through secondary processing. Synthetic rutile is a chemically modified ilmenite that has had most of the iron removed. Titanium dioxide feedstock products are categorized based on the level of TiO_2 they contain. The higher the TiO_2 the more valuable the feedstock product. Table 1 shows the typical titanium forms and TiO_2 content of each product.

Table 1: Typical Titanium Feedstock Forms and Grades

Form of Titanium	TiO_2 Content %	Magnetic Susceptibility	Chemical Formula
Ilmenite			
- Sulfate process route	52-54	High	$FeO.TiO_2$
- Chloride process route	58-62	High	$Fe_2O_3.3TiO_2$
Rutile	95-97	Low	TiO_2
Synthetic Rutile	88-95	-	
Leucoxene	70-91	Semi	$Fe_2O_3.TiO_2.mH_2O$
Titanium Slag			
- Sulfate process route	80-95	-	
- Chloride process route	85-90	-	
- Upgraded	95	-	

Source: Iluka Resources

Low-grade TiO_2 feedstock is used to produce TiO_2 pigment via the sulfate process. High grade feedstock (> 57 percent TiO_2) is usually used to produce TiO_2 pigment via the chloride process. Historically, major western pigment producers typically use high-grade TiO_2 feedstocks (which includes rutile) and the chloride process, while Chinese pigment producers typically rely on low-grade sulfate ilmenite as their main feedstock for the sulfate process. Over the past few years, however, China has been increasing its capacity to produce high-grade feedstock and producing chloride pigments through its own technology development. However, the chloride process requires large capital investment because of the more sophisticated technology as well as higher quality raw materials.

Pigment demand has a high correlation with global GDP, and in particular with the construction industry (mainly coatings). Titanium feedstock production represents an approximately $4.5 billion per annum industry and the TiO_2 pigment supply chain has annual revenues of over $15 billion.[16]

TZMI does not usually grant permission to use its proprietary data for reproduction, and third parties (mining and pigment companies) are the only occasional sources of this information. Other sources on the titanium market include the U.S. Geological Survey (USGS), the International Titanium Association, the Titanium Dioxide Manufacturers Association (TDMA), and the European Commission.

Annex 1 contains more detail on titanium ores, and Annex 2 contains more detail on titanium mining and processing.

[16] Kenmare Resources.

3. TITANIUM RESERVES AND RESOURCES

Economic concentrations of titanium mainly comprise the minerals ilmenite and rutile, with some leucoxene (leucoxene is produced from the weathering of ilmenite), although smaller quantities are produced from other minerals (*See* pg. 8). Ilmenite is the most common titanium mineral in the earth's crust and accounts for 93 percent of the world's titanium mineral production.[17] These titanium minerals are sourced from heavy mineral sands and commonly distributed in hard rock deposits (although not economic).

Table 2 shows the global reserves of ilmenite and rutile listed separately, based on contained TiO_2 content, as reported by the USGS.[18] The USGS also states that world resources of TiO_2 total more than 2.0 billion tonnes. Table 2 also contains details of reserves and resources totaling 2.45 billion tonnes as compiled from the S&P Global Intelligence database, which reports company data from mines and projects.

Table 2: Global Titanium Reserves and Resources

Country	USGS Reserves Ilmenite TiO_2 kt	USGS Reserves Rutile TiO_2 kt	S&P Reserves & Resources equivalent TiO_2 kt
China	230,000	-	71,939
Australia	160,000	31,000	567,164
India	85,000	7,400	829
Brazil	43,000	-	90,720
Norway	37,000	-	12,046
Canada	31,000	-	175,102
South Africa	30,000	6,500	315,090
Mozambique	26,000	890	201,413
Madagascar	22,000	400	80,952
Ukraine	5,900	2,500	-
United States	2,000	-	160,849
Paraguay	-	-	381,000
Russia	-	-	184,461
Other	27,990	660	213,239
Total	**699,890**	**49,350**	**2,454,805**

Source: USGS 2022, S&P Global Intelligence – Includes company reported ilmenite (53 percent TiO_2), rutile (95 percent TiO_2), and titanium (TiO_2) reserves and resources.

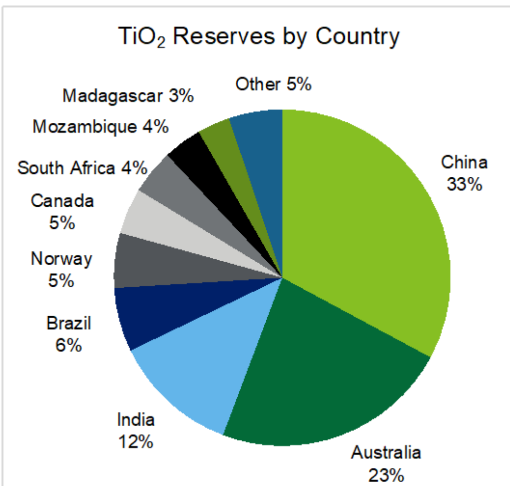
[17] Titanium: An Overview of Resources and Production Methods – MDPI.

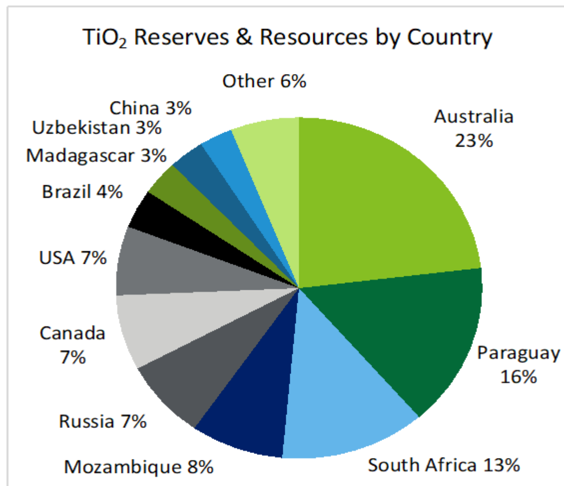
[18] USGS sources include academic articles, company reports, presentations, trade journal articles, etc. Only small portions of these reserves have been prepared in accordance with NI 43-101 or JORC procedures. . China generally does not report detailed company reserve and resources data

Reserves and resources are reported in a number of different ways by mining companies. Some report the grade of TiO_2, some present grades of ilmenite, rutile, and leucoxene when contained, which contain different quantities of TiO_2, and others report the grade of heavy minerals (HM) − a combination of the titanium minerals that may also include zircon, alumina-silicates, magnetite, iron, REE, and tin, as well as occasional inclusions of radioactive elements such as uranium and thorium in small amounts. The different reporting complicates the aggregation and comparison of resource tonnages and grades.

Figure 3 show that world titanium reserves and resources are concentrated in Australia (23 percent), Paraguay (16 percent), and South Africa (13 percent), with Mozambique, Russia, Canada, and the United States also holding significant resources. Brazil holds about 3.7 percent of global reserves and resources.

Figure 3: Global Titanium Reserves and Resources





Source: USGS 2022, S&P Global Intelligence.

Titanium is abundant in the earth's crust and widely distributed but is not commonly found in economic concentrations with suitable mineralogy and grade. USGS notes that there are four major classifications of titanium mineral deposit types:

(a) magmatic deposits in igneous and related rocks with ilmenite as the primary ore mineral;

(b) metamorphic deposits with rutile as the primary ore mineral;

(c) rutile in hydrothermal porphyry deposits; and

(d) heavy-mineral concentrations in unconsolidated and lithified sand deposits that may include rutile, ilmenite, and alteration products, such as leucoxene.

Most deposit types can be further altered by weathering, at times upgrading the titanium content of the ilmenite, if present. *Annex 1 contains more detail on titanium ores.*

The most important economic source of titanium is mineral sands. Most mineral sands deposits are produced by weathering and erosion of the earth's surface and are carried by sedimentary action to coastlines where a combination of wave action (strand deposits) and, to a lesser extent wind action (dunal deposits), result in concentrations in bodies of silica (quartz) sand along ancient beach lines and associated environments. Mineral sand deposits are typically found in unconsolidated fossil shorelines up to hundreds of kilometers inland from present coastlines.

Mineral sands deposits are characterized by their grade (the percentage of heavy minerals found in a deposit) and their assemblage (the relative proportion of valuable heavy minerals components of ilmenite, rutile, and zircon). The typical composition of a mineral sands deposit has a heavy minerals grade ranging from 0.5 to above 20 percent.

Table 3 shows the 20 largest titanium operations and projects that have reported reserves and/or resources, accounting for 72 percent of the global total.[19]

- Five of these deposits are currently in operation: Moma, Lac Allard, QMM, Zhuge Shangyu, and Murray Basin (although Murray Basin is currently idled);
- One project is at FID (Thunderbird); and
- Five projects are at the feasibility stage: Veremo, Mokopane, Tebinbulak, Balla, and Toliara, with the balance at an earlier stage of exploration.

Table 3: Largest Reported Titanium Resources

Mine/Project	Country	Owner	Primary Product	Development Stage	Resource kt TiO_2
Alto Parana	Paraguay	Uranium Energy	Ilmenite	PF/Scoping	381,000
Speewah Dome	Australia	King River Res.	Vanadium	PF/Scoping	155,700
Iron Hill	USA	NA	REE	Res. Dev.	150,180
Veremo	South	Kermas	Iron Ore	Feasibility	132,624
Mokopane	South	Bushveld Minerals	Vanadium	Feasibility	118,490
Moma	Mozambiqu	Kenmare Res.	Ilmenite	Operating	104,723
Kharlovsky Cluster	Russia	NA	Iron Ore	Res. Dev.	102,416
Tebinbulak	Uzbekistan	Uzbekistan	Titanium	Feasibility	77,298
Lac Allard	Canada	Rio Tinto Group	Ilmenite	Operating	76,479
Balla	Australia	The Todd Corp.	Iron Ore	Feasibility	62,472
Mutamba	Mozambiqu	Rio Tinto Group	Ilmenite	PF/Scoping	56,298
Serra Negra	Brazil	NA	Titanium	Closed	55,400
Yugo-Vostochnaya	Russia	NA	Titanium	Adv. Expl.	49,793
Toliara	Madagasca	Base Resources	HMS	Feasibility	42,739
Corridor	Mozambiqu	MRG Metals	HMS	PF/Scoping	40,072
QMM	Madagasca	Rio Tinto Group	Ilmenite	Operating	38,213
McCalls	Australia	Image Resources	Ilmenite	PF/Scoping	37,323
Thunderbird	Australia	Sheffield Res.	Ilmenite	FID	33,040
Zhuge Shangyu	China	Add New Energy	Ilmenite	Operating	30,710
Murray Basin	Australia	Iluka Resources	Ilmenite	Operating	28,915
Total					**1,773,886**

Source: S&P Global Intelligence. NB. PF = Pre-feasibility

[19] The remaining 28 percent consists of very small projects.

No activity appears to be taking place at four of the projects: Iron Hill, Kharlovsky Cluster, Serra Negra, and Yugo-Vostochnaya, and have no identified owner, but are included for completeness. Of the 20 deposits, 14 are primarily ilmenite/titanium mines/projects, with two vanadium, one REE, and three iron ore projects.

Figure 4 shows a map of the world's major titanium mines and deposits and highlights the prevalence of sedimentary deposits around the world.

Figure 4: Major Titanium Mines & Deposits

Source: USGS 2017

3.1. Brazilian Titanium Resources

The USGS reports that in 2021 Brazil had 43 Mt of ilmenite reserves, equivalent to 6.1 percent of global ilmenite reserves. The titanium reserves are mainly located on the northeast coast of Paraíba. Other important ilmenite deposits not yet properly evaluated occur along the Brazilian coast, in the form of deposits of beach placers or in marine terraces, on the northeast, southeast, and south coast of the country.[20]

In May 2022, U.S.-based Energy Fuels [NYSE: UUUU] announced an agreement to acquire the Bahia project, located on the coast in the State of Bahia. The project comprises of marine placers containing heavy mineral sands (ilmenite, rutile, and zircon), and REE in the form of monazite. The property has already been drilled and Energy Fuels plans exploration work during 2022.

Anatase titanium ore resources in Brazil are also estimated to be significant. Some 90 percent of these resources are in the State of Minais Gerais and 10 percent in the State of Goiás. The largest known deposits are the carbonatites of Tapira and Salitre, located in Minais Gerais, and Catalão in Goiás. All of the deposits are being mined for phosphate, and partly niobium.

In these carbonatites, perovskite has weathered to anatase, which is finely intergrown with quartz. Iluka Resources (Australia) looked into producing a marketable titanium mineral concentrate from the Tapira project (from 2014 to 2016) but was not able to achieve an economic product using currently known conventional or alternative technological routes.[21]

[21] Deutsche Rohstoffagentur (DERA) - The HiTi feedstock market.

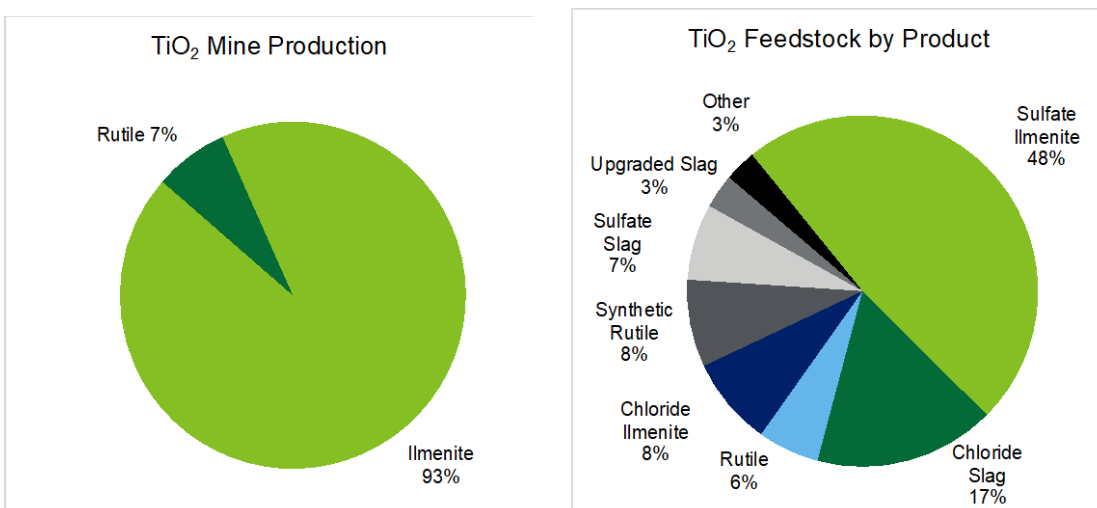
4. TITANIUM SUPPLY

The mined production of TiO_2 in the form of rutile and ilmenite totaled some 9.04 Mt of TiO_2 units in 2021, according to the USGS. This production, however, does not take into account the different grades of ilmenite, and that some of the lower grade ilmenite is upgraded to titanium slag and synthetic rutile, as feedstock to intermediate markets. TZMI reports that titanium feedstock production totaled 8.28 Mt of TiO_2 in 2021. Mine production has grown at a CAGR of 2.5 percent since 2013 and feedstock production has grown at a CAGR of 3.6 percent.

4.1. Industry Structure

The principal TiO_2 feedstock products are ilmenite, rutile, and upgraded products of synthetic rutile and titanium slag (*See* Section 4.3), as shown in Figure 5. Ilmenite and rutile (along with small quantities of leucoxene) are mined principally from mineral sands deposits but also from some hard rock deposits. The main use of titanium minerals is to produce titanium pigments (90 percent) with some 6 percent used to produce titanium metal and the balance used for direct use in products, principally as a flux.[22]

Figure 5: TiO_2 Mine Production and Feedstock Production by Product



Source: USGS 2022, TZMI, Eramet.

Titanium dioxide pigments are produced from two chemical processes: the sulfate and the chloride process. The chloride process produces TiO_2 products by reacting titanium mine concentrates with chlorine gas. The sulfate process produces TiO_2 products by reacting titanium mine concentrates with sulfuric acid. Supply of chloride quality raw materials accounts for around 46 percent of global supply compared with 54 percent for sulfate quality raw materials.

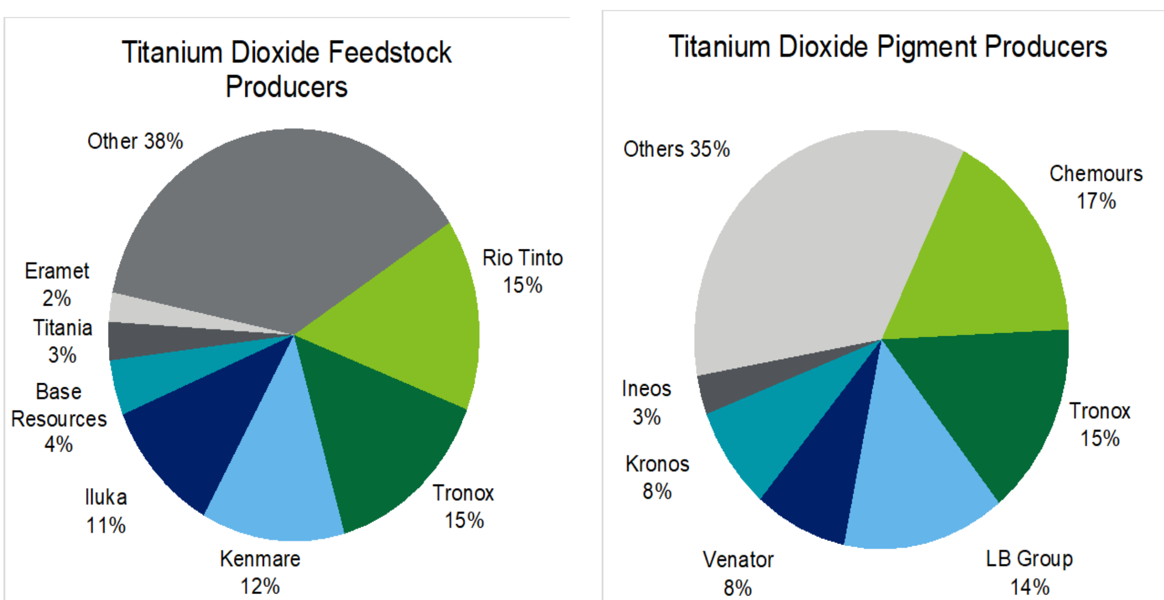
The chloride process uses high grade feedstock (ilmenite >58 percent TiO_2, leucoxene, natural rutile, synthetic rutile, or a titanium slag with >85 percent TiO_2) to produce high quality TiO_2 pigment. The chloride process is used in western countries and is technologically more difficult than the sulfate process and is protected by proprietary knowledge. End-use customers in the paints, printing inks, and plastics industries prefer chloride TiO_2 pigments for its superior technical qualities.

[22] A substance mixed with a solid to lower its melting point.

The sulfate process uses low-grade TiO_2 feedstock (a TiO_2 content of at least 44 percent or a titanium slag with 70 to 80 percent TiO_2) to produce lower quality pigments, which are used more often in the production of paper, ceramics, rubber, chemical fibers, food products, and cosmetics. This is an older technology and tends to be simpler, but less efficient and it also produces a number of waste products that are difficult to treat (*see Annex 2 on mining and processing*). The sulfate process is dominant in countries such as China, Vietnam, Russia, and Ukraine.

Figure 6 shows the TiO_2 feedstock and pigment producers. TiO_2 feedstock producers are typically the mining companies. They supply feedstock to the TiO_2 pigment producers who are usually chemical companies, although a few companies like Tronox (mines in South Africa, Australia, and Brazil) and Chemours (country of mines is not reported) also have mining operations. In the pigment industry, new investment has taken place in high-quality pigment capacity (chloride) in western countries and low-quality capacity (sulfate) has been added in China. In recent years however, China has also constructed new chloride capacity through its own technology development. End-use consumers of pigments are increasingly using high quality pigments produced by the chloride process. The segmentation on grade of feedstock and pigments causes different supply and demand dynamics and pricing, although some crossover of products can occur.

Figure 6: Titanium Dioxide Feedstock and Pigment Producers



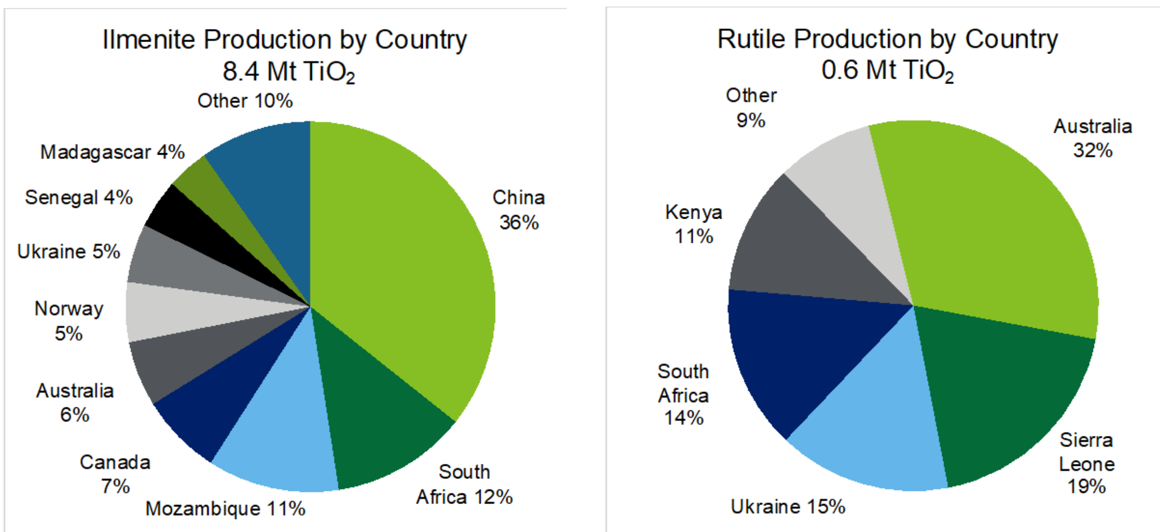
Source: Company Reports, Deloitte estimates

The titanium feedstock and TiO_2 pigment markets are controlled by a relatively small number of companies. This partly reflects the scarcity of economic deposits and the relative difficulty in processing the products. In addition, in recent years, the industry has had periods of relatively low profitability due to an over supplied market, and consolidation has taken place to help improve the economics of the industry.

4.2. Mined Titanium Supply

Titanium is mainly produced from mining the minerals ilmenite and rutile. The main ilmenite deposits are located in Australia, China, Norway, Canada, Madagascar, India, South Africa, and Vietnam, while rutile deposits are found in Sierra Leone, United States, India, and South Africa, although the two minerals are typically found in combination with each other. Ilmenite's main sources are heavy mineral sands (alluvial deposits) but are also found in hard rock deposits. Ilmenite accounts for approximately 93 percent of the world's titanium mineral production. Figure 7 shows ilmenite and rutile production by country. Table 4 gives the combined global TiO_2 production with China accounting for a combined 33 percent, South Africa 12 percent, Mozambique 11 percent, and Australia 8 percent. Brazil accounts for 0.7 percent of global TiO_2 production.

Figure 7: Ilmenite and Rutile Production by Country



Source: USGS 2022.

Table 4: Global Titanium Mine Production by Country (TiO_2 kt)

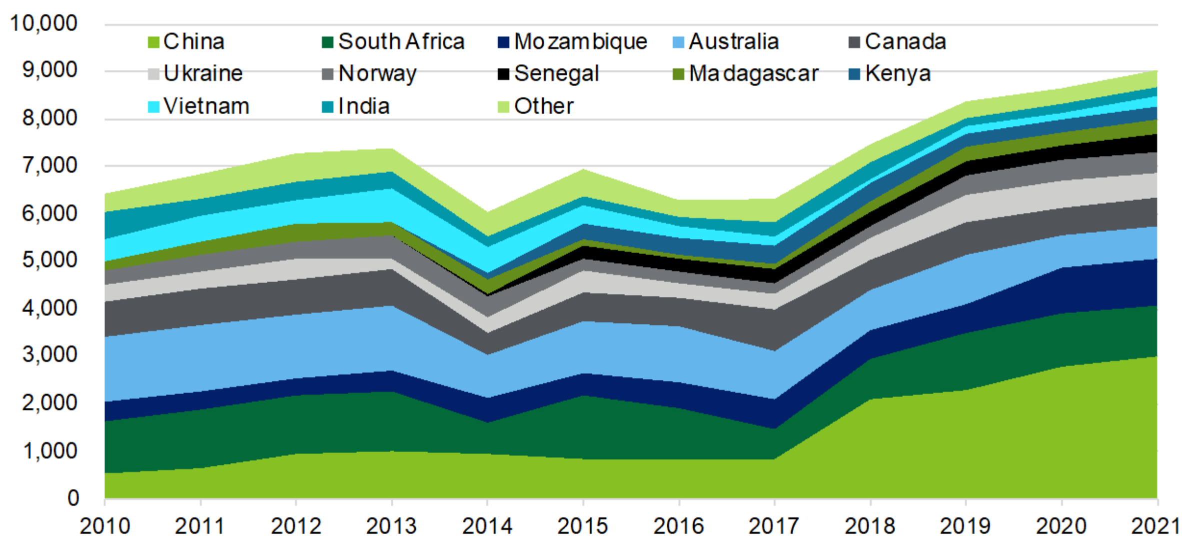
Country	2016	2017	2018	2019	2020	2021e
China	840	840	2,100	2,300	2,800	3,000
South Africa	1,087	645	868	1,210	1,106	1,090
Mozambique	547	609	583	596	971	979
Australia	1,160	1,020	861	1,040	670	680
Canada	595	880	630	680	595	600
Ukraine	305	325	467	584	559	525
Norway	260	220	236	400	444	440
Senegal	259	310	306	319	309	370
Madagascar	92	110	228	280	262	320
Kenya	364	367	362	284	274	261
Vietnam	240	200	105	160	138	220

Country	2016	2017	2018	2019	2020	2021e
India	199	310	334	173	185	191
Sierra Leone	130	160	114	129	114	120
United States	100	100	100	100	100	100
Brazil	48	50	66	25	34	66
Other	79	163	104	95	80	80
Total	**6,305**	**6,309**	**7,464**	**8,375**	**8,641**	**9,042**

Source: USGS 2022.

Table 4 also shows the TiO_2 mine production by country from 2016 to 2021 and Figure 8 shows the data from 2010 to 2021. From 2010 to 2020 overall, TiO_2 production has grown at a CAGR of 3.1 percent. Ilmenite production has increased at a CAGR of 3.5 percent while rutile production has declined as a CAGR of 0.6 percent due to the limited availability of new rutile deposits. The overall growth has partly been a function of increased output in China from 2017 onwards.

Figure 8: Combined Ilmenite and Rutile Production by Country 2010-2021



Source: USGS 2022.

4.2.1. Titanium from Mineral Sands Deposits

Mineral sands are concentrations of heavy minerals, including the two core products, TiO_2 (ilmenite and rutile) and zircon, which make up the majority of the ore, and in some cases REE are present. Deposits of mineral sands are typically formed as a result of coastal marine sedimentary processes and are found in unconsolidated fossil shorelines up to hundreds of kilometers inland from present coastlines. The size of mineral sands deposits varies, but they are typically 100 to 200 meters wide, 5 to 20 meters thick, and 2 to 20 kilometers long. The major known locations of mineral sands orebodies are Australia, India, southern Africa, and the southern United States. The majority of heavy minerals occur in sand-style deposits and specialized recovery systems equipped with spiral separators, electrostatic separators, and magnetic separators are required for concentration and separation.

Mineral sands deposits are characterized by their grade and assemblage. A typical mineral sands deposit has a heavy mineral grade ranging from 0.5 to over 20 percent, with TiO_2 products normally being five times more abundant than zircon. Consequently, the differing grades and assemblage characteristics of a titanium deposit can influence the relative cost and value stream of minerals produced from any specific deposit.

Another important factor in consideration of identifying an economic mineral sands deposit is the type and quantity of impurities and process contaminants contained within the deposit, because not all impurities can be economically removed. The commercial value of titanium feedstock is a function not only of TiO_2 content and prices, but also particle size, trace element geochemistry, logistics, and other factors.

It typically takes three to five years to prove the economics of a mineral sands deposit, and a further three to four years to develop and build the mine and processing facilities. Even then, because of the large variability of geological environments and range of products in the mineral sands, it can still take some time to optimize the operation. The industry has a long list of projects that looked promising but never made it to development, and others that failed or had significant difficulties after start-up. Examples include: BHP that abandoned the Beenup mineral sands mine in Australia in 1999 after two years of operation; Rio Tinto that had difficulties in bringing the QMM mineral sands mine in Madagascar to full production in 2016; and Kenmare that took several years longer than expected to get its Moma mine in Mozambique to full capacity.

4.2.2. Titanium from Hard Rock Deposits

Titanium-bearing mineral ilmenite is also mined from hard rock deposits in Canada, China, and Norway. Much of the TiO_2 feedstock produced in China is recovered as a by-product of mining iron ore, with operations concentrated in the Sichuan Province in central China. In Canada, Rio Tinto [LSE: RIO] operates the Lac Tio open pit TiO_2 mine in Quebec, reported to be the largest hard rock ilmenite deposit in the world. At its metallurgical complex in Sorel-Tracy, Quebec, the company extracts high-quality TiO_2 feedstock, pig iron, and metal powders from the ore. In Norway, the Tellnes mine is another large hard rock titanium mine owned and operated by Titania A/S, a private company. Both of these operations are examples of magmatic titanium mines. Titaniferous magnetite as a group of iron-titanium-oxide ore minerals contains between about 1 percent and about 15 percent titanium. These deposits are mined by conventional open pit methods.

4.3. Upgraded Mined Titanium Products

Low-grade titanium ores can be processed to form titanium slag or synthetic rutile using various processes to increase their primary TiO_2 content. Approximately 50 percent of upgrading capacity is integrated with feedstock production and about 50 percent is non-integrated. The proportion of non-integrated capacity has been increasing over time. Chinese domestic ilmenite is unsuitable for upgrading (Kenmare Resources) and so the demand for imported ilmenite to China for upgrading has increased.

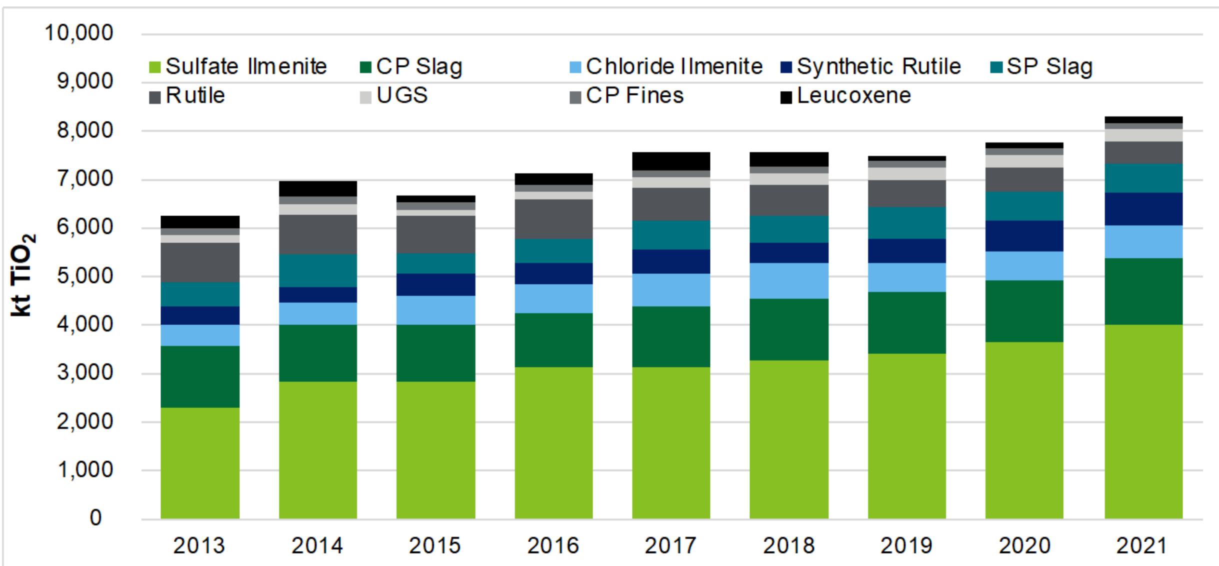
4.3.1. Titanium Slag

Titanium slag can be formed by reducing ilmenite with carbon in an electric furnace. Low-grade ilmenites are the preferred feedstock for smelting because the high iron content provides suitable thermodynamic conditions. Pig iron is always generated in large quantities as a valuable by-product. The slag is most often used by pigment manufacturers as feedstock in the sulfate process (sulfate slag > 75 percent TiO_2) and chloride process (chloride slag > 85 percent TiO_2) although some companies use it in titanium sponge production (an intermediary product used to make titanium metal). The final quality of the slag is highly dependent on the quality of the ilmenite as virtually all the impurities report to the slag.

4.3.2. Synthetic Rutile

Synthetic rutile is one of the basic raw materials used in the chloride process and is therefore also suitable for metal production using the Kroll process.[23] The process for the manufacture of synthetic rutile consists of the complete or partial reduction of the iron bound up in the ilmenite in a rotary reduction kiln, and subsequent leaching and separation from the TiO_2. The process uses high-grade ilmenite, as the use of low-grade ilmenite is not suitable for the manufacture of synthetic rutile because the contaminants will remain in the synthetic rutile and require expensive additional acid-leaching steps to remove. Typically, one tonne of ilmenite will produce between 0.50 to 0.63 tonnes of synthetic rutile with a TiO_2 composition of 88 to 95 percent. Figure 9 shows the titanium feedstock supply by product from 2013 to 2021.

Figure 9: Titanium Dioxide Feedstock Supply by Product



Source: Eramet, TZMI. SP = Sulfide Produced. CP = Chloride Produced.

4.4. Titanium Mining Operations

Details of mining operations and production numbers for a significant proportion of titanium feedstock producers are limited. This is because some are owned by chemical companies, while others are privately owned. Some information is available for the larger producers like Rio Tinto, Tronox, Iluka, Kenmare, Eramet, and Base Resources, which accounted for about 60 percent of mined output in 2021 (Table 5).

Rio Tinto is the largest producer of TiO_2 feedstock. It owns 74 percent of Richards Bay Minerals in South Africa, 100 percent of QIT in Canada and 80 percent of QMM in Madagascar. The company's mining operations produced an estimated 1.36 Mt of TiO_2 in 2021 and reported 1.0 Mt of titanium slag.

[23] The Kroll process is based on the principle of the separation of the titanium from titanium tetrachloride by means of the addition of magnesium to produce titanium sponge. Due to its porosity and remaining impurities, the titanium sponge is typically melted down into blocks or ingots of titanium metal.

Table 5: Significant Producers of Mined TiO_2 – Production and Resources

Company	Production 2020 kt TiO_2	Production 2021 kt TiO_2	Resources Ore Mt	Ilmenite Mt TiO_2	Rutile Mt TiO_2	Zircon Zi Mt
Rio Tinto*	1,350	1,360	3,362	250.6	NA	76.5
Tronox	1,333	1,356	3,759	83.8	13.1	15.0
Kenmare Resources	1,128	762	7,859	190.1	4.1	12.7
Iluka	960	856	3,105	87.8	11.3	24.7
Base Resources	390	434	2,725	77.8	1.5	6.5
Eramet	209	199	3,542	25.9	0.5	3.0
Total	**4,727**	**5,731**	**24,547**	**718**	**31**	**139**

Source: Company reports. *Rio Tinto are estimates of mine production as only slag production is reported.

Tronox is the second largest producer of TiO_2 feedstock. It operates mineral sands mining operations in South Africa, Australia, and Brazil. Tronox produced 1.2 Mt of ilmenite and 142 kt of rutile in 2021. Tronox is also the world's largest TiO_2 pigment producer. The group owns six TiO_2 feedstock operations, five upgrading facilities, and nine TiO_2 pigment plants with a combined capacity of 1.3 Mt/y.

Kenmare Resources is the third largest producer of TiO_2 and operates the Moma operations in Mozambique. In 2021, the company produced 960 kt of TiO_2.

Iluka is the largest producer of natural rutile (partly through ownership of Sierra Rutile) and the second largest producer of synthetic rutile, manufactured by upgrading ilmenite. In 2021, the company produced 960 kt of TiO_2 feedstock.

Base Resources operates the Kwale operation in Kenya and is developing the Toliara project in Madagascar. In 2021, the company produced 390 kt of TiO_2.

Eramet operates the Grande Côte mineral sands mine near Dakar, in Senegal which mainly produces ilmenite and zircon. It also operates the TiZir Titanium and Iron (TTI) metallurgical conversion plant in Tyssedal, Norway, which transforms ilmenite to produce TiO_2 slag for the pigments industry and high-purity pig iron. In 2021, the company produced 209 kt of TiO_2.

4.5. Recycling of Titanium

Recycling for titanium is low because there is no recycling of TiO_2 pigments, which account for 90 percent of the market. Recycling of titanium metal takes place but is 5 percent of the titanium metal market. Recycling takes place at the fabrication stage and for post-consumer titanium products, however, there is limited information on volumes of recycling of titanium metal. Titanium is mainly recycled using a processing method called vacuum arc remelting.

4.6. Brazilian Titanium Supply

Brazil produced 66 kt of TiO_2 in 2021, which accounted for 0.7 percent of global TiO_2 production. In Brazil there are currently two TiO_2 producers:

- Tronox Pigmentos do Brasil – operating the Paraíba mine; and
- Indústrias Nucleares do Brasil – operating the Bueno mine.

At the Paraíba operation in Paraíba State on the northeast coast of Brazil, mining operations ceased during 2020 in line with the Tronox's life-of-mine plan; however, the company believes there is enough feedstock to supply its pigment plant through 2023. Historically, this mine has accounted for about 75 percent of the production of ilmenite and rutile concentrates in Brazil. The mine comprised a floating plant and dredge, which performed the extraction of the ilmenite and of zirconite, rutile, and cyanite (used in the ceramic, welding, high precision casting, and refractions industries), as well as four fixed production plants. The feedstock is shipped to a pigment plant in Bahia, located on the North Coast of the State, where it is transformed into TiO_2 pigment.

Indústrias Nucleares do Brasil produces titanium from the processing of tailings from the mining of radioactive mineral sands.

4.7. Mine Supply Outlook

The existing major producers are mainly focused on maintaining existing production levels through the development of satellite mineral sands deposits. The only new project owned by the major producers that is close to FID is the Toliara project in Madagascar owned by Base Resources but is currently delayed because of the negotiation of fiscal terms with the government.

Elsewhere, there are a number of active late-stage development projects and projects at feasibility stage (*See* Section 4.7.2 and Section 4.7.3), although often zircon accounts for the largest proportion of revenue and at some of them, titanium is a secondary product (to niobium and vanadium). Details on the projects are limited in many cases and the level of planned titanium production is sometimes not reported. This makes it difficult to analyze the supply outlook based on publicly available data.

4.7.1. Existing Major Producers

Rio Tinto reported a temporary suspension of its Richards Bay Minerals operation in South Africa in 2021 due to community disruption, which has now stabilized. Currently, there is no significant capital expenditure reported[24] at its titanium business, and the company reports that the Zulti South project at Richards Bay Minerals remains on full suspension.

Tronox reports that it has two significant mining projects currently underway, although both of these appear to be replacement capacity. Most significant is the development of a mine in Eastern Australia called Atlas Campaspe. Atlas Campaspe is intended to replace feedstock supply from its existing Snapper/Ginkgo mines in Eastern Australia which are expected to be mined until at least 2023. The feasibility study indicates that this mine is abundant in natural rutile and high value zircon and will be a significant source of high-grade ilmenite suitable for direct use, synthetic rutile production, or slag processing. In addition, Tronox is expanding its Fairbreeze and Namakwa mines in South Africa. Tronox believes these expansions are also extremely attractive mine development projects, rich in ilmenite, rutile and zircon, which are expected to replace existing mines that would otherwise deplete in 2024 and 2025. Tronox reports that it has numerous other mine development projects in earlier stages of development in Western Australia and on the Eastern and Western Capes of South Africa, all of which are intended to maintain or expand its level of feedstock vertical integration.

Kenmare Resources completed three development projects at its Moma mine between 2018 and 2020 to increase production to 1.2 Mt/y of ilmenite, plus associated co-products, and is now focused on maintaining existing production levels. A pre-feasibility study (PFS) is expected to be completed in 2022 at the Nataka project, which is an extension of the existing operations to maintain production.

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[24] It may be planned, but it has not been reported as planned.

In Australia, **Iluka Resources** is advancing a number of mineral sands projects, at least some of which are extensions to existing mining operations, including the Balranald project (New South Wales) which is progressing to definitive feasibility study (DFS); and PFS are ongoing for the Euston (New South Wales), Atacama (South Australia), Wimmera (Victoria), and South West deposits (Western Australia) projects. In Sierra Leone, Iluka continues to progress work on a feasibility study for the Sembehun rutile project. In April 2022, Iluka announced its intention to demerge Sierra Rutile, subject to approvals, for Sierra Rutile to maximize its growth potential, including the development of the Sembehun project.

Base Resources is currently proceeding with the Bumamani project to extend its Kwale operations mine life by 13 months to December 2024. In addition, the company is currently developing the Toliara project in Madagascar. In September 2021, the company completed an enhanced DFS for the project to incorporate an update to the estimated Ranobe ore reserves and an increase in project scale. The project now plans to produce 960 kt/y ilmenite (sulfate, slag, and chloride), 66 kt/y zircon, and 8 kt/y rutile over a 35-year life; however, timing of FID to proceed with construction of the Toliara project remains subject to agreeing acceptable fiscal terms with the Government of Madagascar, which suspended on-the-ground activities in November 2019 as discussions are ongoing.

Eramet is reviewing de-bottlenecking options in the medium-term for the Senegal production, to achieve incremental production increases between the end of 2022 and 2024. The first stage, which represents limited capital expenditure of approximately $29.9 million (€30 million), aims to increase mineral sands production capacity by around 10 percent. In 2019, Eramet also obtained a mining exploration license in Cameroon for the Akonolinga project. It conducted two drilling campaigns in 2020 and 2021, while a third is in progress. In addition, Eramet conducted a scoping study of an operating plan on a first portion of the concession in 2021. The favorable conclusions of this study resulted in the launch of a PFS, which is being carried out in 2022.

4.7.2. Advanced Development Projects

The most advanced titanium project is Coburn owned by **Strandline Resources** [ASX: STA], which is under construction, and first heavy mineral concentrate is scheduled for the end of 2022. It plans to produce 110 kt/y ilmenite, 24 kt/y rutile, 54 kt/y of zircon concentrate, and 34 kt/y of premium zircon over a 22.5-year mine life. Strandline is also well advanced with the Fungoni project in Tanzania, which has a short life mine (6.2 years) and plans to produce about 31 kt/y ilmenite, 2.5 kt/y rutile, and 13 kt/y of zircon.

Thunderbird, in Western Australia, owned by **Sheffield Resources** [ASX: SFX] is also well advanced. In August 2022, the company announced a $110 million project finance facility. Sheffield expects to raise a further $25 million (A$36 million) of equity to bring Thunderbird into production. It plans to produce 1,395 kt/y of titanium and zircon concentrate products over a 36-year mine life, with about 200 kt/y of TiO_2 being produced (37 percent of output in a magnetic concentrate containing 38.5 percent TiO_2).

The Donald project in Victoria, Australia operated by **Astron Corp.** [ASX: ATR], is at late-stage development and plans to produce about 250 kt/y of heavy mineral sands and REE over a 35-year mine life. Detailed commodity breakdown of planned annual production is not publicly available.

Nordic Mining [OSL: NOM] operates the Engebo rutile and garnet project in Norway. Its feasibility study plans 15 years of open pit mining and 19 years of underground production, with plans to produce about 35 kt/y of rutile (57.1 Mt ore production grading 3.9 percent rutile with a 57 percent recovery).

Titanium is also expected to be produced as a by-product from the Elk Creek niobium project and the Mount Peake vanadium project, both in Australia. **TNG** [ASX: TNG] plans to produce 100 kt/y of TiO_2 from its Mount Peake vanadium project over a 37-year mine life. The Elk Creek niobium project, operated by **NioCorp** [TSX: NB], plans to produce about 12 kt/y of TiO_2 from an underground mine over a 38-year mine life.

4.7.3. Feasibility Projects

The Deloitte team has identified eight further projects at feasibility stage with the potential to come into production over the next few years that will produce titanium (Table 6).

Table 6: Mining Projects at Feasibility Stage with Planned Titanium Production

Project	Primary Commodity	Country	Operating Company	Production ilmenite kt/y	Production TiO_2 kt/y
Toliara	HMS	Madagascar	Base Resources	960	-
Dundas	HMS	Greenland	Bluejay Mining	440	-
Maracás Menchen	Vanadium	Brazil	Largo	59	
Cyclone	HMS	Australia	Diatreme Res.	58	-
Mindarie	Ilmenite	Australia	Murray Zircon	NA	NA
Barrambie	Titanium	Australia	Neometals	NA	NA
Pitombeiras	Vanadium	Brazil	Jangada Mines	-	66
Australian Vanadium	Vanadium	Australia	Australian Vanadium	-	135
Medcalf	Vanadium	Australia	Audalia Resources	-	NA

Source: Company reports, Deloitte estimates. HMS = Heavy Mineral Sands

Brazilian Projects

Included in Table 6 are the Maracás Menchen mine and the Pitombeiras vanadium project in Brazil. **Largo** [TSX: LGO] is planning to construct an ilmenite concentration plant at its existing Maracás Menchen vanadium mine and a TiO_2 pigment processing plant in Camaçari. Phase One will involve the construction in 2022 and 2023 of an ilmenite concentration plant with a capacity to produce 140 kt/y of ilmenite concentrate and a sulfate TiO_2 pigment chemical processing plant that is expected to produce 30 kt/y of TiO_2 pigment beginning in 2024. The company anticipates that the total investment for Phase 1 will be $94 million (C$121.6 million). **Jangada Mines** [LSE: JAN] completed a feasibility study at Pitombeiras in Ceará in April 2022. The mining operation will focus on the extraction of a direct shipping ore comprised of iron ore with a high vanadium content and is assessing the possible extraction of TiO_2. Annual production of 186 kt/y vanadium pentoxide (V_2O_5) concentrate is anticipated with a mine life of nine years.

Other projects in Brazil at an earlier stage include:

- South Atlantic heavy mineral sands (HMS) project in the State of Rio Grande do Sul (Retiro deposit). **Rio Grande Mineração** is exploring project resources of 979.3 Mt of ore sand at a grade of 3.1 percent HMS. About 2.5 Mt of ore sand is planned to be processed every year delivering about 272 kt/y of ilmenite, 37 kt/y of titanomagnetite, 37 kt/y of zircon, and 10 kt/y of rutile. The latter two products will be sold to the domestic market. The expected mine life is in excess of 30 years; however, limited progress appears to have been made in recent years.

- **JFE Mineral** of Japan operates a pilot plant for the production of rutile (and possibly other minerals) from five-meter-thick soil covering deeply weathered granites at Seritinga in the South of Minas Gerais. This pilot unit has a feed processing capacity of 5 tonnes per hour. No further information is known.
- In May 2022, U.S.-based **Energy Fuels** [NYSE: UUUU] announced an agreement to acquire the Bahia project, located on the coast in the State of Bahia. The project comprises marine placers containing heavy mineral sands (ilmenite, rutile, and zircon) and rare-earth oxides in the form of monazite. The property has already been drilled and Energy Fuels plans to perform extensive exploration work during 2022, to further define and quantify the HMS resource. A PEA is anticipated in the first half of 2023.

5. TITANIUM DEMAND

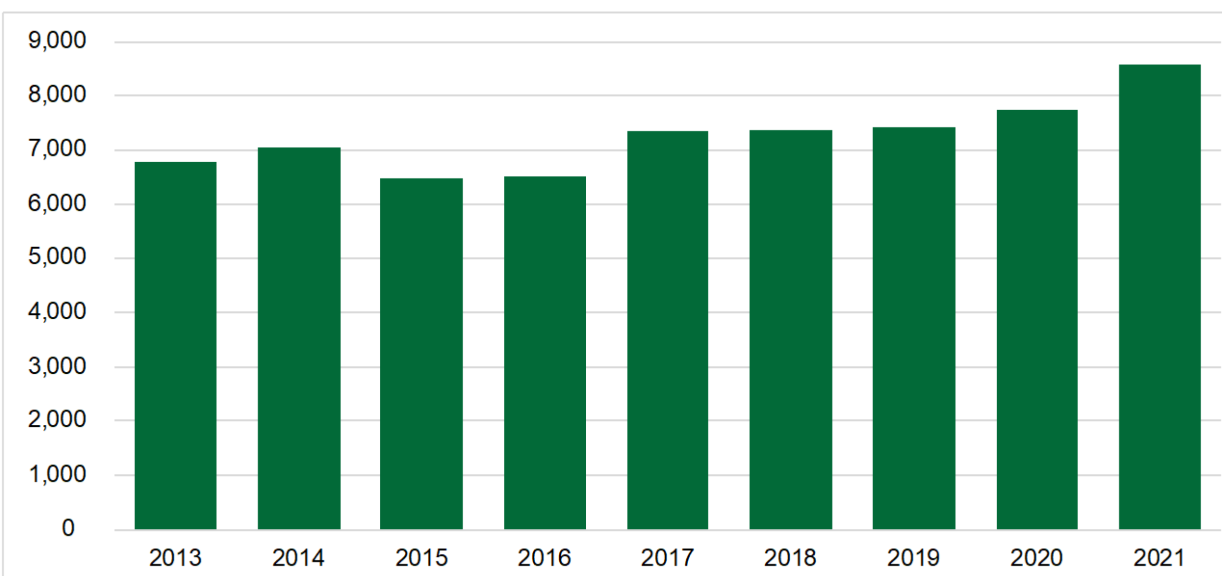
Demand for TiO_2 totaled 8,575 kt in 2021 according to data from Eramet (and TZMI). This comprised demand for TiO_2 pigments, titanium metal, and other minor uses. Figure 10 shows the titanium feedstock demand, by product, from 2013 to 2021. Demand grew by a CAGR of 3.0 percent over this period. In 2021, demand grew strongly as economies recovered from COVID-19 effects, and Kenmare Resources reports that TiO_2 pigment production was unable to meet strong demand because of insufficient TiO_2 feedstocks.

5.1. Titanium Consumption

Over 90 percent of the TiO_2 feedstock produced is processed by pigment producers and used for the production of white pigment. Titanium dioxide pigment has a high refractive index, which means it can scatter and bend light strongly, giving a product the appearance of it being opaque, white, and bright. It also has the ability to absorb UV light, efficiently transforming destructive UV light energy into heat. These qualities are utilized extensively in the manufacture of paints, coatings, plastics, paper, inks, textiles, ceramics, cosmetics, and pharmaceuticals. There is no economic or environmentally safe alternative to TiO_2, and the higher the quality of the end product, the greater the amount of TiO_2 that is required.

The remaining 10 percent consumption of TiO_2 feedstock is used for the production of titanium sponge, or used directly into metal rather than going through the sponge route, and is manufactured into titanium metal and fluxes for welding. The unique properties of titanium metal, including its high strength-to-weight ratio, high melting point, and its low conductivity, make it the preferred metal for a number of demanding applications, including the manufacture of airframes and jet engines for the aerospace industry, medical implants, defense, sporting goods, and components in the offshore mining and petrochemicals industries. Welding is another key market where high-grade titanium feedstocks are used in the manufacture of welding flux wire cord that are consumed in the steel construction and shipbuilding industries.

Figure 10: Titanium Dioxide Feedstock Demand 2013-2021 (kt TiO_2)

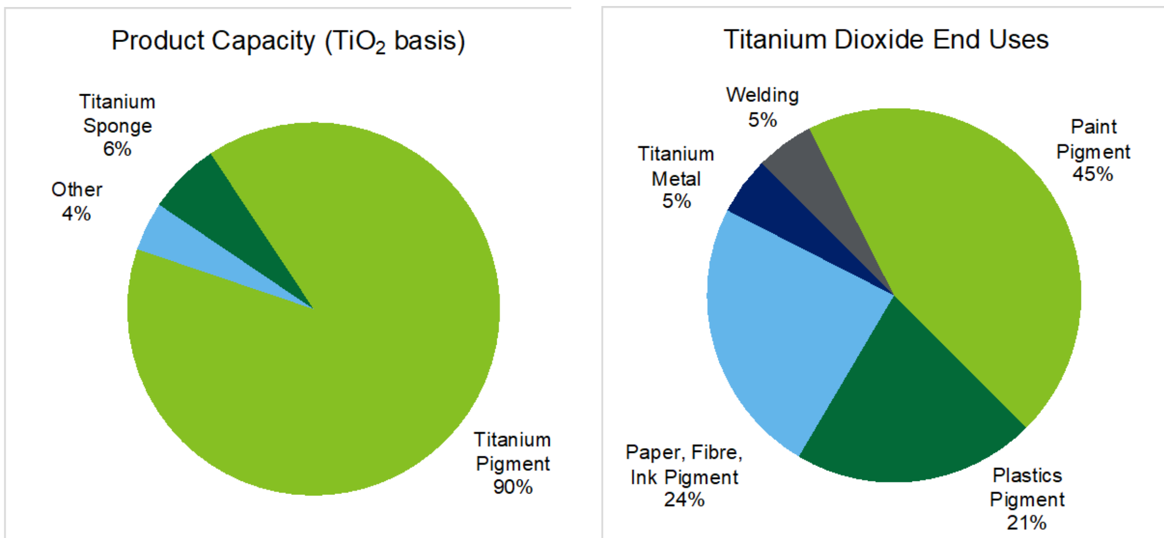


Source: Eramet, TZMI.

A small, but fast-growing sector of titanium demand is in the nanomaterials sector where titanium is utilized in applications such as dye-sensitized solar cells, water purification, cancer treatment, and noise absorption.

Figure 11 shows the feedstock demand for TiO_2 based on installed capacity of intermediary products and feedstock product end use.

Figure 11: Global Titanium Dioxide End Use Demand



Source: USGS 2020, Base Resources, Deloitte estimates

5.1.1. Titanium Dioxide in Paints, Coatings, and Plastics

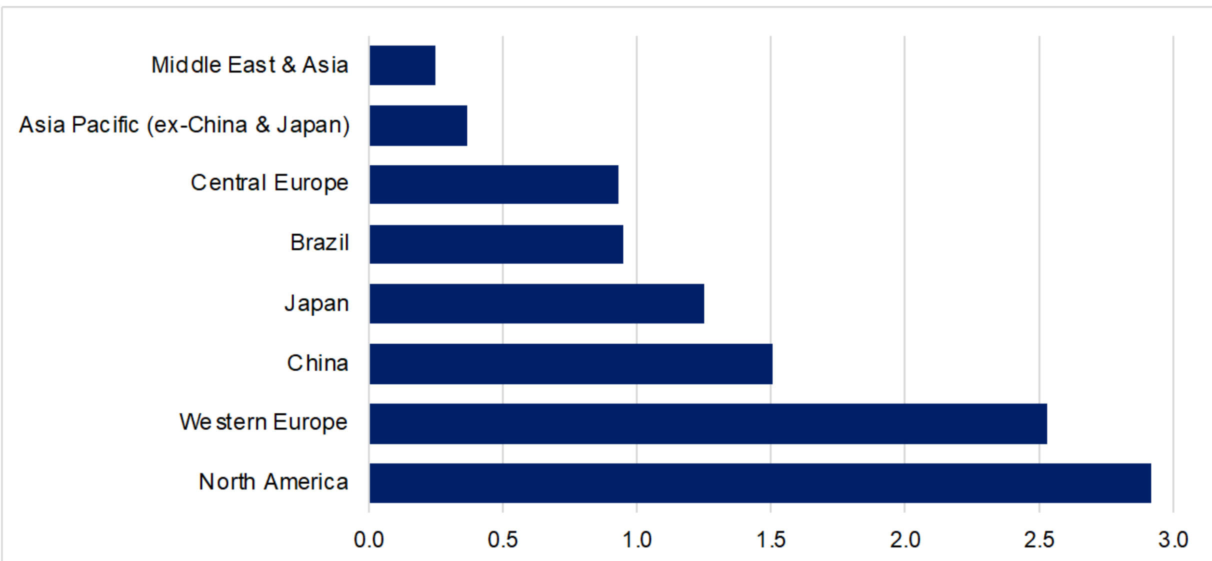
Titanium dioxide is called titanium white when used specifically as a pigment in paints, and sometimes Pigment White 6 or CI 77891. It is also known as 'the perfect white' or 'the whitest white' due to its powerful, pure whitening qualities. Until laws changed in the 1920s, most commercial paint manufacturers used highly toxic white lead as a whitener and did not initially convert to using TiO_2, partly due to its higher cost, until it became legislated. Zinc oxide (ZnO) is also used as a white pigment but is not as effective.

Titanium dioxide is now one of the most common pigments in global use and is the basis for most paint colors. It is also found in other coatings and plastics. These uses of TiO_2 account for 90 percent of its global usage. Its high refractive index means that, as a pigment, it is able to scatter visible light. This results in an opaque color and creates a bright, reflective quality when applied to a surface or incorporated into a product. A key example of its use in these applications is as a coating for wind turbines, providing both a suitable white color and protection from UV degradation. For the same reasons, it is also found in plastic window frames.

The application of TiO_2 pigments in the form of highly concentrated, pourable, pumpable suspensions (slurries) that can be metered volumetrically has increased in recent times. These slurries contain up to 75 percent TiO_2 and are rheologically[25] designed to prevent the formation of sediments, even after longer periods of storage. They represent a dust-free form of TiO_2 pigment application. Furthermore, depending on end-use requirements, various wet processing methods are used to modify the TiO_2, including precipitation of hydrous oxides such as silica and alumina on the pigment particle surface. Individual hydrous oxide treatments or various combinations can be used to optimize performance for specific applications.

Increasing population growth and higher per capita income drive the demand for paints and coatings in end-use sectors such as building and construction, consumer goods, personal care, automotive, and packaging. Figure 12 shows regional pigment consumption in terms of kilograms per capita.

Figure 12: Regional Pigment Consumption 2020 (kg/capita)



Source: Kenmare Resources.

5.1.2. Cosmetics and Skin Care

In skin care and makeup products, TiO_2 is used both as a pigment and as a thickener for creams. As a sunscreen, ultra-fine TiO_2 is used because of its transparency and UV absorbing abilities. In cosmetics, used with other colors, TiO_2 pigment gives intensity and brightness to decorative cosmetics. It also helps soak up oils in the skin, while lending it an opacity that reduces any unwanted shine.

[25] The study of the flow of liquids

5.1.3. Titanium Metal

Only approximately 5 percent of the titanium minerals extracted worldwide are used for the production of titanium metal. All present-day industrial producers use the Kroll process to produce titanium metal. Feedstock for this process is titanium tetrachloride previously produced from natural rutile, synthetic rutile, or titanium slag using the chloride process.

The titanium content of standard-quality titanium sponge is 99.2 percent (with a minimum of 98.5 percent), which is used for production of airframes and non-rotating parts of aircraft engines. Premium quality titanium sponge > 99.7 percent titanium is used in rotating engine parts in the aerospace industry. Titanium metal is also used extensively in non-aerospace industrial applications due to its corrosion and chemical resistance properties such as in equipment for desalination, nuclear power plants, chemical processing equipment, cooling water systems using seawater, medical implants, and other products. The strongest growth is in emerging applications such as medical and dental, architecture, and consumer goods including sporting equipment.

Titanium is often used as an alloy, mixed other chemical elements. Such alloys have very high tensile strength and toughness (even at extreme temperatures). They are light in weight, have extraordinary corrosion resistance and the ability to withstand extreme temperatures. Titanium carbide is used extensively for cutting tools because of its combination of wear resistance and high hardness. It is one of the hardest natural carbides.

For titanium metal, companies such as TIMET (United States), VSMPO (Russia), ATI (United States), Arconic (United States), Kobe Steel (Japan), Toho Titanium (Japan), and Baoji Titanium Industry (China) hold a significant portion of global smelting capacity between them and there is a high degree of downstream integration into the production of mill products.

5.1.4. Welding

High grade titanium feedstocks are used in the manufacture of welding flux wire cord. Approximately 25 to 30 percent of natural rutile is used directly for sheathing of stick welding electrodes as well as filling of flux-cored wire electrodes and manufacture of flux powder for arc welding. Welding powders are preferentially used for the automatic arc welding of larger components with thicker sheets.

5.1.5. Brazilian Consumption

ANM reports in its 2017 Mineral Summary (later summaries for titanium unavailable) that due to the various by-products of titanium and the different grades of those products, it is difficult to determine the amount of apparent titanium consumption in Brazil. Brazilian pigment consumption is shown in Figure 12.

5.2. Substitution

In TiO_2 pigments, TiO_2 can be partially substituted by talc, kaolin, and calcium carbonate, although not in large quantities. Zinc oxide can also be added for white pigments in paints, as it is a cheaper solution but produces an inferior product. Due to the outstanding properties of titanium metal, only few materials can compete with its strength-to-weight ratio and corrosion resistance. When a good corrosion resistance is necessary, titanium can potentially be substituted by aluminum, nickel, specialty steels, or zirconium alloys. For applications where high strength is required, titanium competes with superalloys, steel, composites, aluminum, and intermetallic. Aluminum alloys with REE (such as scandium) can be substituted in some aerospace applications.

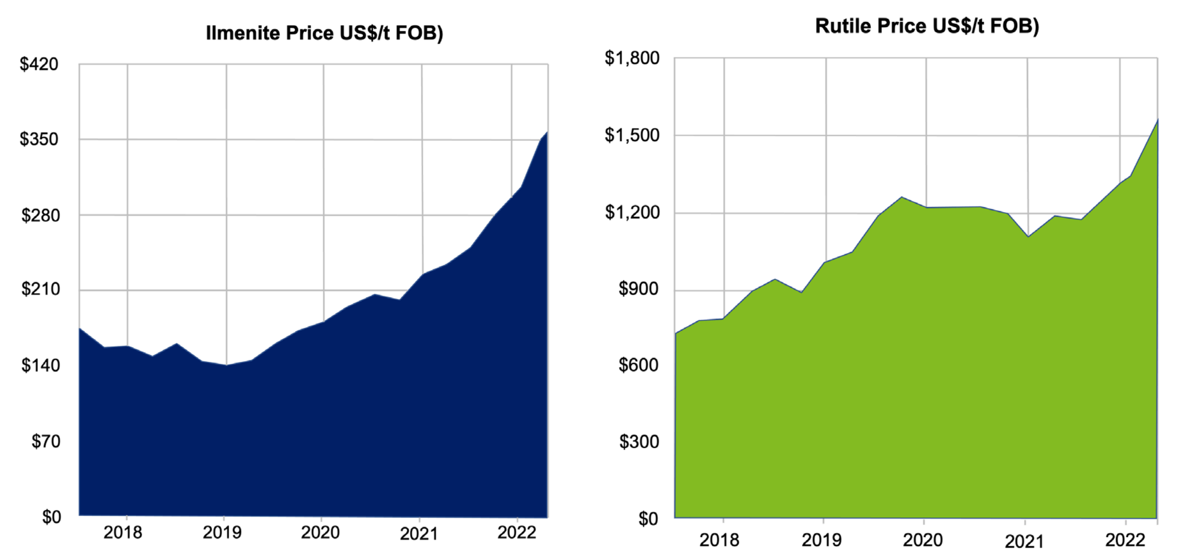
6. TITANIUM PRICES AND TRADE

Pricing of titanium products tends to be somewhat opaque. There is not a significant traded component of titaniferous raw materials, nor an established industry-wide or exchange traded equivalent benchmark price. Pricing is agreed between companies usually based on a combination of spot trades and short- and long-term contracts. In the case of contracts, prices are generally negotiated quarterly or annually. As a result, individual companies often report different average prices in a given period, dependent upon their contract structure.

The majority of the titanium-bearing ores market is transacted on short-term contracts, or longer-term volume contracts with market-based pricing re-negotiated several times per year. This form of market-based ore contract provides flexibility and responsiveness in terms of pricing and quantity obligations. Titanium feedstock demand is intrinsically linked to the TiO_2 pigment sector; therefore, it is also exposed to the pigment producers' stocking and de-stocking cycles and seasonal demand for paint.

The ilmenite market ended 2021 stronger than at any other point during recent years. Demand from all major regions and end-use markets remained firm and global inventories were well below normal levels, causing prices to accelerate in 2021. This positive market momentum has continued into 2022 (Kenmare Resources), particularly with potential added disruption due to the invasion of Ukraine by Russia (Ukraine produces 5.8 percent of global TiO_2 production). Figure 13 shows the prices of ilmenite and rutile over the past five years, both of which have more than doubled over the period. Rutile trades at around four to five times the price of ilmenite because it is an almost pure form to titanium dioxide and requires limited processing compared to ilmenite.

Figure 13: Historical Ilmenite and Rutile Prices 2018-2022 ($/kg)



Source: Base Resources

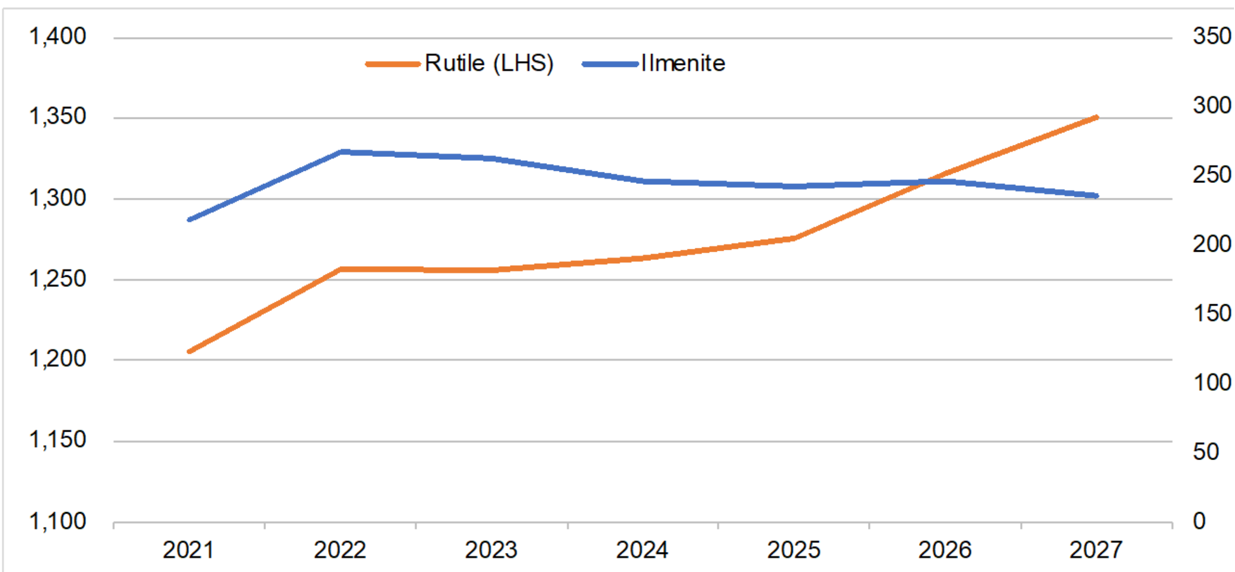
6.1.1. Titanium Trade

In 2020, global trade of titanium ores and concentrates was valued at $2.39 billion, according to the Observatory of Economic Complexity (OEC).[26] The top exporters of titanium were South Africa ($569 million), Australia ($260 million), Norway ($202 million), Mozambique ($183 million), and Sierra Leone ($158 million). The top importers of titanium were China ($337 million), United States ($309 million), Japan ($258 million), Netherlands ($207 million), and Belgium ($170 million). Brazil exported $10.8 million and imported $6.0 million.

6.1.2. Consensus Prices

Figure 14 shows the market consensus prices for ilmenite and rutile in nominal terms out to 2027. The market currently expects a modest decline in the price of ilmenite from current 2022 price levels, but a continued appreciation in the price of rutile due to the more limited number of new rutile projects expected to come on stream.

Figure 14: Consensus Nominal Ilmenite and Rutile Forecast Prices 2022-2027 ($/t)



Source: Consensus Economics August 2022.

[26] The OEC is an online data visualization and distribution platform focused on the geography and dynamic of economic activities.

7. MARKET BALANCE

Market data for titanium supply and demand remains somewhat opaque. Recent data is available in some cases from the mineral sands' producers, but forecast data is largely absent.

7.1. Supply Outlook

Demand for chloride quality TiO_2 raw materials currently accounts for around 46 percent of global demand compared to 54 percent for sulfate quality raw materials. Chloride capacity is expected to grow sharply in coming years to reach 55 percent in 2025, according to Eramet. This trend is confirmed by the reduced capacities for TiO_2 pigments production by sulfate process in China, Japan and in Europe, and by the development of the chloride process in China. In recent years, the leading Chinese producers have been adopting the chloride technology due to the higher quality pigments and for the environmental advantages. Chinese domestic ilmenite, however, is reported to be unsuitable for high-grade feedstock and it must therefore be imported.[27]

The chloride process requires high grade raw materials such as chloride ilmenite, slag, and enriched slag, and natural or synthetic rutile. High grade feedstock from existing producers is declining, according to Iluka, and there is limited new supply from projects due to:

- The high capital cost of building new upgrading facilities;
- Low rutile assemblage of new projects; and
- Increasing jurisdictional risk in some regions.

Furthermore, there is currently limited new capacity generally coming from TiO_2 projects or as a by-product from other new mining operations. Tronox states that a lack of new investment in the feedstock market will lead to higher feedstock prices and pigment supply shortages. The titanium minerals industry is experiencing declining valuable heavy mineral assemblages and grades at current and planned operations. To sustain current levels of production, there is a requirement for technical innovation, the development of unconventional orebodies, and significant capital expenditure. Higher prices are starting to induce more production, but only a few major projects are currently projected to come onstream over the next few years (*See* Section 4.7).

There has also been a decline in the production of sulfate ilmenite in two of the major producer countries; India and Vietnam, according to Neometals. In these countries, government intervention and the implementation of policies restricting the mining and export of ilmenite have drastically reduced export quantities in recent years.

7.2. Demand Outlook

In 2021, China continued to be the main consumer of titanium feedstock. In addition to 3.0 Mt of domestic TiO_2 production (which is unsuitable for high-grade feedstock), China imported a further 3.6 Mt TiO_2 of feedstock, with Mozambique (32 percent), Australia (14 percent), Vietnam (13 percent), and Kenya (9 percent) being the leading exporters to China. Long-term demand dynamics are likely to reflect a growing Chinese pigment sector and increasing environmental emphasis (requiring high-grade feedstock).

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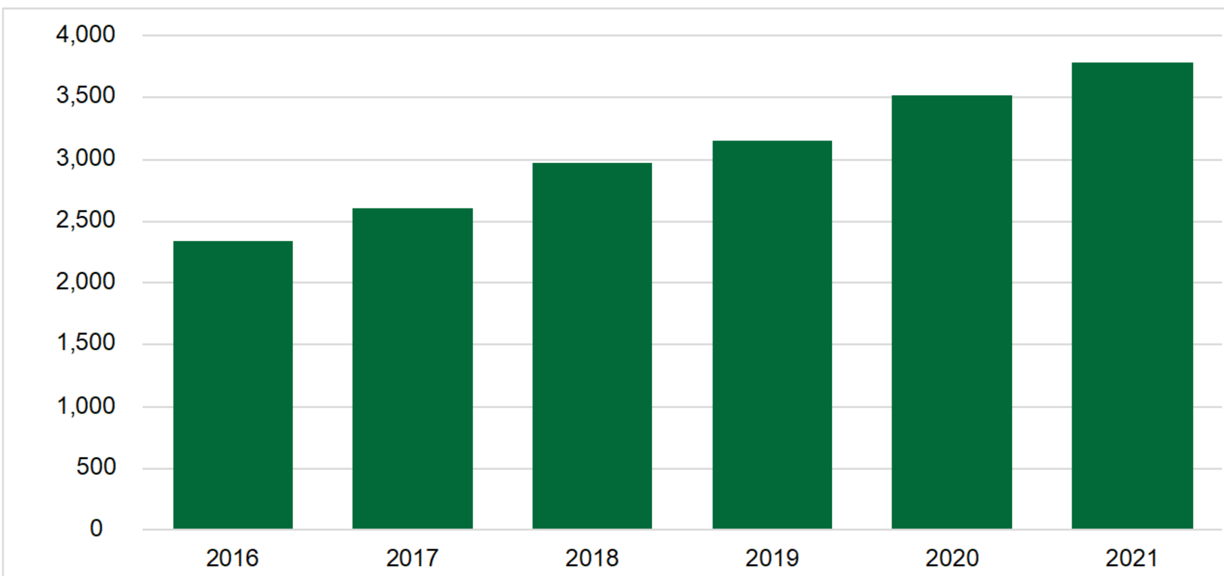
[27] Kenmare Resources 2021 Annual Report.

Inventories of TiO_2 pigment throughout the supply chain have remained at very low levels since the end of 2020, according to Base Resources (February 2022), due to pigment demand continuing to outpace pigment production capacity across all regions. Pigment producers in western countries have continued to target production at capacity levels and have been preferentially seeking the highest grade TiO_2 feedstocks (particularly rutile) to maximize the yield of their pigment plants. Some major chloride pigment producers have reported that, due to logistics challenges and a shortage of raw materials (including TiO_2 feedstock), they have not been able to achieve capacity production rates and have not been able to meet customer demand, a situation that is expected to continue through 2022.

In the chloride sector, producers in the United States have experienced production problems with continued shortages of chlorine, according to Iluka Resources. Costs are also rising in the sulfate sector with higher sulfur prices. In the chloride sector, high energy prices and TiO_2 costs are challenging European pigment producers. Figure 15 shows the growth of Chinese pigment production (sulfate and chloride) from 2016 to 2021, growing at a CAGR of 10.1 percent.

Figure 15: Titanium Pigment Production in China 2016-2021 (kt)



Source: Kenmare Resources

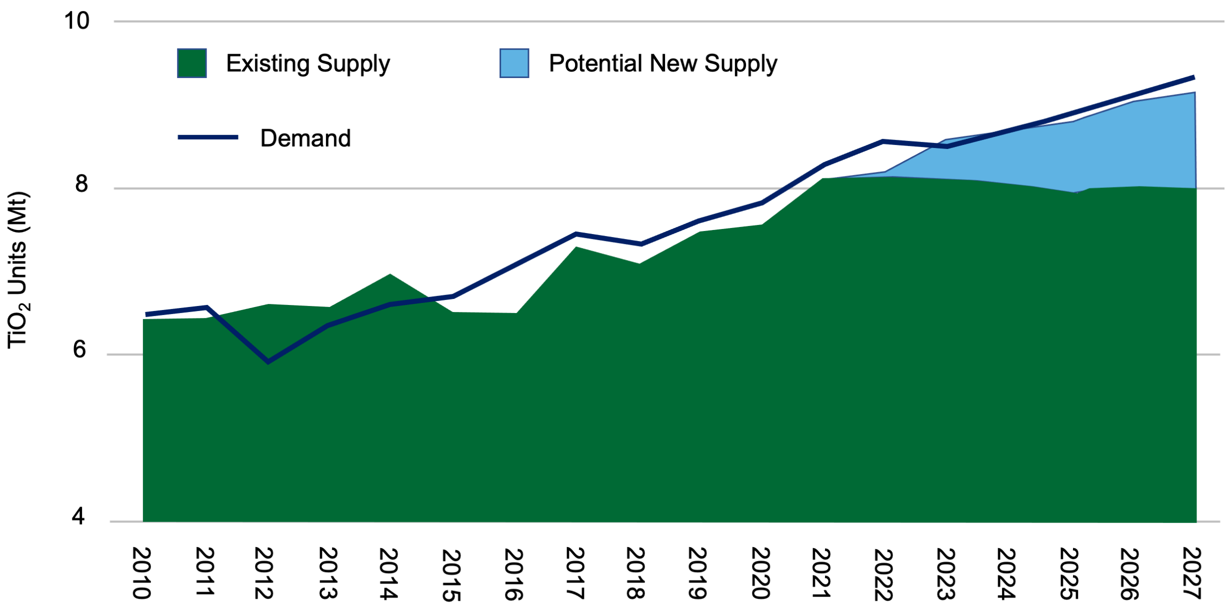
Figure 15 shows the growth of Chinese pigment production (sulfate and chloride) from 2016 to 2021, growing at a CAGR of 10.1 percent.

7.3. Market Balance

7.3.1. Titanium Dioxide Feedstock

Titanium dioxide demand is forecast to grow at a CAGR of 3.3 percent from 2020 to 2027, while TiO_2 supply is forecast to increase by a CAGR of 3.2 percent over the same period, according to data from Kenmare Resources. This will leave the market in slight deficit over the period. In 2021 and into 2022, the feedstock market has been unable to meet strong demand growth from the pigments industry, however, Kenmare reports that higher prices are currently incentivizing additional supply from lower quality ilmenite and ilmenite concentrates. The increasing feedstock is expected to balance the overall market in 2023 and 2024, but the markets are expected to remain tight, and the fundamentals are expected to remain supportive of prices. Figure 16 shows a forecast of TiO_2 supply and demand out to 2027 from Kenmare Resources, suggesting that the market moves back into deficit after 2024. The supply deficit appears more acute in the high-grade feedstock market (particularly for rutile), which supplies the chloride market where demand is the strongest.

Figure 16: Projected Titanium Supply – Demand Market Balance



Source: Kenmare Resources

7.3.2. Titanium Metal

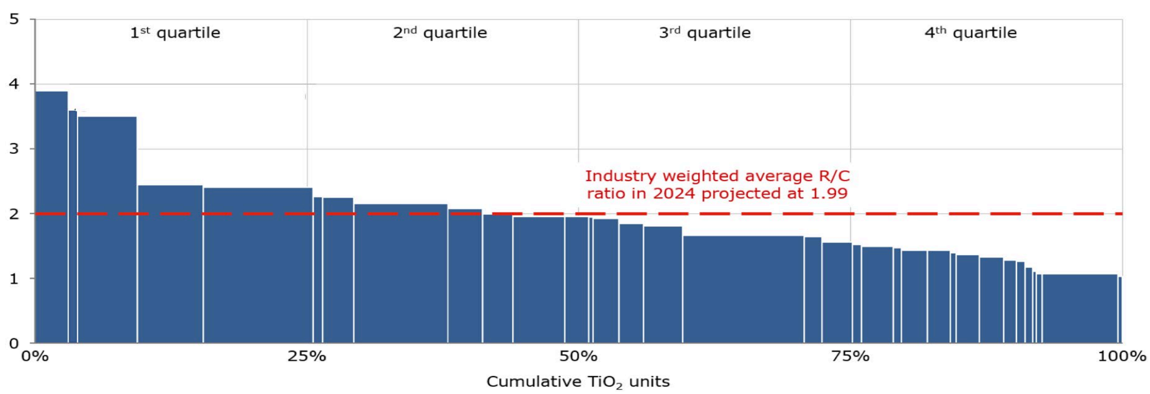
The impact of the very strong demand for rutile by western pigment producers has been compounded by the strong rebound in demand from the welding and titanium metals sectors, and some rebound in demand from the aerospace industry. Demand from these sectors strengthened through 2021 and this strength is expected to continue in 2022.

8. ECONOMIC COMPETITIVENESS

A lack of available reported data about industry costs and revenues, the limited current and new production of titanium in Brazil, and the lack of significant new projects elsewhere makes the analysis of both the industry's and Brazil's relative market competitiveness difficult.

Furthermore, the value stream of minerals produced and the cost structure from any specific deposit can vary considerably because of the differing grades and assemblage characteristics of each titanium deposit. As a result, within the mineral sands sector, focusing on grade can be misleading and margins are a more important indicator of financial returns. Consequently, the industry tends to use a margin curve or revenue to cash cost ratio curve to assess the relative attractiveness of mineral sands deposits, as shown in Figure 17.

Figure 17: Projected Titanium Industry Revenue to Cost Ratios 2024[28]



Source: Nordic Mining, TZMI

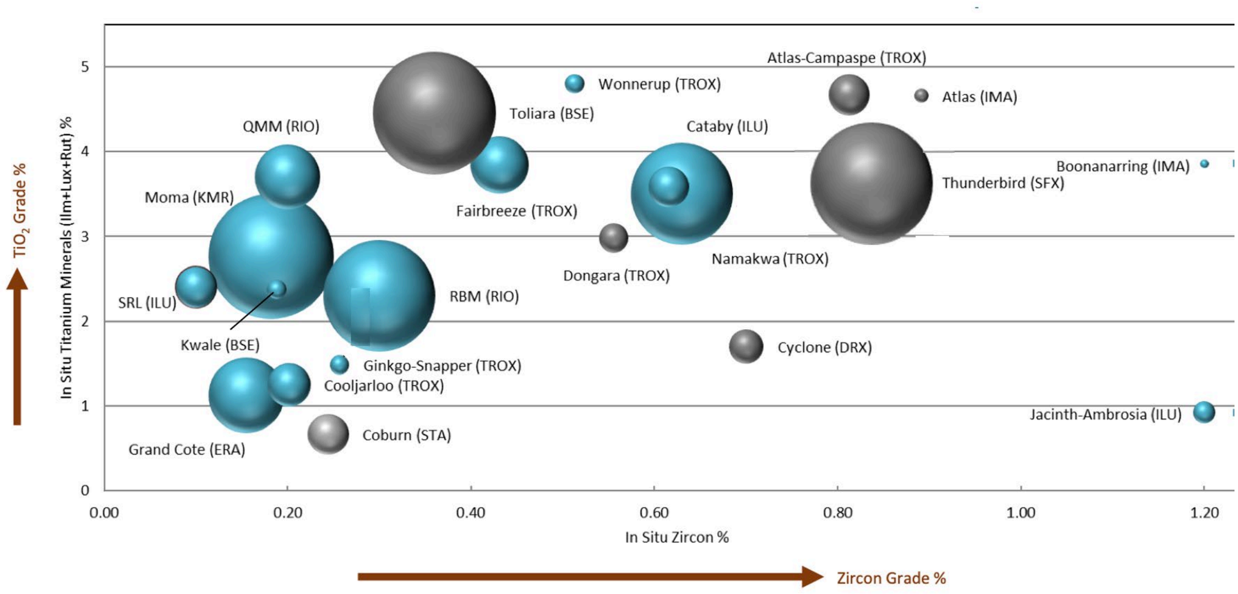
The only company that reports a breakdown of its cash operating costs is Kenmare Resources. In the first half of 2022, Kenmare Resources reported that labor accounted for 23 percent of costs, repairs and maintenance (21 percent), electricity and fuel (18 percent), production overheads, logistics and distribution (26 percent), and other (12 percent).

Kenmare Resources reports that the total cash operating cost per tonne was \$184/t in the first half of 2022, an increase of 29 percent due to higher labor, electricity, and fuel costs. Iluka Resources reports an anticipated cash cost of production of \$630/t (A\$820/t) in 2022 for its Australian operations and \$745/t (A\$970/t) for the operations in Sierra Leone. Base Resources reports an operating cost of \$196/t for financial year 2022 for its operation in Kenya. None of these operating costs is directly comparable, however, due to the different mineral assemblages, upgrading facilities, and final revenue.

Figure 18 shows the ore reserves and the grade of TiO_2 plotted against the grade of zircon for selected mineral sands deposits, both in operation and planned. The blue bubbles represent the operating mines and gray bubbles represent the projects. The grade of zircon is important in the assemblage because this is a high value product. The significance of the Toliara and Thunderbird projects in terms of relatively high grades of both TiO_2 and zircon can be seen, and contained heavy minerals compares favorably to the operating mines Moma, RBM, and Cataby.

[28] This has been obtained from a company report and the positions of individual operations are not reported, however, it provides a benchmark to compare new projects.

Figure 18: Ore Reserves and Grade for Selected Mineral Sands Deposits



Source: Sheffield Resources. (1) Bubble size represents contained heavy minerals in ore reserves

9. CONCLUSION AND RECOMMENDATIONS

The titanium market is not large in size or value (compared with other major commodities), but it is a commodity used in consumer markets as a pigment in paints, plastics, enamels and paper. The Government of Brazil should continue to allow the development of existing assets and should encourage the development of further titanium resources in the longer term, either on a stand-alone basis or as a by-product in association with another commodity, such as vanadium. This is because domestic consumption of TiO_2 pigment is likely to continue rising as Brazil's gross domestic product (GDP) rises, and the consumption of TiO_2 per capita increases. Brazil could then meet this demand domestically, rather than rely on imports. As noted above, Brazil currently produces 66 kt/y of TiO_2. If Brazil raises its consumption closer to U.S. levels, it will require over 400 kt/y more of TiO2.

Key Recommendations

Brazil should consider enhancing titanium-related investment in the longer term by:

- **Examining the potential of Largo Resources upgrading its planned TiO_2 pigment plant from a sulfate plant to a chloride plant.[29]** While the choice of plant is partly dependent on the quality of ilmenite and the TiO_2 pigment demands of the end-market, it may be possible to install a titanium slag upgrading plant and a chloride pigment operation, instead of a sulfate pigment plant. The sulfate process is older, less efficient, and produces a number of waste products that are difficult to treat, while the chloride process uses high grade feedstock to produce high quality TiO_2 pigment. The chloride process offers waste disposal, energy, and quality advantages over the sulfate process. Switching to a chloride plant may result in higher capital costs and additional technology requirements, but the benefits include significantly lower environmental footprint and a higher quality TiO_2 pigment, which is in strong global demand.[30]
- **Increasing access to, and circulation of, up to date titanium resource data to domestic and international exploration to promote titanium development in Brazil.** Increasing access to data may require gathering and distributing more extensive information from those regions (*e.g.,* Paraiba) that are considered to have significant titanium potential. Legacy CPRM geological data, reports, and studies should be made more broadly available online in a range of languages. Brazil should also undertake appropriate marketing of these documents to expand their circulation and increase their impact.

[29] The Largo Resources TiO_2 pigment plant has not yet been built.

[30] Titanium dioxide pigments are produced from two chemical processes: the sulfate and the chloride process. China, the main producer of sulphate pigment, is recently building predominantly new chloride plants.

ANNEX 1 – TITANIUM ORES AND RESOURCES

Titanium is abundant in the earth's crust and widely distributed but is not commonly found in economic concentrations with suitable mineralogy and grade. Titanium is obtained principally from the minerals ilmenite and rutile, and occasionally from anatase.

There are four major classifications of titanium mineral deposit types:[31]

(a) magmatic deposits in igneous and related rocks with ilmenite as the primary ore mineral;

(b) metamorphic deposits with rutile as the primary ore mineral;

(c) rutile in hydrothermal porphyry deposits, and

(d) heavy-mineral concentrations in unconsolidated and lithified sand deposits that may include rutile, ilmenite, and alteration products, such as leucoxene.

Most deposit types can be further altered by weathering, at times upgrading the titanium content of the ilmenite, if present. The economic value and mining potential of a titanium deposit is highly dependent on its mineralogy rather than its overall titanium content.

Ilmenite is the most common titanium mineral in the earth's crust. It is the most important dispersed accessory mineral in almost all intrusive and extrusive rocks. It has overriding significance as a titanium mineral in norites, gabbros, and anorthosites. There is seamless mixing at high temperatures (> 600 degrees Centigrade) between ilmenite and hematite (Fe_2O_3). Part of the iron (Fe) can be replaced by magnesium (Mg), manganese (Mn) and aluminum (Al), and part of the titanium by Mg in the mixed crystals. As the temperature drops, hematite and ilmenite become segregated forming titano-hematite: here thicker or thinner layers of hematite in varying amounts are inserted with ilmenite.

Magnetite Deposits

Titanium magnetite is an important source of titanium minerals. The two spinels magnetite ($Fe^{2+}Fe_2^{3+}O_4$) and ulvite (Fe_2TiO_4) are seamlessly able to mix at high temperatures. Furthermore, part of the Fe^{2+} can be replaced identically by titanium, Mg, Mn, and other elements and part of the Fe^{3+} can be replaced by titanium, Al, vanadium (V) and chromium (Cr) in the magnetite. As the temperature declines, there is segregation into magnetite, ilmenite and ulvite. Complete segregation into pure magnetite and ulvite does not take place. In addition, ilmenite is precipitated in the form of fine layers on the octahedral faces of the magnetite. The slower the cooling, the coarser the segregation structure.

Due to the preferred insertion of Fe instead of titanium, the TiO_2 content in ilmenite can be far below the stoichiometric value of 52.7 percent by mass. The numerous possibilities for the incorporation of impurity ions in ilmenite also partly explain the difference in the chemical analyses of ilmenite concentrates. Impurities due to the incorporation of mineral impurities in solution cavities or by insufficient processing are common. The lower the TiO_2 content of the ilmenite, the lower its commercial value.

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[31] USGS Professional Paper – Titanium.

Metamorphic Deposits

Rutile is the most economically valuable mineral for titanium, but rutile ores are limited in volume. The main exploration focus is on high-grade metamorphic rocks, such as eclogite (a rock composed primarily of garnet and pyroxene, with lesser amounts of rutile, and typically formed under high-pressure conditions). Complications for exploitation of eclogite include highly variable rutile concentrations and grain sizes, retrograde alteration of high-grade metamorphic rutile back to ilmenite or titanite, and the possible presence of impurities, such as calcium, magnesium, iron, and aluminum in trace silicates in rutile concentrates. The only currently active rutile mines in metamorphic rocks are the Daixian rutile deposits in east-central China, which consist of lenses and layers of rutile-bearing high-grade metamorphic rocks that average about 2.0 percent TiO_2.

Metamorphism of deeply weathered rocks, such as laterites and bauxites, can also result in rutile-bearing aluminum-rich rocks. Because these aluminum-rich rocks are stripped of many other elements, they potentially create a low-grade (about 1 percent or less rutile) and commonly low-tonnage but high-quality TiO_2 resource that is generally free of other contaminants. Rutile in such deposits can be a valuable by-product of primary industrial commodities, such as alumina, andalusite, kaolinite, or kyanite.

Minerals Sands Deposits

The most important economic source of titanium is from mineral sands and the majority of the high-grade ilmenite and rutile used today is extracted from unconsolidated heavy minerals. Heavy-mineral sand deposits develop when relatively resistant titanium-bearing minerals and other heavy minerals are eroded from primary parent rocks, then transported and sorted, and finally deposited in fluvial, beach, or wind produced settings. The final member in the weathering process is the mineral mixture leucoxene which predominantly consists of titanium oxides and, to a far lesser degree, iron oxides. The process of weathering is therefore called leucoxenization. Leucoxenization only occurs above groundwater level. In addition to rutile, ilmenite, and leucoxene other heavy minerals such as zircon and REE may enhance or detract from a deposit’s value.

Most mineral sands deposits are produced by weathering and erosion of the earth’s surface and are carried by sedimentary action to coastlines where a combination of wave action (strand deposits) and, to a lesser extent wind action (dunal deposits), resulted in concentrations in bodies of silica (quartz) sand along ancient beach lines and associated environments. Mineral sand deposits are typically found in unconsolidated fossil shorelines up to hundreds of kilometers inland from present coastlines. Mineral sands deposits are characterized by their grade (the percentage of heavy minerals found in a deposit) and their assemblage (the relative proportion of valuable heavy minerals components of ilmenite, rutile and zircon). The typical composition of a mineral sands deposit has a heavy minerals grade ranging from 0.5 to above 20 percent.

ANNEX 2 – MINING AND PROCESSING OF TITANIUM

Titanium minerals are mined from hard rock deposits and mineral sands deposits. Mineral sands are the most abundant class of economic titanium deposits. The mineral sands industry primarily involves the mining of the heavy minerals and processing the two main product streams, titanium dioxide and zircon. Mineral sands are extracted using either dry or wet mining techniques. Dry mining involves trucks, excavators, scrapers, and loaders to recover ore in an open pit. The ore is then moved to a wet concentrator plant using a slurry pipeline or overland conveyor. Wet mining involves using floating dredges on man-made ponds to mine the ore and then pumping it in a slurry form to a floating concentrator, as shown in Figure 19.

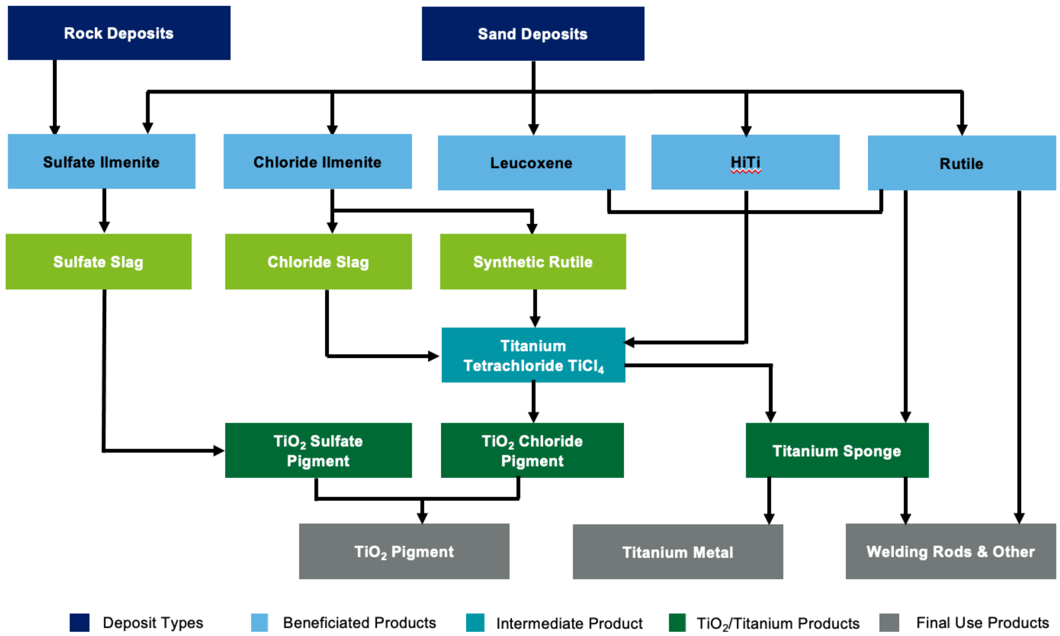
Figure 19: Floating Mining and Concentration Unit for Mineral Sands, Mozambique

Source: Kenmare Resources

The selection of the most appropriate mining method primarily depends on the geography, geology, feed grade, tonnage being processed, water table, and ground conditions. As dry mining is more precise, it is usually used on high-grade and discontinuous orebodies. Wet mining is generally employed on large tonnage orebodies, where the deposit could be below the water table and the ground is not too consolidated (free flowing sands are the best). Wet mining has the lowest cost of solid handling per tonne, but usually entails a higher initial capital cost, however, wet mining is only possible if the sands contain very few clay particles.

Processing of mineral sand products involves the use of a concentrator plant and a mineral separation plant. In the concentrator, the sand is washed through a series of spiral separators that utilize the differences in specific gravity to separate heavy mineral sands from lighter quartz and clay impurities. Following this, a separation plant separates heavy mineral concentrate into valuable minerals and non-valuable minerals. Valuable minerals are further processed into different product grades of ilmenite, rutile, and zircon to meet specific customer requirements.

Figure 20: Titanium Mineral Processing



Source: Deloitte

Figure 20 shows the processing route for TiO_2 minerals. There are two industrial processes for the manufacture of TiO_2 pigments, the sulfate and the chloride process. The sulfate process has been used for manufacturing titanium dioxide since 1919 and is still important today in countries such as China, Vietnam, Russia, and Ukraine, however, it has been replaced by the chloride process in most plants in the western world due to the environmental burden of the sulfate process.

Sulfate Process

The sulfate process requires either ilmenite with a TiO_2 content of at least 44 percent or a titanium slag with 70 to 80 percent TiO_2 as initial raw materials and the titanium feedstock is dissolved in concentrated sulfuric acid. The iron oxide contained in the ore reacts to become iron sulfate while the titanium ore becomes titanium oxysulfate. During this process, large quantities of sulfur dioxide are produced which is largely neutralized with caustic soda solution minimizing the amount of sulfuric dioxide released into the environment. The iron sulfate is separated from titanium sulfate by crystallization. Due to its superior solubility in water, the iron sulfate crystallizes out as green iron (II) sulfate which can then be removed. Titanium oxysulfate is broken down into titanium oxide hydrate relatively easily by boiling in large vats of water, which results again in the parallel production of large quantities of dilute acid as an undesirable by-product.

The titanium oxide hydrate is annealed to pure white titanium dioxide in large rotating kilns at temperatures of between 800 and 1,000 degrees Centigrade following a lengthy washing process. To improve the optical and physical properties, the fine pigment particles are post-treated using different substances and processes. For each tonne of TiO_2 produced using the sulfate process, approx. 1.7 to 2.5 tonnes of low-grade ilmenite (45 percent TiO_2) and 4.4 tonnes of sulfuric acid, or 1.0 to 1.4 tonnes of titanium slag (80 percent TiO_2) and 2.4 tonnes of sulfuric acid are required. In addition to 4.5 tonnes of iron sulfate, around 6 to 9 tonnes of dilute acid with a sulfuric acid concentration of up to 23 percent by volume are produced. This dilute acid cannot be processed further due to its low sulfuric acid content.

The dilute acid is also usually contaminated with heavy metal salts such as lead or chromium salts. As a result, most manufacturers apply a subsequent process in which the acid content is increased, and the metal salts (predominantly the iron sulfate) are crystallized out. However, this process consumes relatively large amounts of energy. The higher concentrated sulfuric acid produced in this way can then be recycled back into the process. The iron sulfate is used in wastewater treatment. It converts phosphate salts in the wastewater from fertilizers and detergents into iron phosphate that is insoluble in water. This can then be extracted from the water using the usual separation methods in sewage treatment plants. The iron oxides produced during TiO_2 production are in part recycled or dumped in landfills.

Chloride Process

The chloride process requires intensely weathered ilmenite of >58 percent TiO_2, leucoxene, natural rutile, synthetic rutile, or a titanium slag with >85 percent TiO_2 as the basic raw materials. The demand for this high-grade titanium feedstock has risen in line with the demand for TiO_2 pigments as more and more companies worldwide switch from the sulfate process to the chloride process.

In this process, ore rich in TiO_2 is initially mixed with coke and then with chloride gas at approximately 1,000 degrees Centigrade in a fluidized bed furnace particularly resistant to chloride. The chloride reacts with the titanium dioxide in the ore and the added carbon to form gaseous titanium tetrachloride, carbon monoxide, and carbon dioxide. Iron (II) chloride produced by chlorination is dissolved in water and separated out. At the same time, hydrochloric acid is produced as a result of the reaction between the chloride with the residual moisture contained in the raw ore and is leached out and can be sold as a raw material. Following this, the gaseous titanium tetrachloride is condensed into a solid substance, and this is treated repeatedly by distillation to remove impurities. After re-condensing, pure titanium tetrachloride is produced that can be supplied to the next processing step. Pure titanium dioxide is produced by heating the titanium tetrachloride to high temperatures and adding pure oxygen.

Titanium Slag

Titanium slag can be formed by reducing ilmenite with carbon in an electric furnace at temperatures of between 1,650 and 1,700 degrees Centigrade. Low-grade ilmenites are the preferred feedstock for smelting because the high iron content provides suitable thermodynamic conditions. Pig iron is always generated in large quantities as a valuable by-product.

Due to their differing densities, the slag floats on the iron and mainly consists of unreacted ilmenite, titanium oxides and other impurity oxides. The slag is most often used by pigment manufacturers as feedstock in the sulfate process (sulfate slag >75 percent TiO_2) and chloride process (chloride slag >85 percent TiO_2) although some companies use it in titanium sponge production. The fines produced when crushing chloride slag are called ‘chloride fines’ and can be used as feedstock in the sulfate pigment industry. The final quality of the slag is highly dependent on the quality of the ilmenite as virtually all the impurities, together with any impurities in the reductant report to the slag.

Synthetic Rutile

Synthetic rutile serves as one of the possible basic raw materials in the chloride process and is therefore also suitable for metal production using the Kroll process. The process for the manufacture of synthetic rutile consists of the complete or partial reduction of the iron bound up in the ilmenite in a rotary reduction kiln at 1,050 to 1,150 degrees Centigrade and subsequent leaching and separation from the titanium dioxide. One tonne of ilmenite yields approximately 0.6 tonnes of synthetic rutile. The process is not suitable for low-grade ilmenite because the silicate gangue will remain in the synthetic rutile.

Numerous special processes have been developed to produce synthetic rutile. Most of them even allow the amount of minor contaminants to be reduced, however, low-impurity ilmenite is still the preferred feedstock as the removal of contaminants, with the exception of iron and manganese, requires costly additional acid-leaching steps.

Titanium Metal

The Kroll process is used for production of titanium metal. Feedstock for this process is titanium tetrachloride previously produced from natural rutile, synthetic rutile, or titanium slag using the chloride process. It is based on the principle of the separation of the titanium from titanium tetrachloride by means of adding magnesium.

The reduction of the $TiCl_4$ is performed using argon gas to create an inert atmosphere, since titanium has a high affinity to atmospheric gases. The process is carried out in a reactor made of steel or chromium-nickel steel. Depending on the size of the reactor, 1.5 to 7.0 tonnes of titanium sponge is produced in each batch. Magnesium is melted in the reactor at the beginning of the process. $TiCl_4$ is then continually added dropwise over the course of several days or fed from above into the reactor in gaseous form. The magnesium chloride is liquid and sinks to the reactor floor due to its higher apparent density compared to titanium and magnesium. The liquid $MgCl_2$ therefore accumulates below the magnesium melt and can be extracted discontinuously. The titanium sponge, however, precipitates in the reactor and forms a solid crust above the magnesium melt. The magnesium rises through the porous titanium sponge to its surface due to capillary action where it further reacts with the gaseous $TiCl_4$. The addition of $TiCl_4$ is stopped when the magnesium placed in the reactor at the beginning has been consumed. Afterwards, the titanium sponge must be cleaned of magnesium and $MgCl_2$ residues. The production of 1.0 tonne of titanium sponge typically consumes 4.4 tonnes of titanium tetrachloride.

The titanium sponge cake is removed mechanically from the reactor and crushed into large lumps and then into smaller pieces afterwards. As impurities from minor components differ from piece to piece, all pieces are thoroughly mixed and blended to produce a uniform quality. The normal titanium content of standard-quality titanium sponge is 99.2 percent (minimum 98.5 percent), which is used for production of airframes and non-rotating parts of aircraft engines, as well as in non-aerospace industrial applications such as equipment for desalination, nuclear power plants, chemical processing equipment, medical implants, and other products. Premium quality >99.7 percent titanium is used in rotating engine parts in the aerospace industry.

ANNEX 3 – CONSOLIDATION IN THE TITANIUM INDUSTRY

There have been a number of consolidations and rationalizations in recent years in both the titanium dioxide feedstock and the pigment markets. These are arguably leading to some improved discipline in the industry as the number of competitors has been reduced.

Of these, the largest was the acquisition of Cristal by Tronox to become a major integrated TiO_2 producer. In 2018, Tronox acquired Cristal's TiO_2 business for $1.7 billion in cash and shares, representing 24 percent of Tronox. In 2019, Tronox sold the North American pigment business of Cristal to Ineos for $700 million, as required by antitrust authorities in the United States and Europe.

In October 2016, Henan Billions Chemicals completed the acquisition of Sichuan Lomon for some $1.3 billion. The new company, Lomon Billions (LB Group), is the largest TiO_2 pigment producer in Asia, operating both sulfate and chloride operations in China. It has subsequently constructed a new chloride plant with technology licensed from PPG Industries and now has five TiO_2 pigment production sites, three sulfate process plants, and two chloride process plants. It currently has a capacity of 1,100 kt TiO_2 and states that it plans to significantly increase its production capacity.

In December 2016 Iluka acquired Sierra Rutile, the world's second largest rutile producer with assets based in Sierra Leone, for $330 million. In June 2022, Iluka announced the demerger of Sierra Rutile as a separate company.

Huntsman became a significant TiO_2 pigment producer in 2014 following the acquisition of Rockwood's TiO_2 business for $1.1 billion. In 2017, Huntsman completed an IPO of its TiO_2 business (70 percent) and other additives businesses (30 percent) in a company called Venator Materials. Huntsman retained a 49 percent economic ownership which it subsequently sold in 2020 to SK Capital.

In 2018, Eramet acquired Mineral Deposits Ltd (MDL) of Australia for approximately $260 million. Eramet and MDL jointly owned the TiZir titanium dioxide and zircon operations in Senegal and Norway. An agreement for the sale of TiZir's Norwegian plant signed in May 2020 between Eramet and Tronox failed to secure the approval of the UK's competition authorities. This prompted Tronox to unilaterally decide in January 2021 to withdraw from the proposed.

Deloitte & Touche LLP
1919 N. Lynn Street
Arlington, VA 22209
Phone: +1 571 882 5000
Fax: +1 571 882 5100