TITANIUM

THE FORTHCOMING STRUCTURAL IMBALANCE

The Future of the Titanium Market

February 20, 2026

Oculus Research

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0. Executive Summary

0.1 Core Thesis

- The Titanium market is distinct due to its high technological barriers, lower price transparency, and extreme supply concentration.

- Titanium is a critical metal with unique properties of significance in a wide range of critical applications, with narrow substitution possibilities.
- Market narratives of oversupply diverge from physical realities of qualified supply deficits, particularly in high-grade demand segments like aerospace.
- Technological developments in AI and Robotics and emerging applications have a high probability of meaningfully reshaping the current supply-demand balance.

Supply-Demand Dynamics

- The low-grade segment of the market faces weaker demand and surpluses suppressing the prices for raw sponge. The high-grade segment of the market, however, experiences tighter supplies with shortages in high grade ore (Rutile) and processed, high-purity sponge, ingots, and finished products.

- While the market is well supplied with ore, the complex, energy intensive, geopolitically sensitive, processing of ore into sponge and finished products create a considerable bottleneck in supply, particularly in high-purity aerospace and defense grade Titanium.

The Future of the Titanium market: Defining Features

- Defense and biomedical applications are experiencing accelerated growth.
- A new demand segment is emerging in robotics: humanoids, drones, autonomous vehicles, and industrial robots
- Technological innovation – creation of additional demand segments.
- Processing capacity expansion is constrained by capital and energy intensity, technological complexity, regulatory considerations, and long lead times.

NARRATIVE

- Aerospace demand (engines, airframes)
- Robotics applications

-Defense demand

Flow: Drives

↓

PHYSICAL SYSTEMS

- Mining (rutile/ilmenite)
- Kroll process (TiCl4 reduction)
- Sponge production (Mg reduction)
- Melting/ingot (VAR furnace)
- Forging/alloying

Flow: Limited by

↓

MATERIAL CONSTRAINTS

- High production costs
- Low workability (room temp)
- Impurity sensitivity (O, N)
- Wear resistance limits

0.2 Key Takeaways

- **Demand-side drivers**

- Defense and Aerospace currently account for more than half of global titanium metal production demand. The defense segment is projected to grow exponentially as countries increasingly prioritize defense and military spending. Industrial applications (including power generation) are the second largest demand segment, accounting for approx. 25% global supply. The biomedical demand segment only accounts for approx. 10% of consumption but demand is surging for patient-specific 3D-printed implants and surgical instruments. Robotics and autonomous physical AI systems demand is the smallest segment of the market but is the fastest growing. The growth of Robotics has the potential to meaningfully increase demand for Titanium.

- **Supply-side constraints**

- Processing of high-purity titanium is the key constraint in the supply of defense and aerospace grade Titanium products, the largest segment of demand. Supply for high-purity Titanium is tight. Geopolitical constraints and export restrictions for defense grade titanium create additional supply constraints.

- **Substitution limits**

- While substitution (primarily with Aluminum) is possible in some applications, Titanium's unique properties prevent substitution in critical applications across all demand segments due to its unique molecular properties.

0.3 Outlook Summary

Base case: 8.7% CAGR

Titanium demand expands steadily supported by the growth of aerospace and defense segments. In the near-term robotic related demand remains negligible but demand share will accelerate meaningfully in the outer years.

Supply growth in the near-term horizon can scale meaningfully by utilizing excess capacity. In outer years incremental supply will be largely inelastic and unable to meet increasing demand.

Accelerated case: 12.6 %

Geopolitical tensions maintain their trajectory and result in substantial increases in global defense spending and subsequent Titanium demand. The deployment of humanoid robotics and AI driven Industrial applications scale rapidly.

While supply is currently able to accommodate short-term incremental demand, supply will not be able to meet accelerated demand particularly in the outer years after producers reach name plate capacity.

Stress case: 5.6%

Macro conditions weaken capital deployment and subdue overall demand. Growth in robotics and autonomous systems fail to meet projections.

Technological innovations in substitution and advancements in recycling meaningfully increase supply and subdue direct production demand. Supply demand remains balanced until deficits begin to emerge in the outer years.

1. Titanium Market Overview

1.1 Titanium

Titanium (Ti) is classified as a transition metal. It is the 9th most abundant element. The pure form is silver-gray, with low density, and exceptional strength. It occurs naturally in the earth's crust primarily as oxide, Rutile ($Ti0_2$), and Ilmenite ($FeTi0_3$). The metal is rarely found in its metallic form in nature due to its high reactivity with oxygen, nitrogen, and other elements.

Titanium exists in two primary allotropic forms: alpha (hexagonal close-packed structure [stable at room temperature, and beta (body-centered cubic structure [stable above 882°]), enabling for alloying for tailored properties for specific applications. There are three alloy categorizations: alpha, alpha-beta, and beta types.   Common alloys like Ti-6Al-fV (Grade 5) dominate the industrial industry due to their balanced strength, ductility, and heat resistance.

Unique Properties:

- **Density and Strength-to-Weight Ratio:**
  (Ultimate tensile strength (UTS) = 400-1,200 comparable to steel but half the weight)
  - Value: Allows for thinner lighter structures without compromising strength

- **Corrosion Resistance:**
  (Forms a passive TiO_2 layer (2-5nm thick) that self-heals, resists acids, chlorides, and seawater better than steel)
  - Value: Reduces maintenance by 50-70% in chemical plants and offshore oil rigs. High area-volume efficiency in thin-walled pipes/tanks.

- **High Temperature Performance:**
  (Melting point of 1,668 °C with creep resistance of up to 600 °C in alloys and low thermal conductivity)
  - Value: Withstands 1,000-1,200 °C environments (turbine blades), less material volume needed for heat management.

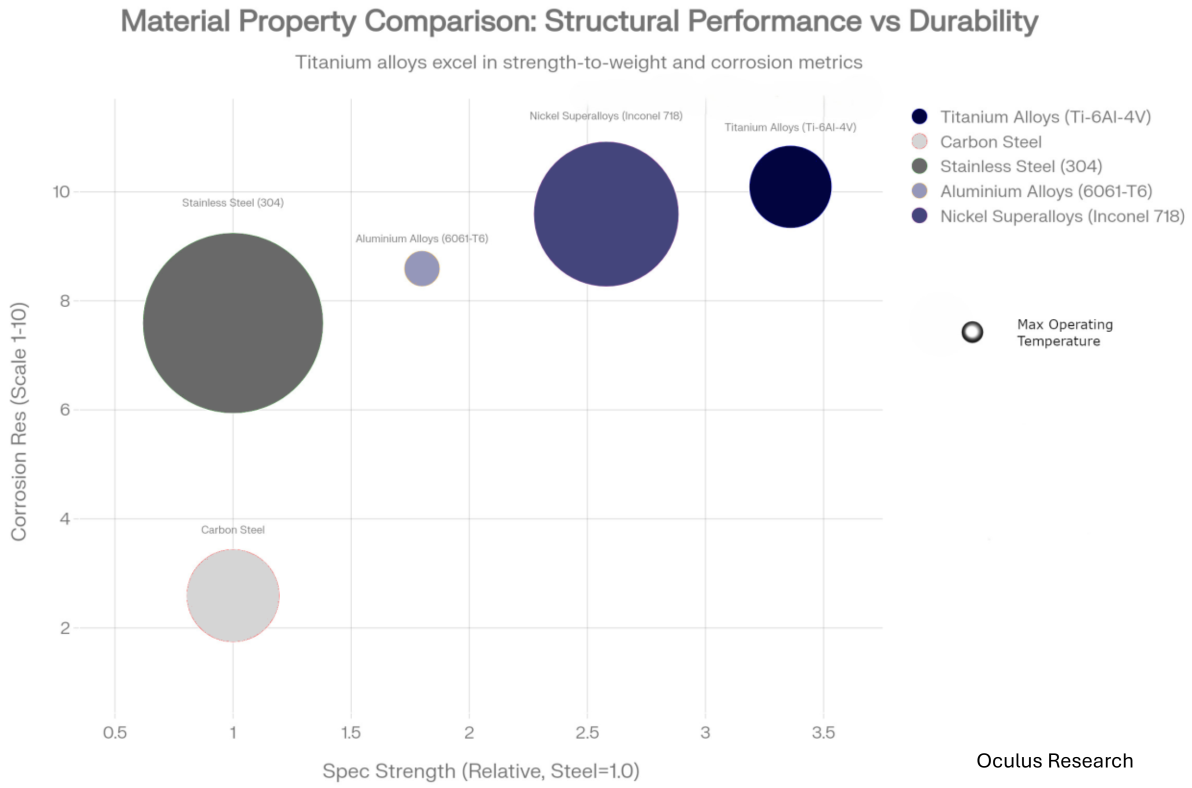
- **Biocompatibility and Non-Magnetic Properties:**
  (Non-toxic, with modulus elasticity (~110 GPa) close to bone (10-30 GPa), Non-magnetic (magnetic susceptibility ~180×10^{-6}) enable MRI-compatibility.)
  - Value: Longevity (20+ years) in prosthetics, low-density allows for compact lightweight implants without sacrificing strength.

- **Fatigue and Fracture Toughness:**

  (Fatigue strength ~50% of UTS, Fracture Toughness (K_IC) 40-80 MPa ·m ½
  - Value: Extends service life in cycling loads (aircraft landing gear) 2-3x over aluminum.

Material Properties Comparison

Property	Titanium (Ti-6Al–V)	Steel (Mild / Carbon Steel)	Aluminum (6061-T6)
Density (g/cm³)	4,43–4.51	7,85–800	2.70–2.71
Ultimate Tensile Strength (MPa)	900–1,200	400–700 (mild)–up Go for alleys	310
Yield Strength (MPa)	830–1,100	230–413	276
Specific Strength (KN m/kg)	200–250	50–100	70–150
Modulus of Elasticity (GPa)	110–116	200–210	69
Melting Point (°C)	1.600–1.668	1.370–1,530	582–652
Corrosion Resistance	Excellent	Moderate	Good
Thermal Conductivity (W/m-K)	6,7–21	40–50	167–237
Electrical Conductivity (% IACS)	~1–3	10–15	40–43
Fatigue Strength (MPa)	~500–600	200–400	96–110
Cost (USD/kg)	15–30	0.5–2	2–4



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Why Titanium is not a Bulk Industrial Metal:

- **Extraction Challenges:**

  Titanium ore is abundant, but conversion to metal requires high temperatures and vacuum conditions to prevent contamination.

- **Reactivity and Processing Difficulties:**

  Titanium reacts readily with oxygen – problematic during smelting and welding.

- **Supply Chain and Market Dynamics:**
  Production concentration in a few countries with geopolitical risk. Cyclical demand

- **Economic Scale:**

  Titanium facilities are small vs Bulk metals w massive plants/vertical integration.

1.2 Titanium Value Chain

The Titanium value chain is a complex, multi-stage process that transforms raw ores into high-performance products. Production is energy intensive with high barriers to entry. Processing is concentrated in a few key countries, namely China, Japan, & Russia. Global annual production of Titanium sponge is approx. 200,000-260,000 metric tons.

Mining:

The initial stage involves extracting Titanium-bearing ores, Ilmenite and Rutile from mineral sands or hard-rock deposits. Global ore production is ~8-10 million tons annually, however only ~5% is used for metal production. ~95% of production is used for pigments (TiO_2).

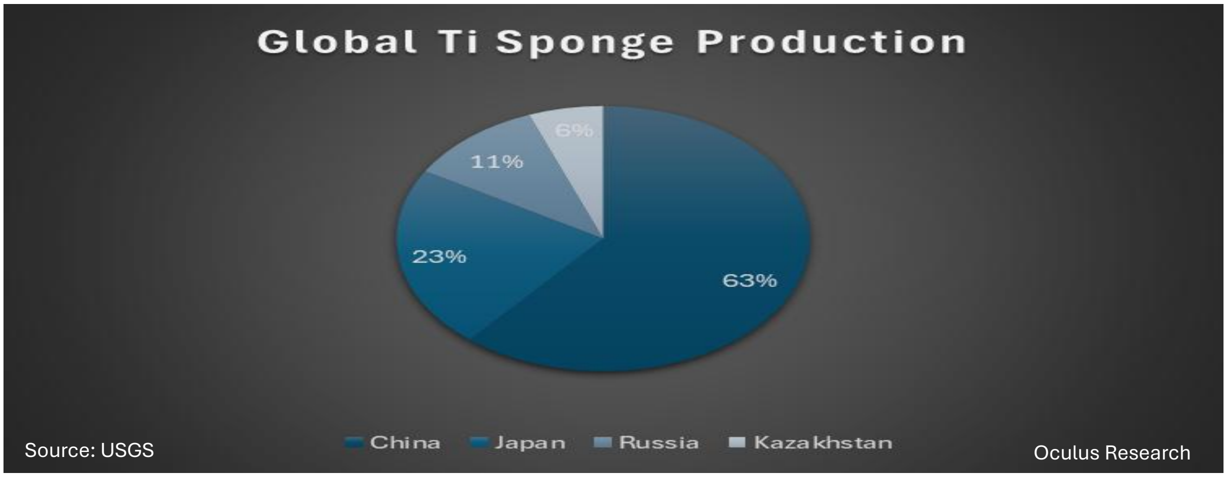
Value Creation: Moderate

Although a few producers maintain high margins, Ores are commodities ~ Rutile ($1000-1,500/ton), Ilmenite ($200-500/ton). This segment is most susceptible to market price fluctuations and over-supply from low-cost producers (China). Rutile ore miners maintain more pricing power and higher margins. Value accrues predominantly through vertical integration and processing segments.

Bottlenecks: Geopolitical risks - Supply concentration in Australia/China (~50% combined). Limited new discoveries, permitting delays (5-10 years), and cost increases due to environmental regulations.

Processing (Sponge):

Ores are refined to Titanium tetrachloride (TiCI baby 4 fix) via chlorination then reduced (primarily via the Kroll process) to transform ores into porous Titanium sponge. China dominates (60-65%) of global production, followed by Japan (20-25%), and Russia (10-12%). Global capacity is ~300,000 tons a year with production at 200,000-260,000 tons.



Source: USGS

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Value Creation: Moderate-High

Sponge is a tradable intermediate (~$5-12/kg) with 10-20% margin requiring expertise and scale. Aerospace-grade sponge commands premiums (10-20% higher). Potential technological improvements could reduce costs (up to 50%) and increase margins.

Bottlenecks: Severe capacity constraints. Aerospace-qualified sponge is limited. Kroll process is largely inefficient (50% yield). Geopolitical risks - high dependency on imports.

Alloying:

Sponge is melted (often with alloys) in a vacuum arc remelting (VAR) or electron beam furnaces to produce ingots. Predominate alloy is Ti-6Al-4V (80% of use). Global ingot production is 150,000-200,000 tons/years. Russia leads production (30%).

Value Creation: Moderate

Alloying tailors' properties for specific use cases. Recycling scrap accounts for 50% of inputs, reducing costs by 20-30% in circular economies. Ingots trade for ~$20-50/kg.

Bottlenecks: Geopolitical risk**~** Dependency on alloying elements (V) from Russia & China. High barriers to entry~ melting requires specialized equipment.

Manufacturing:

Ingots are converted into mill products (bars, sheets, tubes) via forging/rolling. Mill products are then finished through machining, casting, or additive manufacturing (AM). Global mill production ~ 100,000-150,000 tons/year with high waste (buy-to-fly ratio 5-1-:1)

Value Creation: Moderate

Value creation is differentiated by use case. Manufacturing involves precision engineering. Finished parts ~ $50-200/kg+. AM reduces waste (buy-to-fly ~1.5:1) adding 20-50% value via efficiency. Specialized firms (US/EU) earn 40-50% margin on aerospace/medical parts.

Bottlenecks: Upstream supply disruptions (6–12-month lead times). Mostly costly stage (50-70%) due to high tool wear and scrap rates (70-90% material loss).

End-Use Integration:

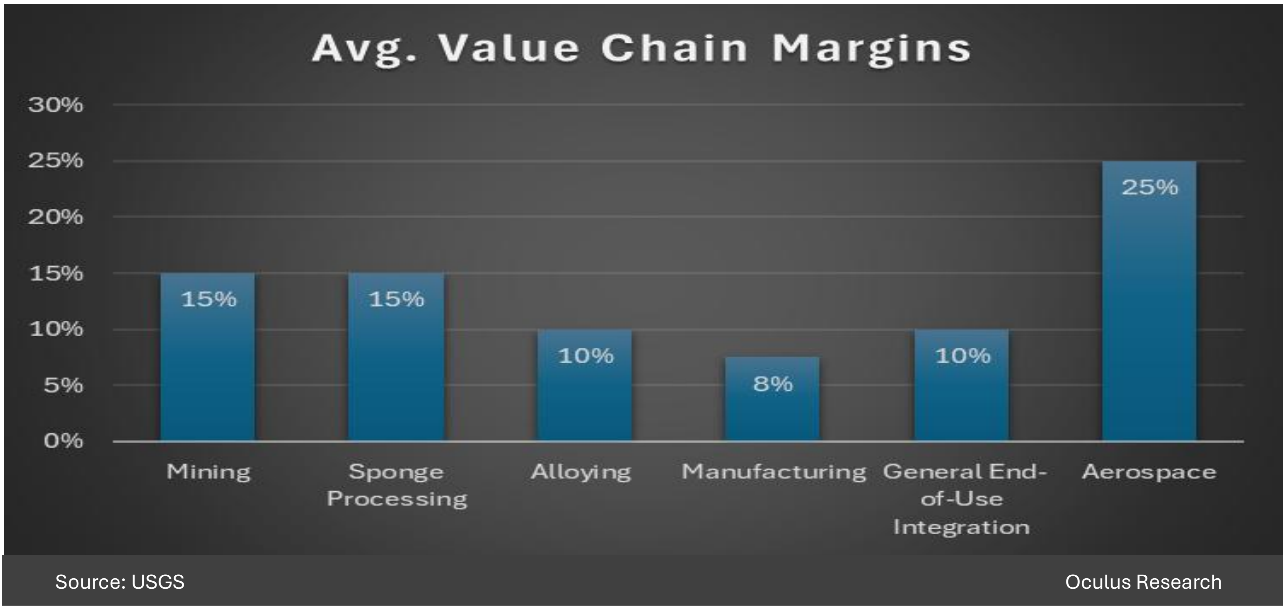
Finished parts are integrated into products like aircraft engines, medical implants, chemical equipment, and more recently, robotics.

Value Creation: High

Maximum value in performance benefits. End-users capture value through innovation and long-term contracts (e.g. fuel savings via weight savings in aerospace), and IP.

Bottlenecks: Qualification/certification delays (2-5 years for aerospace) and demand volatility (post covid recovery supply strain), Export restrictions (5x increase last 15 years).

Value Chain Margins:



Source: USGS

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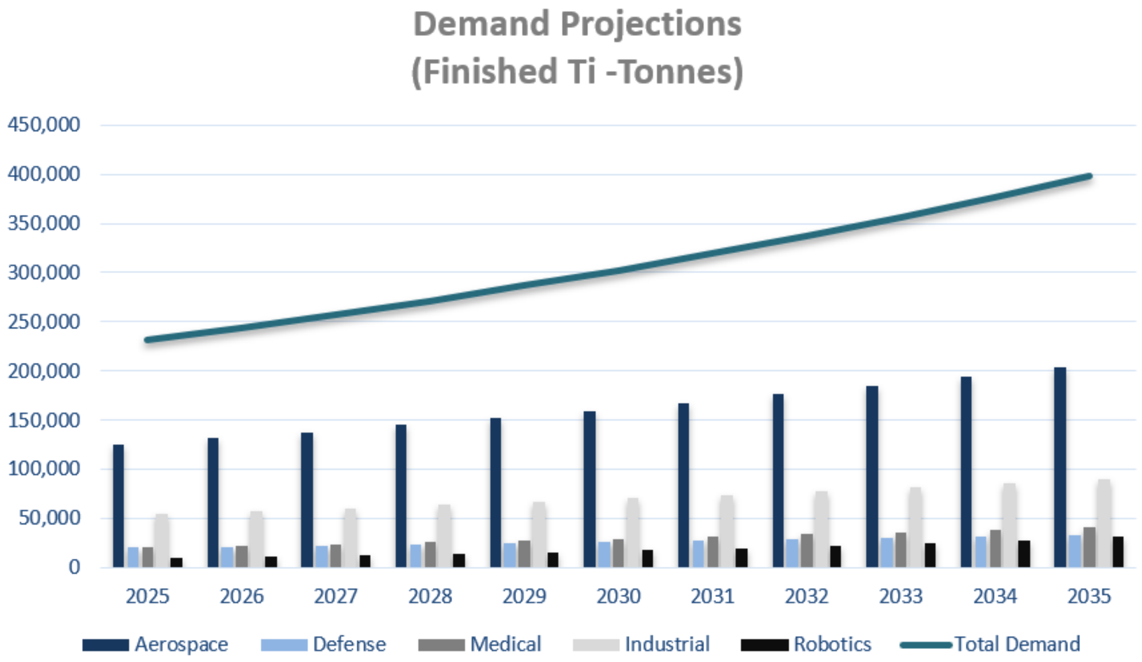
Margins vary considerably across regions, purity/grade and are sensitive to market price fluctuations. Post covid, margins have recovered significantly. High-purity titanium (aerospace, defense, biomedical grade) is on the top end of the margin spectrum across the chain.

2. Demand Structure

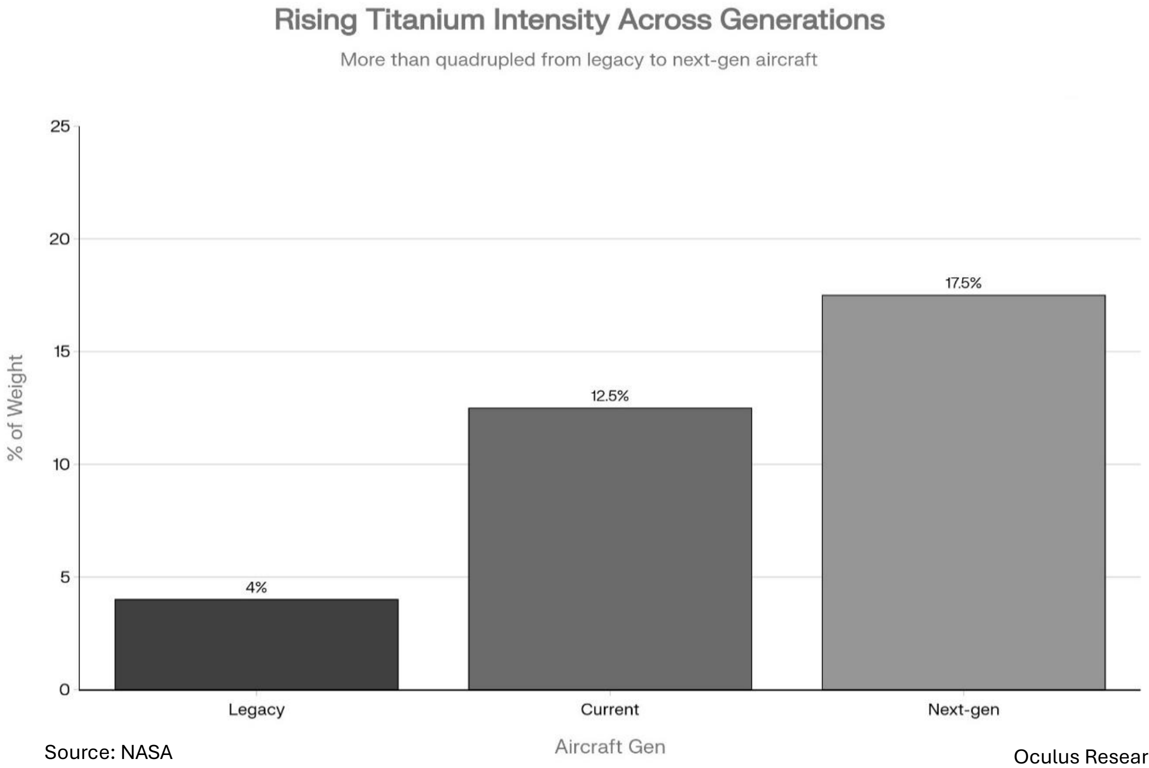
Titanium demand spans diverse sectors with aerospace dominating due to performance requirements, while emerging uses in robotics gain traction. The demand segments and their structural growth are outlined below.



Source: Mordor Intelligence Oculus Research

2.1 Aerospace & Aviation

Titanium intensity is rising due to its superior strength-to-weight ratio, enabling lighter structures that cut fuel consumption amid rising costs. Engine components use more titanium alloys for heat resistance up to 600°C in fans and compressors, while airframes favor commercially pure titanium for corrosion resistance with composites. New generations have higher usage versus older models driven by efficient engines like LEAP with titanium-aluminum parts.



Rising Titanium Intensity Across Generations

More than quadrupled from legacy to next-gen aircraft

Source: NASA

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Commercial Aviation

Demand drivers: Fuel efficiency mandates favor titanium's strength-to-weight ratio.

Growth dynamics: Next Generation Aircraft Ti increasing percentage of structural weight.

Price sensitivity: Low; fuel savings justify premiums.

Substitution risk: Minimal; composites complement but don't replace.

Regulatory exposure: FAA/EASA certification locks specs.

Strategic importance: High for OEMs like Airbus/Boeing (Ti ~43,000 tons globally)

Space Systems

Titanium's role in space systems include spacecraft, satellites, rockets, and launch vehicles. The increasing focus on space exploration, subsequent development of new spacecraft, and satellite constellations is expected to grow.

Demand drivers: Industry expansion. Performance properties

Growth dynamics: Projected 5.3-7.8% CAGR (satellite constellations & spacecraft)

Price sensitivity: Low – reliability prioritization

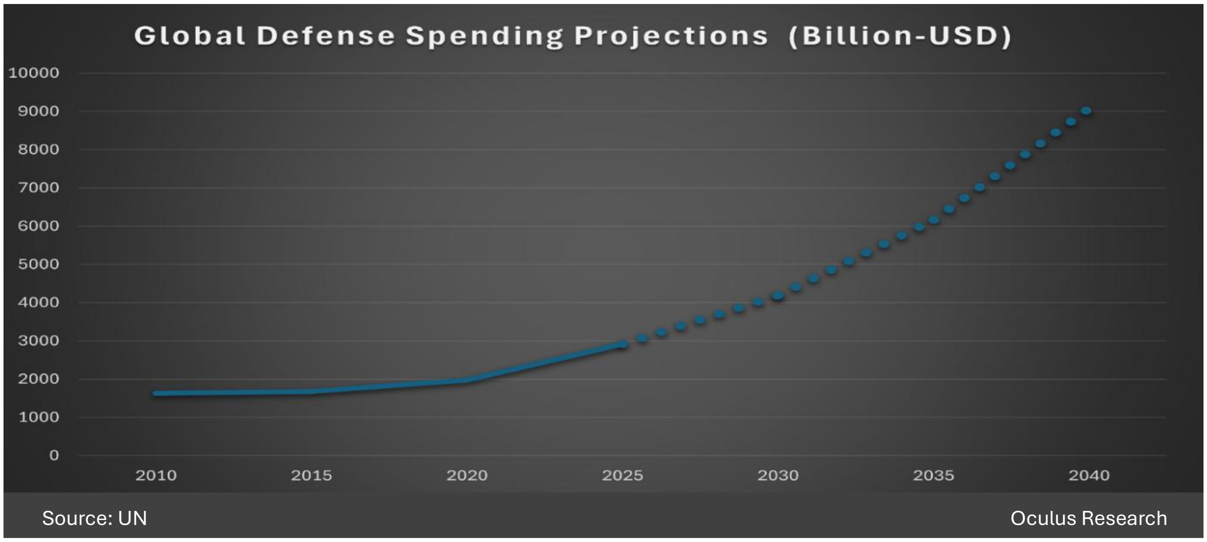
Substitution risk: Aluminum alloys for satellite structures. Stainless steel in rockets. Substitutes lack resistance in propulsion/re-entry.

Regulatory exposure: NASA/ESA certifications for space-grade quality and safety.

Strategic importance: National security (satellites). Global implications (US-China)

2.2 Defense & Military Systems

Titanium holds strategic importance for jets, submarines, and missiles due to its irreplaceable high-temperature strength and lightweight properties. Titanium's unrivaled strength and resistance to ballistic impacts make it an indispensable material in the construction of military aircraft and armored vehicles. The demand for Titanium in military and defense applications is largely inelastic, where performance, reliability, and durability are mission critical. Emerging markets and developed countries like US, China, India, and Russia are ramping up their defense spending.



Source: UN

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Defense Aviation

Demand drivers: High-temp engine parts, stealth airframes, drones, F-35 modernization

Growth dynamics: CAGR 5-7% - defense procurement & hypersonic programs

Price sensitivity: Negligible amid budget surges. Performance prioritization

Substitution risk: Aluminum alloys (airframes), carbon composites (stealth components)

Regulatory exposure: DoD/MIL-STD, ASTM/AMS military specs rigidify supply (quality).

Strategic importance: Critical (fighter jets, drones, hypersonic tech)- stockpiles mandated

Missile Systems

Demand drivers: Missile casings/structures (improving range – payload efficiency)

Growth dynamics: Hypersonic ramp up & missile modernization.

Price sensitivity: Negligible. Performance prioritization

Substitution risk: Steels/composites in casings, nickel alloys for some heat-resistant parts

Regulatory: DoD/MIL-STD, ASTM/AMS for missile-grade quality

Strategic: Deterrence. Critical for military superiority

Naval Systems

Demand drivers: Corrosion resistance in saltwater (exposed components)

Growth dynamics: Projected demand ~7-10 Tons (2035) from 4-6 tons (2025)

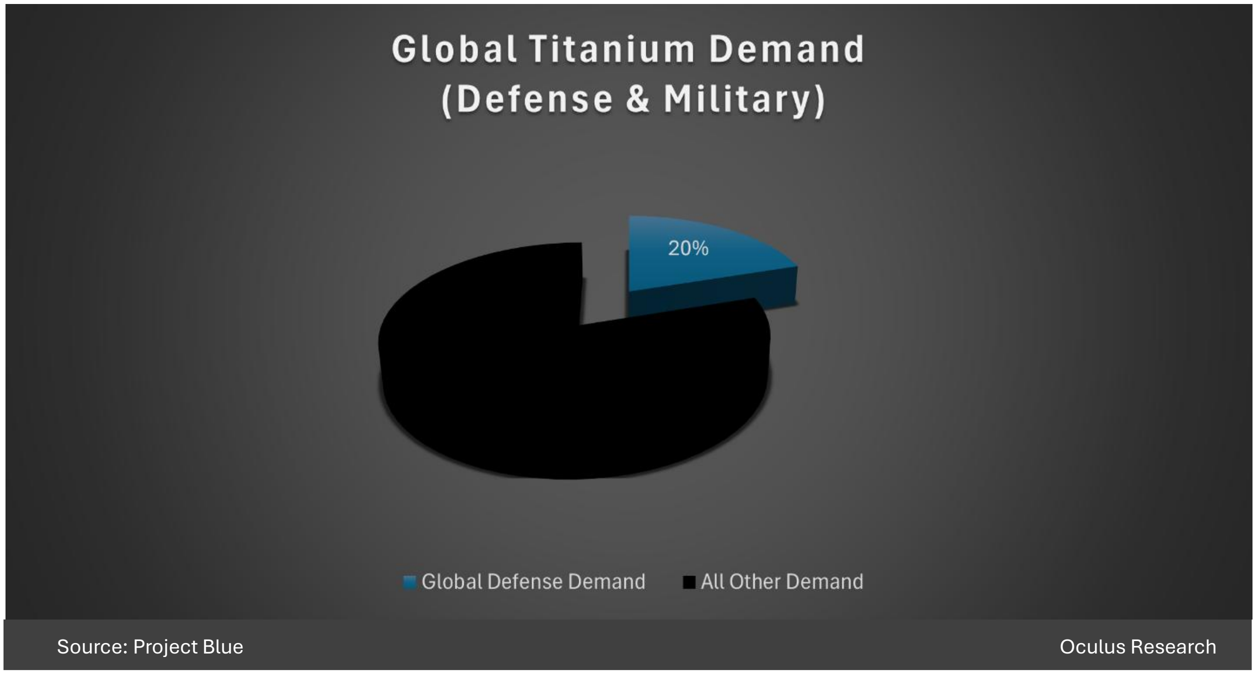
Price sensitivity: Low – durability prioritization

Substitution risk: Steel coating (hulls), Copper-nickel (piping)- cheaper/heavier

Regulatory: MIL-STD, ASTM/AMS for naval-grade quality/certification

Strategic: National security – essential for submarines, vessels (naval superiority)

Global Titanium Defense Demand (Percentage of Titanium Metal Demand)



Source: Project Blue

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2.3 Medical & Biomedical

The use of Titanium in medical applications is driven by aging populations and an increase in technological advancements in AI integration and 3D printing. The medical alloys segment of the market has a 9.4% CAGR. Titanium offers superior biocompatibility for implant devices ranging from hip and knee replacements, spinal fusion hardware, dental implants, and bone plates. The market demand is largely inelastic except for substitutions in temporary implants and higher price sensitivity in consumer-facing segments like personal prosthetics, where cost affects accessibility.

Implants:

Demand drivers: Superior biocompatibility, aging population growth, 3D printing adv.

Growth dynamics: Increasing adoption in emerging markets

Price sensitivity: Low-medium. Initial costs are offset by reduced revision surgeries

Substitution risk: Few alt. like cobalt-chromium/ceramics exist but lack strength & biocompatibility Alt. for temporary implants – Titanium std. for permanent implants.

Regulatory exposure: stringent FDA, EU MDR, and ISO standards (clinical trials)

Strategic importance: Critical for global healthcare supply chains

Prosthetics:

Demand drivers: Growing amputee population (diabetes, trauma, & vascular diseases)

Growth dynamics: innovation-supported by broader medical alloy market CAGR ~9.4%

Price sensitivity: Medium- High sensitivity -consumer facing segments (cost-accessibility)

Substitution risk: Medium – carbon fiber/aluminum alternatives offer lighter weight but compromise on strength/biocompatibility.

Regulatory exposure: Significant- FDA Class 2/3 classifications (testing)

Strategic importance: Vital for rehabilitation- post-conflict or disaster recovery

Surgical devices:

Demand drivers: non-reactivity, sterilizability, MRI compatibility, Non-magnetic, and corrosion resistant properties drive use in surgical procedures.

Growth dynamics: boosted by role in advanced tools technological innovations.

Price sensitivity: Low-moderate - Costs offset by longevity/reduced maintenance costs

Substitution risk: Low - Stainless steel alt. exists (inferior in corrosion resistance/weight)

Regulatory exposure: FDA 510(k) clearances/ISO 13485 (manufacturing quality)

Strategic importance: Supports surgical capacity – key in pandemic response.

2.4 Industrial & Chemical Applications

Titanium's corrosive-resistant makes it a superior option for a wide range of industrial and chemical applications. In chemical processing exceptional corrosion resistance is essential to aggressive chemicals and elevated temperatures. It is crucial in the long-term reliability of water treatment plants. This is segment that is growing steadily due shortfalls in water availability fueling expansion capacity build outs in middle east, Asia-pacific, and north America. Emerging markets in Africa and Sout America are accelerating adoption. The most elastic segment of industrial and chemical applications is the oil and gas sector in which investment is price sensitive due to volatility in the price of oil and gas.

Chemical processing:

Demand drivers: Superior corrosion resistance in harsh environments (chlor-alkali production, geothermal plants, & petrochemical processing). Emerging economies growth

Growth dynamics: Demand in chemical processing projected CAGR 6-7%. Innovations increasing adoption- Expansion of applications (nuclear waste storage/reactor shields).

Price sensitivity: moderate – processor sensitivity exists but longevity/reliability prioritized

Substitution risk: medium – Alt (stainless steel/nickel alloy) exist but offer inferior corrosion resistance leading to higher lifecycle costs

Regulatory exposure: High – environmental regulations (ISO/EPA traceability & safety)

Strategic importance: Critical for operational efficiency/safety in chemical industries.

Desalination:

Demand drivers: Water scarcity exacerbation by population growth & climate change

Growth dynamics: boost in infrastructure investments – steady growth in brackish water/seawater applications.

Price sensitivity: Moderate – influenced by public-private partnerships- longevity/long-term operational savings from reduced maintenance justify premium pricing.

Substitution risk: Low- alt. underperform in high-salinity environments (increasing failures)

Regulatory exposure: High – UN Water/ EPA equivalents (brine discharge/energy use)

Strategic importance: Vital – addressing global water crises – ensuring supply in water-stressed areas supporting agriculture, industry, and urban development.

Offshore infrastructure:

Demand drivers: Expansion in offshore oil/gas exploration- particularly in deepwater fields

Growth dynamics: driven by offshore investments.

Price sensitivity: High-cost pressures from oil price volatility

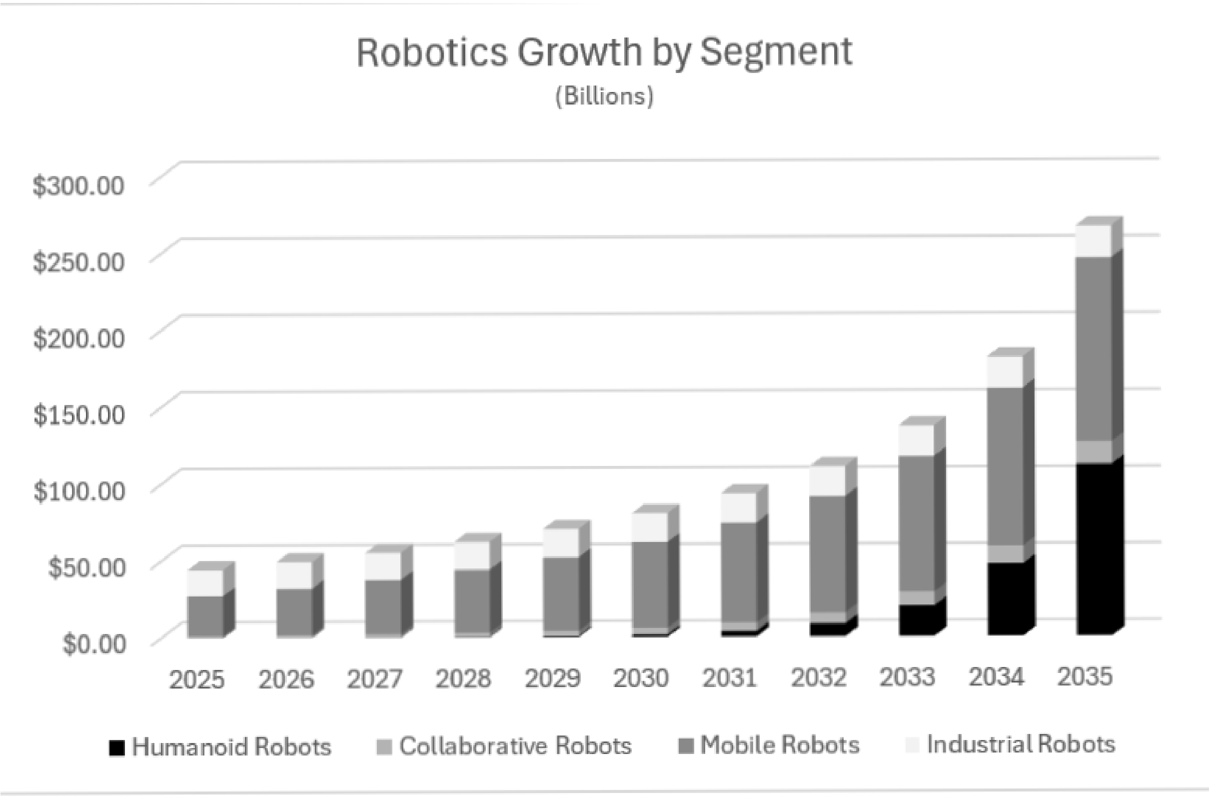
Substitution risk: Medium – carbon steel coatings/superalloy alt – but titanium excels in corrosive offshore settings.

Regulatory exposure: High- API/OSHA safety standards, Environmental regulations. Exposure to shifting energy policy, tariffs, and geopolitical risks affecting supply chains.

Strategic importance: Essential to energy security

2.5 Robotics, AI & Autonomous Systems

Titanium demand in robotics is structurally small today but highly leveraged to long-run unit growth, with usage concentrated in high-stress, safety-critical, and mobility-constrained components across humanoids, drones, autonomous vehicles, and industrial robots. The introduction of robotics, particularly humanoids, will create a cycle that is material different from prior cycles because it pushes mechanical systems into continuous human-like use cycles with strict energy, fatigue resistance, and durability first-order designs. While use of Titanium in autonomous vehicles and industrial applications remains modest, use in humanoids and cobots is significant with significant substitution limitations. Growth of the humanoid & cobot subsegment will be a key driver of future demand. Projected CAGR of robotics is ~ 14-18% with humanoid robotics projected CAGR of ~ 53-76% (Bank of America).



Source: ABI Research

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What makes robots, humanoids & Cobots different:

High-cycle operation: Robots (industrial/service) must be designed for millions of repeat cycles. They will endure fatigue and stress that is far more demanding than typical consumer hardware.

Strict energy & power constraints: Robots live on batteries – every kilogram removed from the design structure result in smaller batteries, lower actuator torque, and longer run-time.

Human-scale kinematics & safety: Humanoids and cobots require a combination of speed and safety – forces high stiffness-to-weight ratios and predictable failure modes.

Unit-level material intensity:

Humanoid Robots:

Structural Titanium: approx. ~2kg TI per advanced humanoid (optimized/high stress joints, spine, key linkages, fasteners)

Drones (UAVs):

Small commercial drones: Ti limited to grams in fasteners/special mounts.

Large military & long-endurance UAVs: single-digit Kg per airframe in critical fittings, landing structures, and high-load nodes.

Autonomous vehicles:

Mainstream Avs: Ti limited to grams-to-hundreds-of-grams range for specialty brackets, fasteners, or protective housing.

Specialized autonomous vehicles/platforms: Several kg of Ti in protective or high-load components (defense, mining, harsh environments).

Industrial & medical robots:

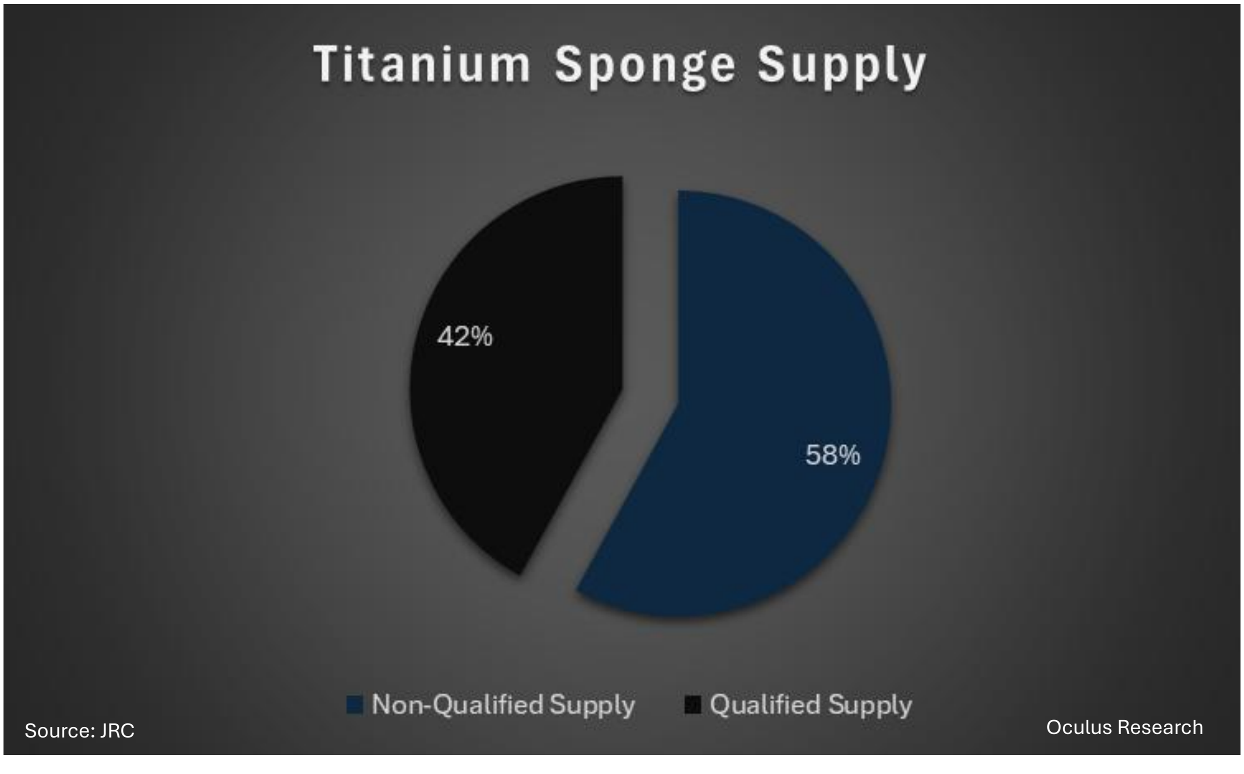
Standard industrial arms: Ti confined to high-precision or corrosion-sensitive parts.

Surgical & high-end robots: Single digit Kgs in joints, arms, and end-effectors to combine biocompatibility, fatigue resistance, and sterilization/corrosion performance.

3. Supply Structure

3.1 Global Production Overview

Current annual Global production of Titanium ore is approx. 9-10 million metric Tons. The ore is primarily extracted from mineral deposits containing oxide minerals (ilmenite and rutile. Ilmenite, the most abundant and widely disturbed ore, accounts for approx. 92-95% of global mineral production. Deposits often occur in coastal areas or near-shore sands. High grade feed stock is crucial in reducing necessary processing steps, lowering energy consumption, and improving economics of raw ore refinement into sponge. The key distinction in Titanium production is the fact that ultimate supply control does not sit primarily at the mining segment the way it does in copper or iron ore. The choke point is in conversion and qualification (sponge, alloys, certification) not raw feedstock. The supply constraint is accentuated in high-quality sponge required for aerospace, defense, and biomedical applications.



Source: JRC

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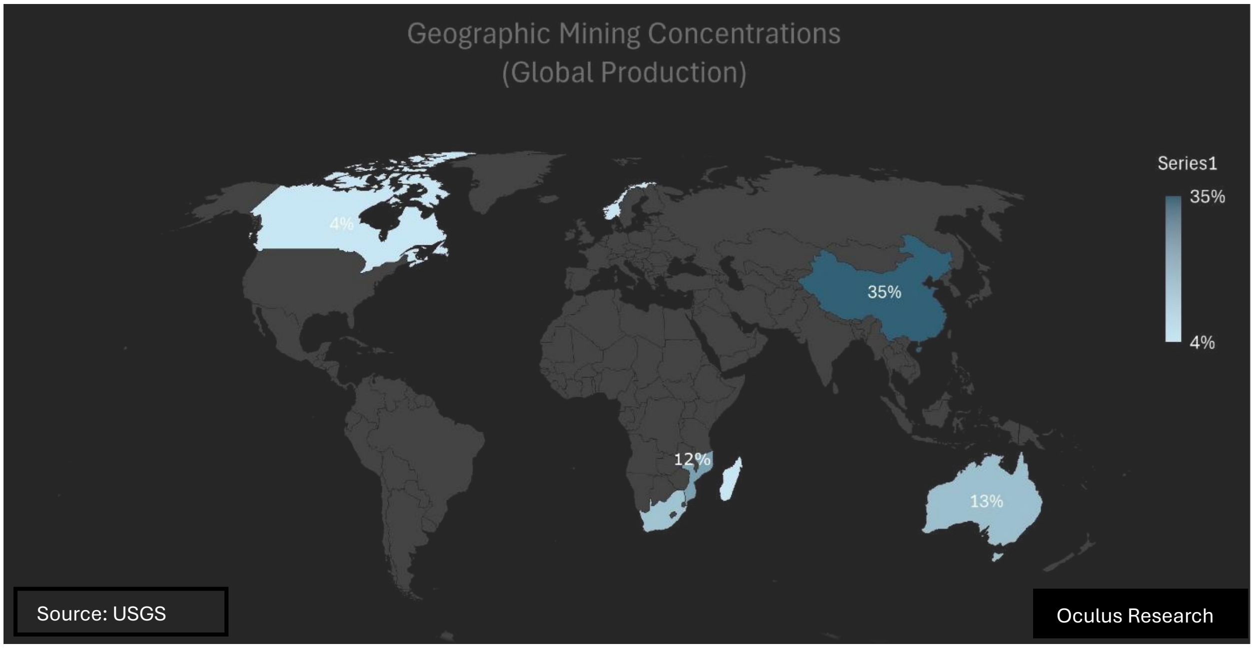
Feedstock Production (Mining):

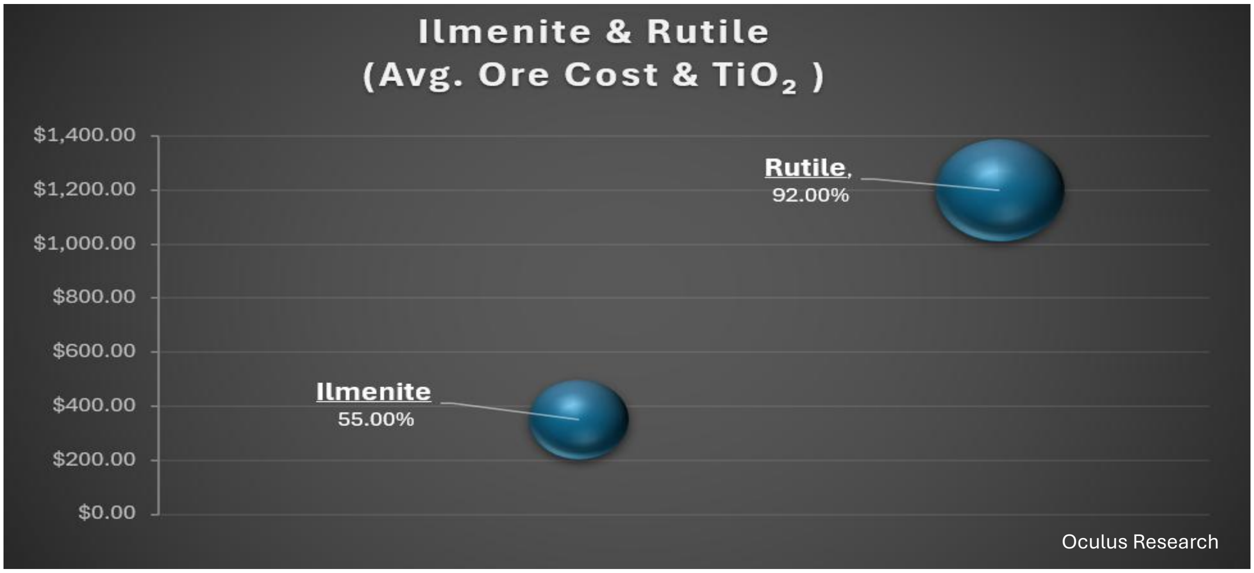
Titanium mining is concentrated in a few countries with top producers accounting 80% of production. China accounts for a third of global mining production, followed by Mozambique (18-20%), South Africa (12%), Australia (12%), Madagascar (4%), Norway (4%), and Canada (4%).



Source: USGS

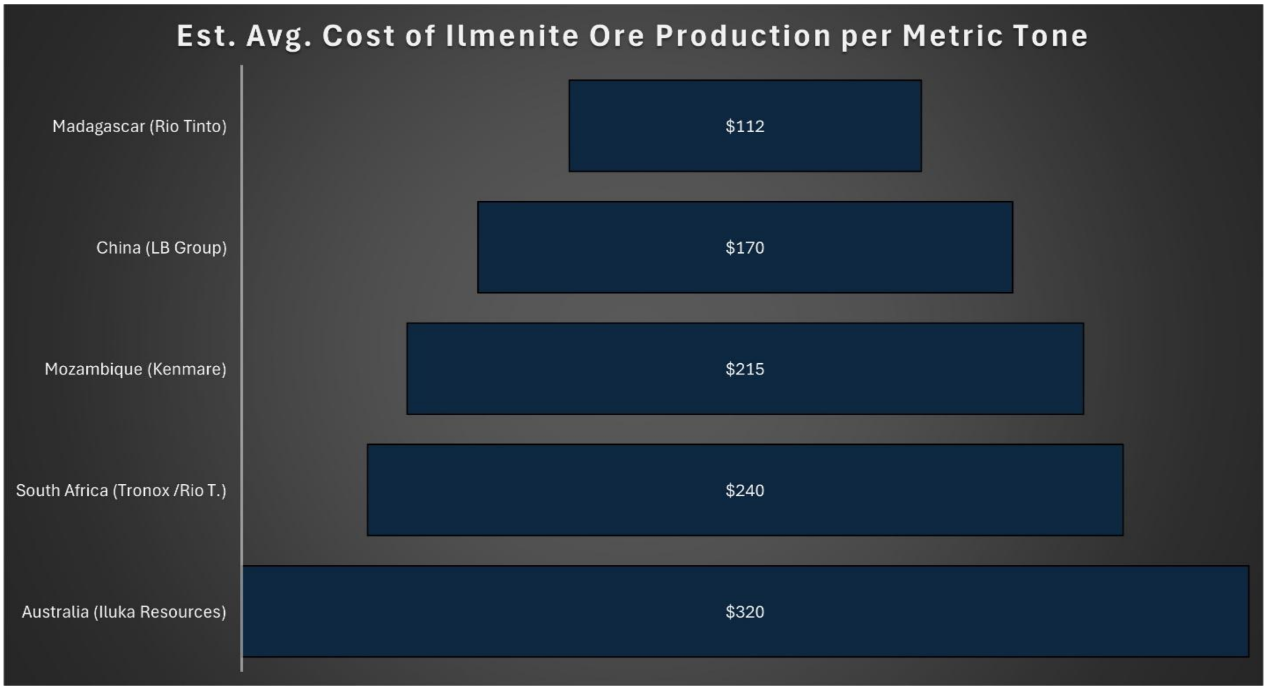
Feed stock Cost Structure & Quality Differences:

Quality differences are measured by TiO_2 content and impurities (e.g. iron) that directly impact mining and downstream costs. Rutile, which only accounts for approx. ~5-10% of global feedstock production, is a high-grade ore. It's purity (92-95%) reduces extraction complexity and processing requirements – reducing overall costs by ~20-30% compared to lower purity (44-70% TiO_2) Ilmenite. Low grade ores increase waste ratios and chemical usage – elevating costs and complicating environmental regulatory constraints. High-quality Rutile Ores have higher mining costs and trade for a considerable premium to Ilmenite ores.



Cost positioning:

Titanium mining companies exhibit varied cost positions based on asset quality, integration and scale. Chinese firms, with less regulatory and environmental constraints dominate due to subsidies and scale. Low-cost leaders in Mozambique and Africa/Madagascar benefit from high-volume placer deposits and vertical integration. Mid-tier producers in Australia and South Africa benefit form diversified reserves but face higher regulatory costs.

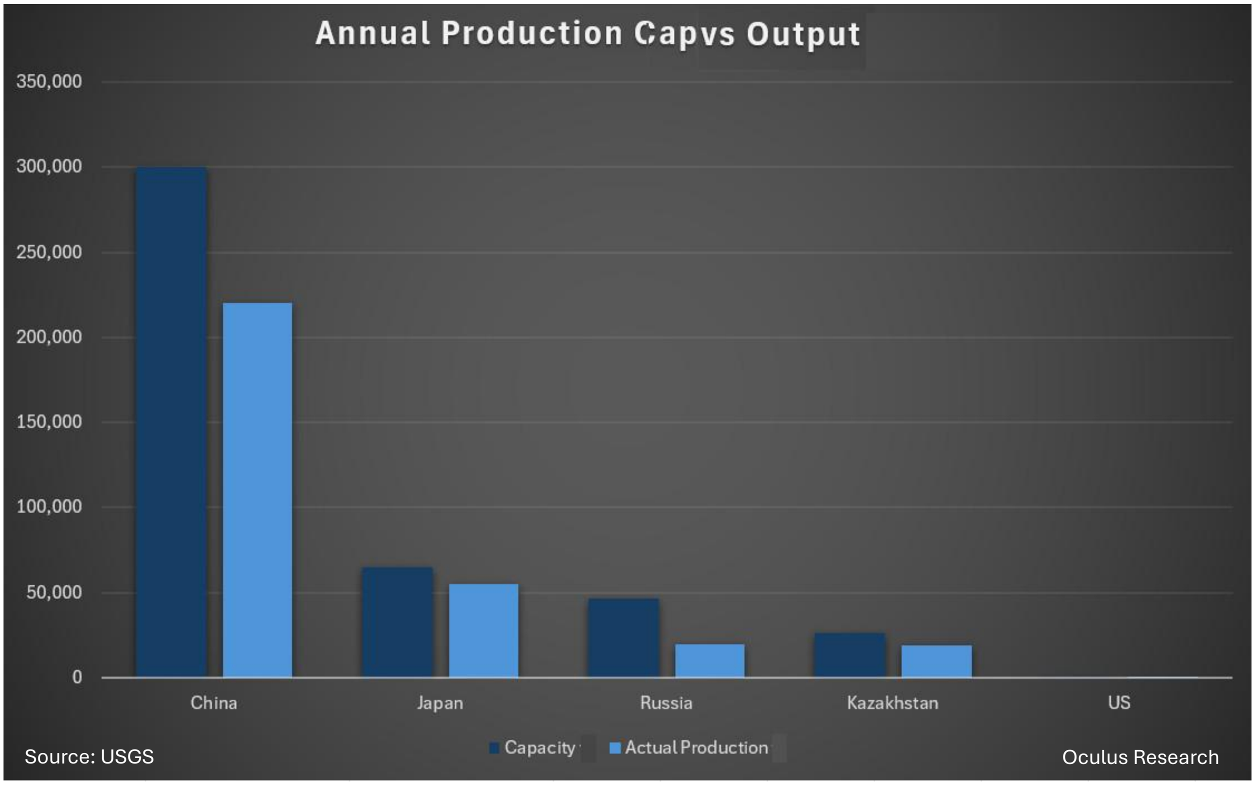


Feedstock quality, logistics, and production costs vary materially by region and producer.

3.2 Conversions & Processing Constraints:

Titanium processing involves transforming ore into sponge (primarily via the Kroll process), followed by refining of the sponge into ingots and alloys. China dominates sponge output by volume, while key countries dominate high-grade refined production that meets stringent aerospace qualifications. This stage of the supply chain is narrow: highly reliant on process know-how, qualifications, imports and subject to geopolitical tensions.

Sponge Production vs Capacity:



Source: USGS

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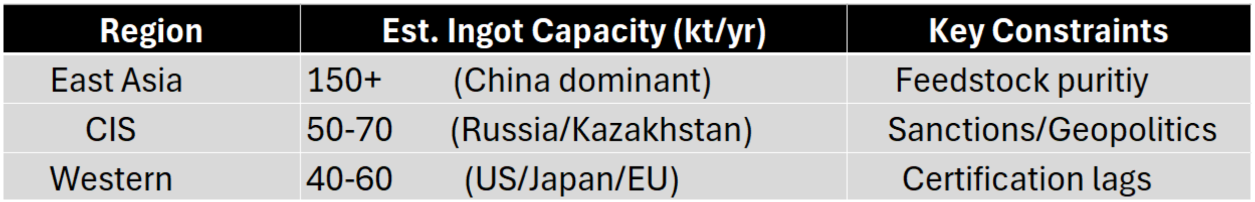
Titanium sponge is concentrated among a handful of producers. Chinese producers collectively represent a large yet quality-differentiated share of output. Only a subset of producers, however, currently supply certified aerospace and defense Titanium sponge. This creates supply asymmetry where Russia and Japan retain disproportionate influence.

Refining:

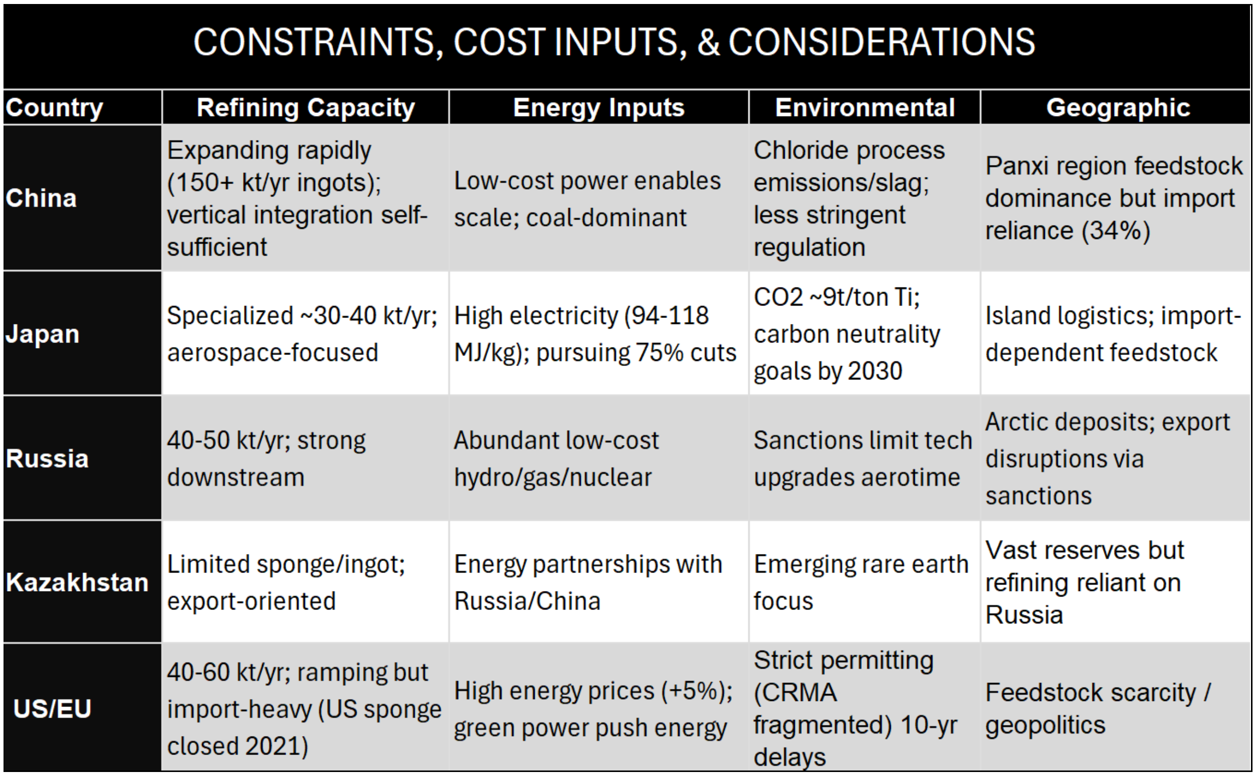
China leads refining and sponge capacity (by volume) through vertical integration. Japan and US maintain specialized aerospace-grade facilities. Western capacity relies on imports, with Europe facing shortages due to Ukraine/Russia supply chain disruptions.



Region	Est. Ingot Capacity (kt/yr)	Key Constraints
East Asia	150+ (China dominant)	Feedstock puritiy
CIS	50-70 (Russia/Kazakhstan)	Sanctions/Geopolitics
Western	40-60 (US/Japan/EU)	Certification lags

Key Refining Constraints:

The aerospace and defense certified Titanium ingot production are considerable chokepoints in the supply chain. Sponge overcapacity can exist (Japan) while high-grade Titanium ingots remain scarce. Qualified Titanium ingot production demands certified, impurity-free facilities. Geopolitical risks surrounding key producers (Russia) create additional bottlenecks in the supply chain.



CONSTRAINTS, COST INPUTS, & CONSIDERATIONS

Country	Refining Capacity	Energy Inputs	Environmental	Geographic
China	Expanding rapidly (150+ kt/yr ingots); vertical integration self-sufficient	Low-cost power enables scale; coal-dominant	Chloride process emissions/slag; less stringent regulation	Panxi region feedstock dominance but import reliance (34%)
Japan	Specialized ~30-40 kt/yr; aerospace-focused	High electricity (94-118 MJ/kg); pursuing 75% cuts	CO2 ~9t/ton Ti; carbon neutrality goals by 2030	Island logistics; import-dependent feedstock
Russia	40-50 kt/yr; strong downstream	Abundant low-cost hydro/gas/nuclear	Sanctions limit tech upgrades aerotime	Arctic deposits; export disruptions via sanctions
Kazakhstan	Limited sponge/ingot; export-oriented	Energy partnerships with Russia/China	Emerging rare earth focus	Vast reserves but refining reliant on Russia
US/EU	40-60 kt/yr; ramping but import-heavy (US sponge closed 2021)	High energy prices (+5%); green power push energy	Strict permitting (CRMA fragmented) 10-yr delays	Feedstock scarcity / geopolitics

3.3 Importance of Vertical Integration

- Supply chain security and stability: guaranteed availability of feed stock and reduced reliance on third-party suppliers.
- Cost Reduction/Efficiency: Vertical integration reduces expenses related to raw materials and intermediate products. Integrated firms benefit from energy usage optimization.
- Enhanced Quality Control: allows for control, ensuring consistency and quality.
- Geopolitical Resilience: Vertical integration is key in securing domestic defense and industrial bases.
- Faster Product Development: Firms bypass bottlenecks and accelerate timeline

4.4 Cost Structure and Marginal Supply:

Titanium production features high fixed and variable costs, primarily in raw materials (Ti ore, chlorine, magnesium), energy, and labor.

Cost breakdown:

Cost Table

Component	Typical Share/Cost	Main Factors
Raw Materials	(40-50%) $4,500–$5,500/t	Ore, chlorine, magnesium volatility
Energy/Fuel	(23-30%) $2,000–$2,500/t	Kroll process intensity
Electricity	(21%)	Melting/refining
Labor/Maintenance	(10-15%)	Skilled operations, compliance
Other (Utilities)	Balance	Waste, transport

4.5 Marginal Supply Dynamics:

Marginal costs are the highest for high-purity sponges required for aerospace-grade. Chinese dominance enables lower marginal output while Western Chloride-process reliance for aerospace demand pushes feedstock costs higher. Oversupply from China and Russia squeezes the highest costs producers.

Supply Chain Dynamics

Stage	Metric	Leading countries / producers	Approx. share / scale	Comments
Mining	Titanium mineral concentrates (ilmenite + rutile) – country-level production	China, Mozambique, South Africa, Australia, Norway, Canada, Madagascar	China 1/3 of global ilmenite output; Mozambique and South Africa among top additional producers	Ore supply is geographically diverse but increasingly centered on China and a small group of mineral sands exporters.
Mining	Primary titanium minerals – market share by country	China, Mozambique, South Africa as top 3; others include Australia, India, Kenya, Madagascar	China 34% of primary minerals; Mozambique 17.5%; South Africa a major additional share	Concentrated supply gives these countries leverage over feedstock for both pigment and metal.
Mining	Major ilmenite/rutile mining companies	Rio Tinto, Iluka Resources, Kenmare Resources, Trimex, and other mineral-sands	Top few firms control a large share of high-grade feedstock (rutile, upgraded ilmenite)	Corporate concentration is meaningful at the high-grade end even where country production is more fragmented.
Refining	Titanium sponge – country-level production capacity	China, Japan, Russia, Kazakhstan, Saudi Arabia, India, Ukraine	China 260–320 kt capacity (~63–70%+ of global); Japan 65 kt (15%) ; Russia 20–27 kt; Kazakhstan 14–16 kt.	Sponge capacity is far more geographically concentrated than ore, with a dominant Chinese position.
Refining	Titanium sponge – market share by producer region	China + CIS (Russia, Kazakhstan) + Japan	China ~66–70% of global sponge output; CIS adds significant share; Japan is the main high-grade non-Chinese supplier.	70–80% of world sponge from China and CIS; Japan supplies much of aerospace grade sponge to Western buyers.
Refining	Key sponge producers (corporate)	China's state and private producers; Toho Titanium and Osaka Titanium (Japan); UKTMP (Kazakhstan); Russian producers (partly sanctioned)	Western markets rely heavily on Japanese and Kazakh producers for qualified aerospace sponge.	Corporate and geopolitical risk is highest at the refining stage, not at the raw ore mining stage.

4. Structural Constraints

The Constraints in Titanium production are physical, economic, regulatory, and geopolitical. The key structural constraints are rooted in limits in capacity expansion and geopolitical dependencies. Constraints and shortages are particularly heightened in aero-space and defense grade applications.

4.1 Physical Constraints

- **Technical complexity** – The Kroll process requires sequential steps: high temperature chlorination, magnesium reduction, vacuum distillation, and melting. Each step requires precise control to avoid contamination and impurities.

- **Processing inefficiencies** - During batch operations the reactor must be opened multiple times to load raw materials and unload finished Ti sponge. When the reactor is opened, the sponge is exposed to the atmosphere and instantly reacts with oxygen, nitrogen, and moisture forming a brittle oxide/nitride layer. The contaminated layer cannot be used for high-grade applications and must be chemically treated or machined off. This results in inhomogeneity of batches and substantially lower yields of usable high-purity aerospace grade Titanium.

  - The process of prolonged heating (before) and cooling (after) each cycle cap output.

  - Ti's low thermal conductivity creates heat buildup in tools/machinery reducing life

- **Material science limits:**

-Aerospace and defense application require stringent qualifications.

-Purity must exceed 99.6% Ti with oxygen <0.015% and hardness <110 BHN for ductility

- Minor impurities lower fatigue resistance and reduce weldability

4.2 Economic Constraints

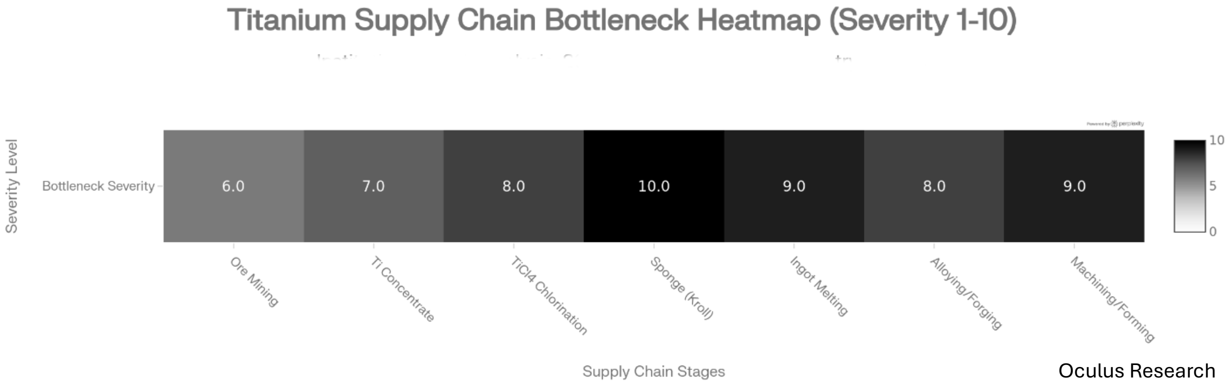
- Capex intensity: Sponge plants require significant investments in chlorinators, reactors, and vacuum furnaces. Specialized processing (CNC/vacuum forging) 10-15x that of steel.
- ROI timelines: Full scale processing facilities require 12-24 months set up after permitting.
- Capital availability: Risks from energy prices, ore supply disruptions limit capex-heavy expansions. Western firms lag compared to state-backed (China) capacity.

4.3 Regulatory & Environmental Constraints

- Permitting timelines: Strict global standards delay build outs. Key approvals span years due to engineering, procurement, and agency reviews.
- Environmental compliance costs: Kroll processing emits high levels of CO2. Regulatory (Paris Agreement, OSHA/REACH) compliance ads 10-15% costs. Carbon fines and sustainability mandates pressures producers.

4.4 Geopolitical Constraints

- Strategic material designation: Dual-Use/Critical (commercial aircraft/defense)
- Export controls: Strict licensing and export controls for high-grade (ITAR/EAR)
- National security prioritization: Prioritization diverts high-grade output to defense



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5. Substitution & Elasticity Analysis

Titanium's unique properties render it irreplaceable in high-performance applications. Partial substitution occurs in less demanding segments. The primary substitute for Titanium is Aluminum alloys, accounting for approx. 90-95% of interchangeable applications.

5.1 Where Titanium Is Irreplaceable

- Performance thresholds: High-grade Titanium is critical in Aerospace (jet engines, hypersonic vehicles) and defense (aircraft, submarines, armored vehicles, missiles).
- Safety-critical applications: Titanium's Biocompatibility renders it critical in implants. In aerospace Titanium is essential in critical applications were failure results in mortality.

5.2 Partial Substitution Scenarios

- **Aluminum:**

-Aerospace: low-temp structures (wings, fasters, landing gear, engine mounts) in non-critical applications

- Automotive: Body panels and chassis, engine components (low temp areas), and suspension/braking systems

- Consumer electronics: aluminum superior heat dissipation renders it ideal for use in phone/laptop frames, and heat sinks/cooling plates.

- Marine/Industrial: Aluminums moderate corrosion and chemical resistance are adequate for use in marine environments (fasteners, bracket) and low-pressure systems (pipe fittings and valves)

- Manufacturing: Aluminum is used extensively in prototyping (cheaper, faster to produce) before implementing titanium in the final product.

- **Additional notable Substitutes:**

- Stainless steel: High strength/corrosion resistance but much heavier
- Carbon Fiber Reinforced Polymer: use extensively in aerospace (reduces weight)
- Nickel-based alloys: Used in extreme high-temp applications
- Zirconium/Niobium alloys: Specific medical implants (dental/ orthopedic)

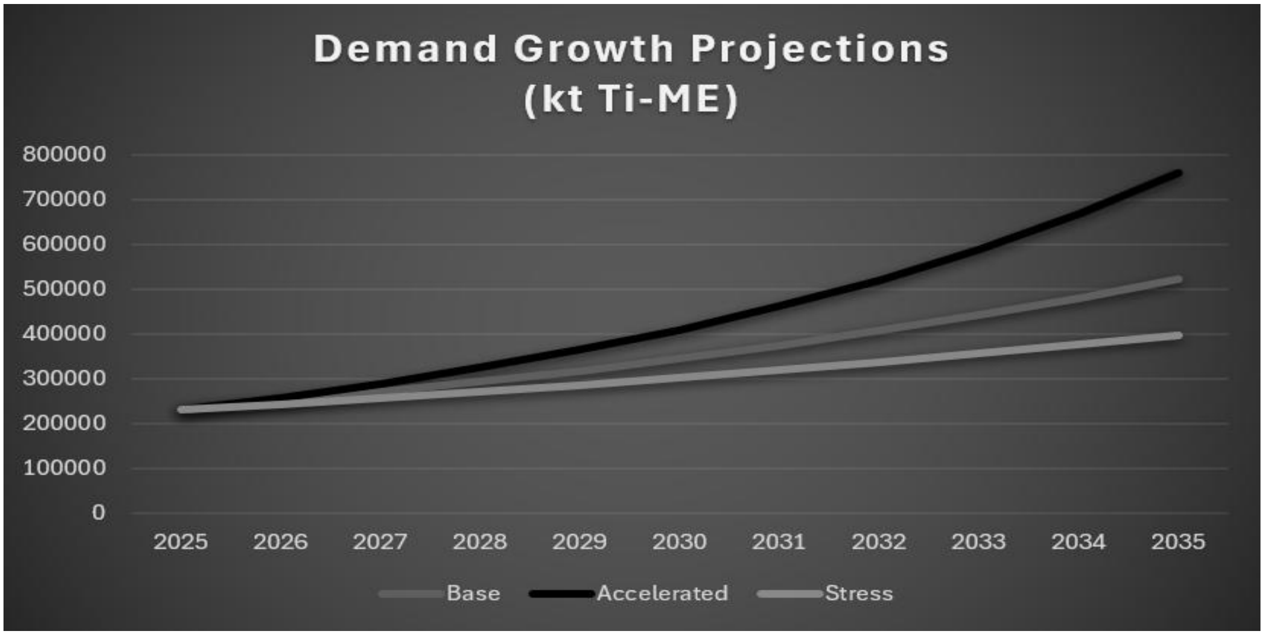
Material/Substitute	**Key Advantages Over Ti**	**Limitations vs. Ti**	**Viable Segments**
Aluminum	Lower cost, easier machining	Poor heat (>200°C), lower fatigue strength	Wings, non-structural skins
Composites (PEEK/CFRP)	60% lighter, high stiffness	Brittle impact, poor repairability	Panels, brackets (non-safety)
Advanced Steels	Cheaper, higher hardness	Heavier, corrosion-prone	Fasteners, low-corrosion gears

5.3 Elasticity Assessment

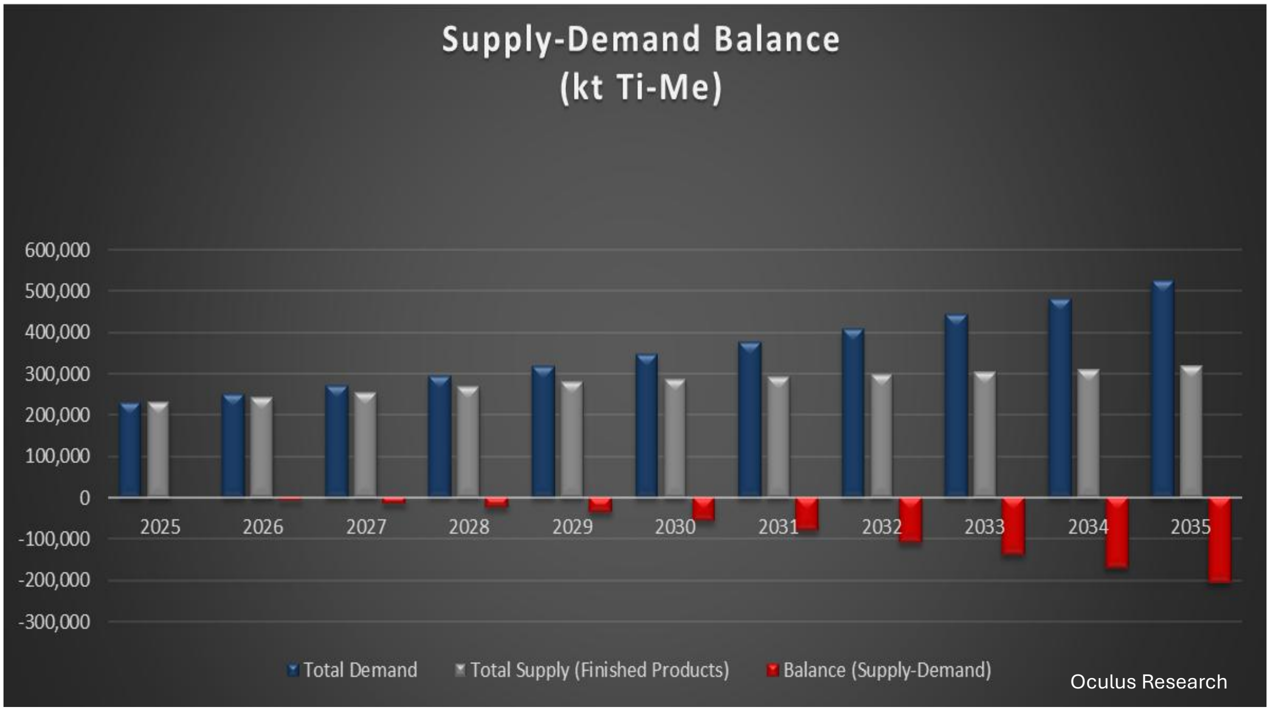
- Price-Sensitive segments: Highest elasticity exists in industrial, chemical processing, power generation, and automotive segments.

- Non-Price-Sensitive Segments: Aerospace, defense, and medical segments.

6. Supply–Demand Balance Models

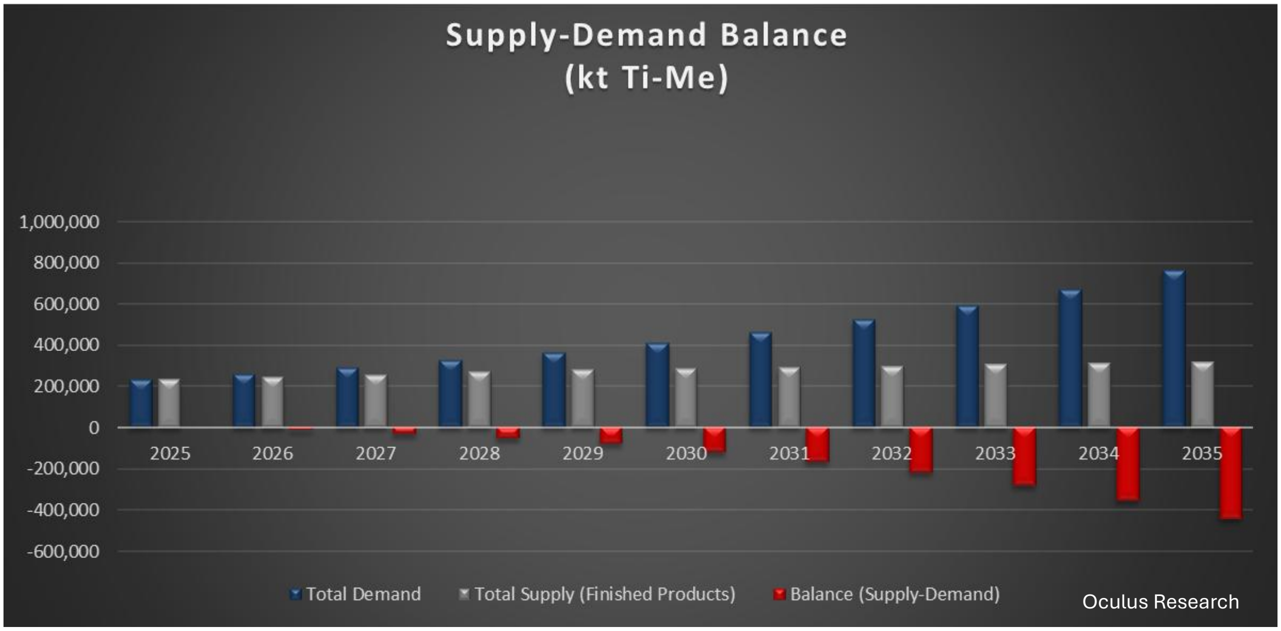


6.1 Base Case



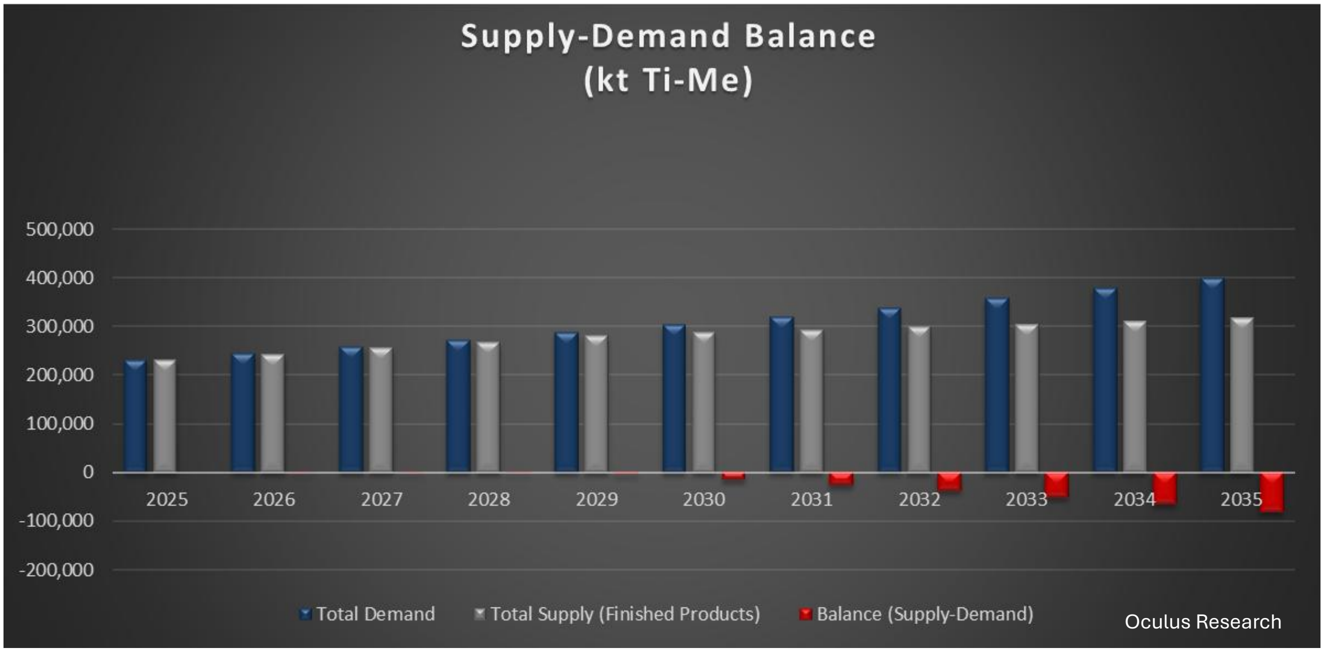
Robotics adoption progresses gradually, aerospace demand remains firm, and supply expands through utilization of capacity before tightening structurally post 2030.

6.2 Accelerated Scenario



Geopolitical tensions escalate resulting in substantial increases in defense spending. Humanoid robotics growth exceeds projections alongside sustained aerospace growth.

6.3 Stress Scenario



Stress Scenario Assumptions: Easing of geopolitical tensions softens defense spending. Advancements in viable substitution alternatives reduce demand in aerospace applications. A cyclical industrial slowdown and delayed robotics deployment reduces incremental demand growth, easing balance pressures despite long-term supply rigidity. Technological advancements in recycling subdue direct production demand.

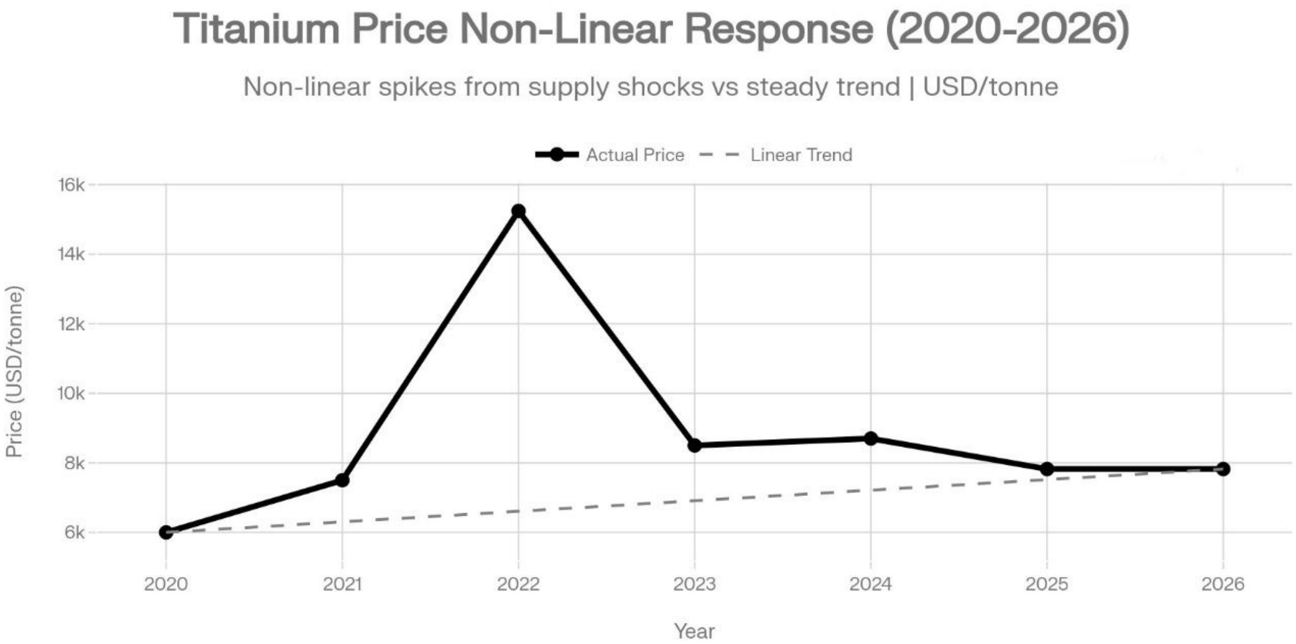
General Supply Assumptions:

Near-term titanium supply growth reflects utilization uplift as producers ramp toward nameplate capacity. Beyond 2030. Incremental supply is modeled at a lower structural rate given long lead times and capital intensity associated with new processing and production capacity.

7. Price Formation & Market Mechanics

- **Cost floors**
    - China's low costs, influenced by scale and subsidies set global floors on ore. Tariffs underpin the price floor but oversupply pressures them downward.
- **Scarcity premiums**
    - Quality demands ands geopolitical risk evelate prices above costs floors. High purity Rutile, which accounts for approx. 5% of global or production is scarce and demands a significant premium to ilmenite ore.
- **Strategic stockpiling**
    - China maintains large stockpiles. In 2026 U.S. launched "Project Vault" a critical materials reserve, that includes Titanium to buffer supply disruptions. Japan and Korea hold reserves through agencies.

Non-Linear Price Response:



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8. Risk Factors

- **Technology substitution risk**
    - In Aerospace, a key segment of demand, titanium faces competition from aluminum, composites, intermetallic, steel and superalloys for high in high strength requirement applications.   Technological innovations in these substitutes have the potential to reduce demand by 10-20%.
    - Titanium faces additional competition from Aluminum, nickel, specialty steels, and zirconium alloys for corrosion-resistant applications.

- **Demand delays**
    - Primary demand delays stem from cyclical segments aerospace and pigments. Aircraft production backlogs have the potential to defer demand by 1-2 years. Delays in EV adoption have the potential to affect titanium demand in alloys.

- **Policy shifts**
    - Policy shifts, tariffs, and export controls pose significant uncertainty to supply chains. The critical Mineral Ministries (54 nations excluding China) have proposed preferential trading regions and price floors to reduce dependencies. Recent geopolitical tension with China, a dominant producer, has placed shifted emphasis on onshoring of Titanium production.

- **Recycling improvements**
    - Advances in scrap-to powder recycling in U.S. (currently 125 tons) are targeted to reach 10,000 tons by 2030, potentially offsetting U.S imports by 20-30%. The overall scrap recycling market is projected to grow inline broad market growth.

9. Strategic Implications

- Structural asymmetry arises from supply concentrations, processing bottlenecks and inelastic demand. Disruptions have the greatest impact on consumers of finished titanium products, particularly in demand segments that require high-purity finished products with specific quality requirements. Demand in these segments is largely inelastic due to limited alternatives and viable substitutes.

- The Titanium market is primarily a contract market. The markets' opacity, and oligopolistic structure allow for deviations from fundamentals. The key conflicting forces in the market are the over supply of ore and constraints, bottlenecks in processing and finishing of titanium products.

- Market narratives of oversupply diverge from physical realities of qualified supply deficits, particularly in high-grade demand in key segments.

Investment implications and positioning frameworks are addressed separately in Oculus Exposure Notes.

10. Conclusion

The titanium market exemplifies a compelling long-duration investment thesis in which enduring structural dynamics dominate over fleeting narrative cycles. The inevitability of structural supply constraints and growing demand support a strong, multi-year value creation opportunity. Depleting high-grade deposits, protracted lead times for new mine developments, combined with narrow processing constraints create an inelastic supply response that eclipse cyclical narratives and economic downturns. This structural tightness is amplified by geographic dominance: China, as the world's largest producer and consumer, accounts for approximately 34% of global ore output yet remains a net importer, exerting outsized influence on trade flows and pricing. Key suppliers like Australia, Mozambique, and South Africa further concentrate supply.

Despite the structural tightness in ore production, the dominant constraint in the titanium market is in the processing and refining of high-grade finished titanium products. Fulfilling demand for aero-space and defense applications requires high-purity qualifications with even narrower concentrations of suppliers (Russia, Japan, West). The complex, and energy intensive nature of titanium processing imposes considerable bottle necks in the supply chain for critical segments of demand (aerospace, defense, and high-growth biomedical applications) that require stringent certification and quality specifications.

Against this backdrop, forward-looking scenarios underscore the market's asymmetric upside. In the base case, constraints sustain premium pricing. While an uplift in production in existing capacity will enable moderate supply recovery in the short-term, capacity expansion in the outer years will be subdued by capex intensity, technological barriers, and protracted lead times. Interim supply recoveries would merely temper, not eliminate, the underlying imbalance. Investors should thus prioritize theses anchored in supply chain resilience, vertical integration, and exposure to high-barrier assets, positioning for a market where structural dominance and constraints inevitably prevail over cyclical noise.

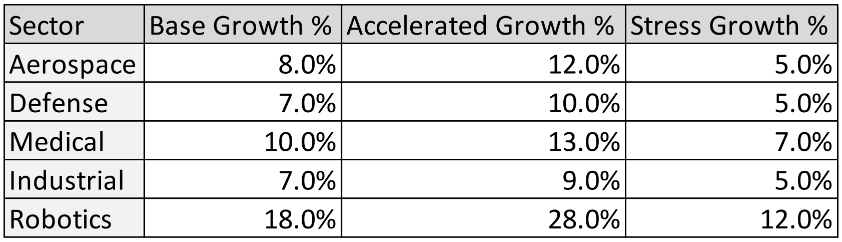
Appendices

A. Data Sources/ Methodology Notes

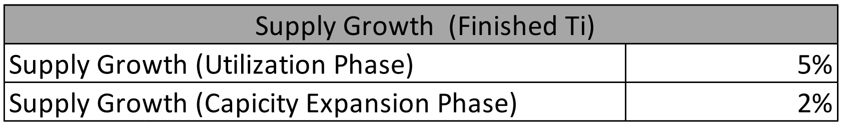
Titanium is an opaque contract market. Estimates vary materially across sources. Our balance framework triangulates USGS production, TZMI sponge capacity, OEM aerospace build rates, and CRU/WoodMac cost benchmarks. Additional sources: IEA, BIS, ITA, NASA, UN, JRC, Project Blue, Bank of America, ABI Research, Mordor Intelligence.

B. Supply-Demand Balance Model Assumptions:

Demand and Supply Assumptions:

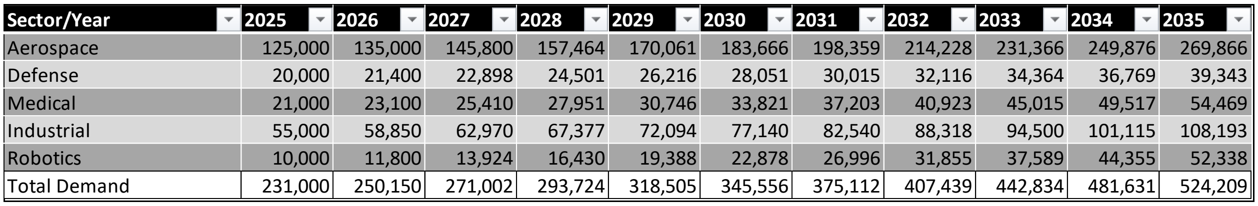


Sector	Base Growth %	Accelerated Growth %	Stress Growth %
Aerospace	8.0%	12.0%	5.0%
Defense	7.0%	10.0%	5.0%
Medical	10.0%	13.0%	7.0%
Industrial	7.0%	9.0%	5.0%
Robotics	18.0%	28.0%	12.0%



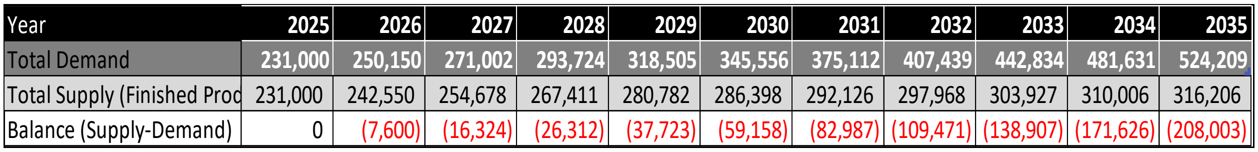
Supply Growth (Finished Ti)	
Supply Growth (Utilization Phase)	5%
Supply Growth (Capicity Expansion Phase)	2%

Base Demand:



Sector/Year	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Aerospace	125,000	135,000	145,800	157,464	170,061	183,666	198,359	214,228	231,366	249,876	269,866
Defense	20,000	21,400	22,898	24,501	26,216	28,051	30,015	32,116	34,364	36,769	39,343
Medical	21,000	23,100	25,410	27,951	30,746	33,821	37,203	40,923	45,015	49,517	54,469
Industrial	55,000	58,850	62,970	67,377	72,094	77,140	82,540	88,318	94,500	101,115	108,193
Robotics	10,000	11,800	13,924	16,430	19,388	22,878	26,996	31,855	37,589	44,355	52,338
Total Demand	231,000	250,150	271,002	293,724	318,505	345,556	375,112	407,439	442,834	481,631	524,209

Base Supply-Demand Balance:

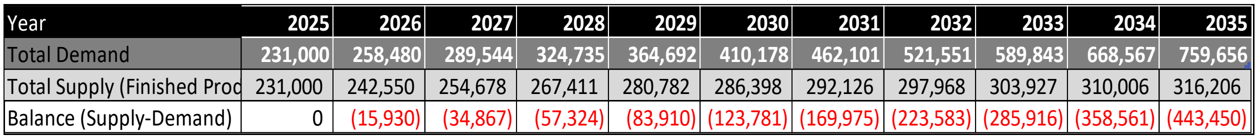


Year	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Total Demand	231,000	250,150	271,002	293,724	318,505	345,556	375,112	407,439	442,834	481,631	524,209
Total Supply (Finished Proc	231,000	242,550	254,678	267,411	280,782	286,398	292,126	297,968	303,927	310,006	316,206
Balance (Supply-Demand)	0	(7,600)	(16,324)	(26,312)	(37,723)	(59,158)	(82,987)	(109,471)	(138,907)	(171,626)	(208,003)

Accelerated Demand:

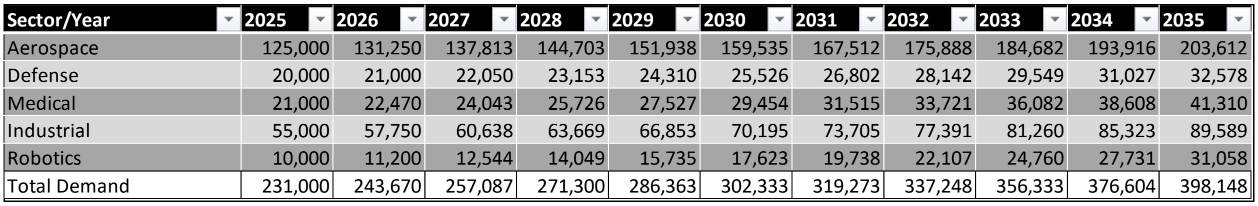
Sector/Year	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Aerospace	125,000	140,000	156,800	175,616	196,690	220,293	246,728	276,335	309,495	346,635	388,231
Defense	20,000	22,000	24,200	26,620	29,282	32,210	35,431	38,974	42,872	47,159	51,875
Medical	21,000	23,730	26,815	30,301	34,240	38,691	43,721	49,405	55,827	63,085	71,286
Industrial	55,000	59,950	65,346	71,227	77,637	84,624	92,241	100,542	109,591	119,454	130,205
Robotics	10,000	12,800	16,384	20,972	26,844	34,360	43,980	56,295	72,058	92,234	118,059
Total Demand	231,000	258,480	289,544	324,735	364,692	410,178	462,101	521,551	589,843	668,567	759,656

Accelerated Supply-Demand Balance:



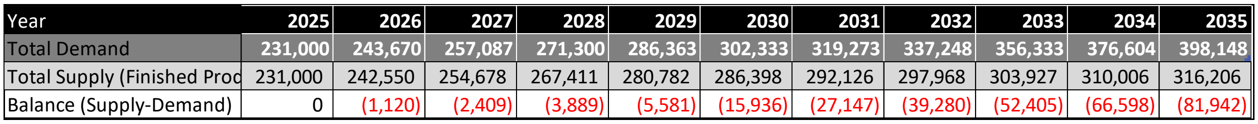
Year	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Total Demand	231,000	258,480	289,544	324,735	364,692	410,178	462,101	521,551	589,843	668,567	759,656
Total Supply (Finished Proc	231,000	242,550	254,678	267,411	280,782	286,398	292,126	297,968	303,927	310,006	316,206
Balance (Supply-Demand)	0	(15,930)	(34,867)	(57,324)	(83,910)	(123,781)	(169,975)	(223,583)	(285,916)	(358,561)	(443,450)

Stress Demand:



Sector/Year	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Aerospace	125,000	131,250	137,813	144,703	151,938	159,535	167,512	175,888	184,682	193,916	203,612
Defense	20,000	21,000	22,050	23,153	24,310	25,526	26,802	28,142	29,549	31,027	32,578
Medical	21,000	22,470	24,043	25,726	27,527	29,454	31,515	33,721	36,082	38,608	41,310
Industrial	55,000	57,750	60,638	63,669	66,853	70,195	73,705	77,391	81,260	85,323	89,589
Robotics	10,000	11,200	12,544	14,049	15,735	17,623	19,738	22,107	24,760	27,731	31,058
Total Demand	231,000	243,670	257,087	271,300	286,363	302,333	319,273	337,248	356,333	376,604	398,148

Stress Supply-Demand Balance:



Year	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
Total Demand	231,000	243,670	257,087	271,300	286,363	302,333	319,273	337,248	356,333	376,604	398,148
Total Supply (Finished Proc	231,000	242,550	254,678	267,411	280,782	286,398	292,126	297,968	303,927	310,006	316,206
Balance (Supply-Demand)	0	(1,120)	(2,409)	(3,889)	(5,581)	(15,936)	(27,147)	(39,280)	(52,405)	(66,598)	(81,942)