

Material Flow Analysis of Titanium Metal in European Aviation: Circular Economy Strategies for reduced import dependence

Stefano Ghirlandi

`stefano.ghirlandi.26@ucl.ac.uk`

German Aerospace Center (DLR e.V.)

Tim Hoff

German Aerospace Center (DLR e.V.)

Catrin Böcher

Leiden University

Benjamin Sprecher

TU Delft

Ahmad Ali Pohya

German Aerospace Center (DLR e.V.)

David Peck

TU Delft

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Abstract

Titanium is an essential metal for modern civil aviation, for which the European Union relies entirely on imports. While both European policy and literature highlight the potential of circular strategies to reduce dependence, quantitative evidence across the entire material system remains missing. To address this gap, we combine a static Material Flow Analysis of the European titanium lifecycle in 2019 with a dynamic stock-driven model projecting stocks and flows to 2040. We focus on three circular interventions: design-stage material intensity reduction, aircraft lifetime extension, and enhanced pre-consumer and end-of-life recycling. To evaluate their individual and combined impacts, we formulate seven scenarios and measure cumulative import reduction against a baseline scenario using a unified metric. We find that while fleet titanium stock expands 70% by 2040, generating 693 kilotonnes of baseline imports, combined circular strategies could reduce these by 25% (175 kilotonnes), less than the sum of their individual effects. Pre-consumer scrap retention performs best (15%), followed by intensity reduction (8%), end-of-life recovery (3%), and lifetime extension (2%). These findings carry a double message for the European strategic autonomy agenda. The largest circular gains sit upstream, in retaining pre-consumer scrap and in design, rather than in recovering end-of-life material. Circular strategies narrow import dependence without closing it. The residual gap lies beyond the reach of circularity, likely in domestic primary processing capacity and trade partnerships.

1. INTRODUCTION

Modern civil aviation depends on Critical Raw Materials (CRMs). Production of CRMs is concentrated in a small number of non-European Union (EU) countries, creating structural import dependence at all stages of their lifecycle (Dolganova et al., 2022). The COVID-19 pandemic and the Russian invasion of Ukraine exposed the risks of such dependence, disrupting supply chains in the EU (European Commission, 2025).

Among these materials, titanium metal^[1] stands out as a prime example of complex industrial reliance. Its exceptional strength-to-weight ratio, corrosion resistance, and compatibility with carbon-fibre reinforced polymers have led it to play an important role in aviation with an increased share in aircraft from negligible levels to approximately 15% of operational empty weight, over five decades (Hoff et al., 2025). The substitution of titanium is extremely challenging at commercial scale for engines, airframes, landing gear, or hydraulic systems (Lefevre et al., 2017; Najafizadeh et al., 2024). For all these reasons, civil aviation accounts for roughly 67% of EU titanium consumption, estimated at 19.9 kt in 2019 (Buesa, Piñero, et al., 2025).

The EU titanium supply chain has multiple constraints. There is no EU-based extraction, refining or processing capacity, relying entirely on imports, mostly from the United States, Russia, Japan, and China (Idoine et al., 2024; SCRREEN3, 2025). Component manufacturing generates large volumes of high-grade scrap at a buy-to-fly ratio of approximately 9:1 (Baldassarre, 2025). Although this scrap could theoretically be remelted domestically, it is bound to US suppliers through long-term buyback

agreements that tie primary titanium supply to the return of generated secondary scrap (Buesa, Georgitzikis, et al., 2025). The EU has no meaningful dismantling and recycling capacity of retired aircraft, preventing access to a valuable secondary supply. (Hoff et al., 2025)

Policymakers and the aviation industry in the EU have raised titanium to a strategic priority in recent years. Firstly, the Critical Raw Materials Act classifies titanium as both critical and strategic, signalling that related projects should obtain faster permitting and financial support (European Commission, 2020). It establishes binding benchmarks for domestic processing and recycling and limits dependence on any single third-countries (Grohol & Veeh, 2023). Secondly, the Aviation Research and Innovation Strategy (ARIS), led by European aviation stakeholders, points at titanium import reliance as a threat to innovation capacity. It argues that circular economy practices are pivotal for sustainability and competitiveness and calls for material reuse rates above 90% through closed-loop systems (Clean Aviation & Sesar, 2025). These targets are embedded in the broader EU agenda for Open Strategic Autonomy, which identifies reduced material dependencies as a precondition for sectors including aviation (Kroll, 2024) .

Circular economy strategies can reduce dependence by acting on titanium already inside the EU. The growing in-use stock of titanium-intensive aircraft is itself a future end-of-life material reserve (Buesa et al., 2025). Maintenance, repair, and overhaul (MRO) keep this high-value, already-processed material in active operation, rather than letting it exit the system through scrap export, downcycling, or retirement (Oestreicher et al., 2025). Expanding MRO capacity therefore builds an operational buffer for strategic autonomy. During a geopolitical crisis or a foreign supply disruption, extending the service life of the existing fleet keeps aircraft flying without depending on vulnerable international raw material pipelines (IATA, 2025).

Three studies have examined the case for titanium circularity from complementary angles. Buesa, et al. (2025) provide the most comprehensive account of EU titanium flows, geopolitical and technological insights and scenarios of circular interventions. However, by modelling trade in Input Output analysis and relying on UN Comtrade datasets, well known mass inconsistencies persist (Hu et al., 2022). Hoff et al. (2025) used a regression model to project 2040 global titanium demand across two aircraft families, focusing on the use phase. They found that life-cycle extension combined with recycling synergistically reduces demand by over 10%, mitigating supply constraints. However, their use-phase boundary excludes material stocks and broader supply-chain impacts. Finally, Baldassarre (2025) qualitatively maps systemic circularity barriers and drivers within the EU titanium supply chain, explicitly requesting quantitative scenario modelling to validate its policy recommendations.

These studies confirm that circular strategies lower primary demand. However, they overlook the quantitative implications for regional import dependence. Addressing this gap aligns with calls for dynamic MFA frameworks capable of projecting long-term demand, stock growth, and secondary material flows (Tukker, 2025). This study aims to quantify the potential of circular economy strategies to reduce the EU's raw material import dependence in civil aviation. To achieve this, we reconstruct the EU

aviation titanium supply chain using a combined static and dynamic MFA approach to project fleet demand to 2040 and evaluate the impact of three key circular interventions.

2. METHODS

This study applies static and dynamic MFA to quantify titanium flows in the EU civil aviation sector. The MFA system boundaries are defined along four dimensions. Spatially, the EU27 countries are treated as a single region, with all external trade aggregated as flows to and from the rest of the world. Temporarily, the static MFA captures 2019 as the last full pre-COVID reference year with available data, while the dynamic MFA spans 2000–2040. The study considers aviation-grade titanium metal only, restricted to passenger aircraft and excluding cargo and military applications. All results are expressed in kilotonnes of titanium metal, enabling consistent comparison across methods and scenarios. All input data, code, and calculations are provided in Supplementary Materials 1 and 2.

The static MFA reconstructs the EU titanium supply chain in 2019. Transfer coefficients derived from the static model are then applied to the dynamic MFA outputs, linking use-phase dynamics to upstream import volumes. Said coefficients are kept unchanged over the scenario period, assuming no structural change in EU titanium processing capacity. The dynamic MFA operates independently, quantifying use-phase inflow and outflow over 2000–2040 without resolving upstream stages. We model three circular economy interventions, two demand-sided and one supply-sided, that in different combinations yield seven different scenarios to investigate the import reduction potential across the titanium supply chain.

2.1 Data sources and system parameterization

2.1.1 Static MFA

The static MFA reconstructs the EU aviation-grade titanium supply chain for 2019, integrating trade statistics, production data, and industry assumptions into a single mass-balanced model. Raw trade data are sourced from UN Comtrade and Eurostat Prodcom, with sector-level allocation following Buesa, Piñero, et al. (2025). All calculations are provided in Supplementary 2 – MFA calculations.

Figure 1 illustrates the full titanium lifecycle from ore beneficiation to end-of-life. Scrap is generated at each stage but can follow multiple recovery routes. High-grade prompt scrap re-enters primary melting through conventional re-smelting. Off-grade sponge and titanium-rich scrap are instead alloyed with iron to produce ferro-titanium, a steelmaking additive (Takeda & Okabe, 2019). Once downcycled, the material cannot re-enter aviation-grade production, representing a permanent loss of embodied processing value (Panigrahi et al., 2010). Additive manufacturing and powder metallurgy offer alternative recovery routes but are excluded here as neither has reached sufficient scale for aerospace-grade production (Hot et al., 2020). Component manufacturing is the most material-intensive stage, due to the aforementioned buy-to-fly ratio of 9:1 (Baldassarre, 2025). Current melting technology imposes a 55% scrap to additive ratio for aerospace-grade metal, meaning that secondary material must always be mixed with primary sponge

(Takeda & Okabe, 2019). The system boundary of this study, indicated by the shaded region in Fig. 1, spans sponge to end-of-life, acknowledging upstream mining and refining without modelling them explicitly.

2.1.2 Dynamic MFA

The dynamic MFA quantifies titanium embedded in the EU civil aviation fleet from 2000 to 2040, producing annual inflow, outflow, in-use stock, and net addition to stock data for both aircraft numbers and titanium tonnage. All input data and code are provided in Supplementary Materials 1 and 2.

There are two main steps in the modelling process: first, EU fleet and model breakdown; second, titanium stock and flow calculations. Observed EU fleet stock from 2000 to 2023 is drawn from (Eurostat, 2024), with year-to-year fluctuations reflecting administrative deregistration during temporary grounding rather than physical decommissioning. For 2025–2040, the fleet size is projected by translating the Eurocontrol long-term forecast of 1.5% annual flight growth into a 0.5% annual EU fleet growth rate (Eurocontrol, 2021), verified against German Aerospace Center (DLR) global fleet projections (Gelhausen, 2020; Gelhausen et al., 2025; DLR, 2026) at five benchmark years. The resulting EU share of the global commercial aircraft fleet declines from 15.3% in 2024 to 14.4% in 2040, consistent with observed shares reported by Cirium (2025) and long-term traffic projections from Airbus (2025). In order to avoid backloading of pre-2000 stock on the first model year, a logistic curve distributes historical aircraft across cohorts from 1960 onwards.

Fleet composition is reconstructed separately for the historical and forecast periods. From 2000 to 2023, aircraft-level records from Cirium (2025) provide the airplane model, production year, operational status, and retirement age for each aircraft. A bottom-up stock accounting approach assigns each aircraft to the fleet stock for every year it was operational. From the fleet stock each year, we derive annual model-level shares. For 2024–2040, model composition is adapted from DLR global projections at discrete time steps, with annual shares obtained through linear interpolation. Titanium intensity is characterised across 61 aircraft models spanning 12 seating categories, with operational empty weight and titanium weight fraction drawn from literature for each model. As reported in S1.2 – Model specification, where there was no source for titanium intensity, it was assumed based on the date of rollout of the model. Annual titanium in-use stock is derived by multiplying the number of aircraft of each model by its titanium intensity, then summing across all models. The resulting annual titanium stock then serves as inputs to a stock-driven model. It assumes a normal distribution for the survival curve with a mean lifetime of 25 years and standard deviation of 12.5 years (Baier et al., 2024). Annual inflow is the difference between the target stock and the titanium tonnage from prior years still in service. Outflow is determined by the age-based retirement probability of each cohort.

2.2 Circular economy interventions

Three circular economy interventions are investigated. Two affect the demand of titanium by narrowing, through intensity reduction at design stage, and slowing the loop, through aircraft lifetime extension

(LTE). One affects the supply of titanium by closing the loop of pre and post-consumer scrap recycling. Intervening respectively at the design, manufacturing, use, and end-of-life stages, they are aligned with existing aviation and critical material policy targets (Clean Aviation & Sesar, 2025; European Commission, 2020). Substitution was excluded because modern aviation applications do not have viable alternatives to titanium (Buesa, Georgitzikis, et al., 2025).

The interventions are combined in seven scenarios plus baseline, each evaluated over the period 2025–2040. A unified import reduction metric is developed and proposed to enable direct cross-scenario comparison. It expresses the import reducing effect of both demand-side and supply-side interventions in a common physical unit. This allows for consistent evaluation without loss of comparability, highlighting long-term trends and synergies.

All scenario assumptions are consolidated in Table 1.

2.2.1 Demand-side interventions

Reduction. The reduction intervention targets the titanium intensity of next generation widebody aircraft in the DLR fleet forecast. The forecast represents new deliveries after 2023 through three flagship models (D239 + M, D300 + M, and D315 + M) to which we assigned a titanium intensity of 17% of operational empty weight, consistent with the historical trend of intensity growth. However, this exceeds that of comparable in-service widebodies: the Airbus A330 and Boeing 777 both carry approximately 14% titanium by operational empty weight (OEW). The intervention therefore assumes next-generation models converge to current-generation equivalents, reducing their assigned intensity from 17% to 14%. The intervention captures net demand-side deceleration regardless of pathway, either that is design efficiency, reduced over-engineering margins, or targeted substitution in non-critical applications. All other model intensities and fleet dynamics remain unchanged from the baseline

LTE. The LTE intervention explores the effect of enhanced MRO operations that prolong aircraft components service life. In the baseline, aircraft retirement follows a survival curve with a mean lifetime of 25 years and standard deviation of 12.5 years (Baier et al., 2024). Under LTE, the mean shifts to 30 years with a standard deviation of 15 years. The latter reflects greater variability in aircraft longevity attributable to differences in maintenance intensity and operator strategy. The intervention is implemented as a parameter change to the survival curve applied to all cohorts entering service from 2025 onwards, with pre-2025 cohorts retaining the baseline curve.

No additional material flows associated with MRO operations, such as component replacement, part overhaul, or consumable inputs, are modelled. LTE is therefore represented exclusively as a change in retirement timing, which reduces the annual reduction demand and consequently the titanium inflow required to maintain the target stock. This modelling choice leads to an underestimation of the full material implications of extended MRO activity.

2.2.2 Supply-side interventions

Recycling. The recycling intervention increases domestic secondary material supply through two complementary flows: enhanced reprocessing of pre-consumer prompt scrap and end-of-life recovery from retired aircraft.

Pre-consumer reprocessing retains the 40% of EU scrap exports not bound by long-term buyback agreements with the United States (UN Comtrade, 2025). This share is derived from the 2019 static MFA and assumed absorbable by existing EU remelting capacity without additional infrastructure investment. From 2025, the domestic reprocessing flow increases immediately to reflect full retention of this available scrap. The remaining 60%, contractually tied to US suppliers, continues to be exported throughout the scenario period.

End-of-life recovery draws from a storage pool initialised from cumulative use-phase outflows between 2000 and 2025. The outflow is first filtered through the collection rate of 0.80 (European Commission et al., 2024) and then a dismantling efficiency of 0.80, with the remainder lost to downcycling from mixed-alloy contamination (Airbus, 2022). The recovered material re-enters the value chain through conventional remelting. While powder metallurgy and additive manufacturing are excluded as they remain insufficiently mature for aviation-grade production at scale (Baldassarre, 2025). The end-of-life recycling share of gross imports is assumed to grow linearly from 0% in 2025 to 5% by 2040, reflecting gradual buildout of dismantling and recovery infrastructure.

Table 1

Model parameters and assumptions by intervention. The dash indicates the intervention does not modify the baseline value.

Parameter	Baseline	Reduction	LTE	Recycling	Source / justification
Fleet stock, 2000–2023	<i>Observed EU27 passenger fleet</i>	☒	☒	☒	Eurostat (2025)
Fleet growth rate, 2025–2040	<i>0.5% per year</i>	☒	☒	☒	Converted from Eurocontrol (2021) 1.5% annual flight growth; verified against DLR (2026)
Model coverage	<i>61 passenger aircraft models, annual fleet share</i>	☒	☒	☒	Cirium (2025); DLR (2026)
Aircraft titanium intensity	<i>Model-specific, from OEW and titanium weight fraction</i>	☒	☒	☒	Supplementary 1
Next-generation flagship models (D239, D300, D315)	<i>17% of OEW</i>	<i>14% of OEW</i>	☒	☒	Observed intensity of comparable in-service A330 and 777 models
Survival curve	<i>Normal, mean 25 years, SD 12.5 years, all cohorts</i>	☒	<i>Normal, mean 30 years, SD 15 years, 2025 < cohorts</i>	☒	Baier et al. (2024); LTE curve is a modelling assumption reflecting enhanced MRO operations
Scrap and recycling					
Share of scrap exports bound by US buyback agreements	<i>60%</i>	☒	☒	☒	UN Comtrade (2025)
Share of scrap available for domestic retention	<i>40% of current exports</i>	☒	☒	☒	Complement of buyback-bound share

Parameter	Baseline	Reduction	LTE	Recycling	Source / justification
Pre-consumer reprocessing share of gross imports	5%	☒	☒	20%, step change from 2025	2019 static MFA; scenario value after 40% export retention, existing EU remelting capacity assumed sufficient
End-of-life recycling share of gross imports	0%	☒	☒	Linear ramp, 0% (2025) to 5% (2040)	Conservative infrastructure build-out assumption
Collection rate	80% of annual use-phase outflow towards storage	☒	☒	☒	European Commission et al. (2024)
Dismantling yield	Not active	☒	☒	0.80 (20% lost to downcycling)	Airbus (2022)
Storage pool initialisation	Not active	☒	☒	Cumulative use-phase outflow 2000–2024 $\times$ 0.80 = 9.1 kt	Hibernating stock held in storage as of 2024
Scrap recycling pathway	Conventional remelting only	☒	☒	☒	AM not at scale for aviation-grade production

2.3 Import reduction

The existing literature on circularity and import dependence addresses supply-side and demand-side interventions in isolation. Studies on secondary supply quantify import reduction through recycling or material substitution without accounting for concurrent demand reduction (Gaustad et al., 2018; Karali & Shah, 2022; Santillán-Saldivar et al., 2021). This supply-side bias is also reflected in CRMA targets focusing on domestic processing and recycling shares, with no equivalent metric for use-phase or design-stage reductions. Studies that do model demand-side interventions treat them in separate scenario families and do not propagate their effects to upstream import volumes (Hoff et al., 2025; Wesselkämper et al., 2024). Stage-level self-sufficiency indicators, while defined at a single processing node, cannot capture how interventions at different supply chain stages interact to produce a combined chain-wide import effect (European Commission et al., 2024). The consequence is that prior approaches precluded direct cross-scenario comparison in a common unit. This study proposes a unified formula that addresses both limitations.

The impact of each scenario on EU import dependence is measured as annual import reduction IR_t . It captures how much an intervention lowers foreign material inputs to the EU titanium supply chain in year t , relative to the baseline.

The analysis rests on the identity:

$$M_t = I_t \times \alpha$$

Where M_t is gross imports in year t , I_t is use-phase inflow from the dynamic MFA and α is the upstream import coefficient defined as the ratio of gross imports to use-phase inflow derived from the static MFA. Following the raw material equivalents approach (Eurostat, 2025), a method that traces traded goods back to the primary material embodied in them, α folds every upstream processing step, from sponge to finished component, into one fixed number, held constant across the scenario period. This allows demand-side interventions, which act on I_t , and supply-side interventions, which substitute a share of M_t directly, to be expressed in a common unit.

Annual import reduction is:

$$IR_t = (M_{baseline,t} - M_{scenario,t})_{demand-side} + (\Delta \phi_{rep} + \phi_{rec,t}) \times M_{scenario,t}_{supply-side}$$

The demand-side term captures import reduction from lower use-phase inflow. The supply-side term captures direct import substitution by domestic secondary material, where the shares are defined as:

$$\phi = \frac{\text{domestic secondary material}}{M_t}$$

$\Delta \phi_{rep}$ is the additional reprocessing share above the 2019 baseline, applied as a step change at the start of the scenario. $\phi_{rec,t}$ is the end-of-life recycling share, rising linearly over the scenario period. Both endpoints come from the static MFA.

The two terms act on distinct variables and are therefore additive without double counting. Using $M_{scenario,t}$ in the supply-side term ensures that when demand reduction is active, recycling shares apply to the already-reduced import base, correctly capturing the sequential structure of the two mechanisms. For standalone scenarios, one term reduces to zero by default: setting $\Delta \phi_{rep} = \phi_{rec,t} = 0$ recovers pure demand-side reduction; setting $M_{scenario,t} = M_{baseline,t}$ recovers pure supply-side reduction.

3. RESULTS

We first present the results for our static MFA for EU titanium supply in 2019. Then we present the in-use stock evolution through the dynamic MFA from 2000 to 2040. Finally, we assess the import reduction potential of our three circular scenarios and their combination.

We find that the demand at the primary melting stage was 20.7 kt in 2019, with 12.4 kt of sponge and 6.2 kt of scrap feed imported (Fig. 2). A substantial share of imported material never entered the fabrication stage. Roughly 10.2 kt of primary melting output was downcycled as additive into ferro-titanium while 3.9 kt went into titanium powders. Domestic fabrication met only one quarter of EU demand for milled titanium products, with the remainder 6.1 kt imported from the United States, China, Russia, and Japan (UN Comtrade, 2025).

The component manufacturing input is estimated at 16 kt based on Buesa, Georgitzikis, et al., (2025). Due to the buy-to-fly ratio of 9:1, only 1.6 kt reached the use phase. Of this, 1.2 kt represents net addition to stock per year and 0.4 kt reached end-of-life waste management, the latter representing the amount leaving the use phase via retiring aircraft. Scrap generation at component manufacturing amounted to approximately 14.4 kt, of which only 2.1 kt was reprocessed domestically. Summing all the scrap generated in the lifecycle, 16.5 kt was exported: first by 60% to the US under buyback agreements, followed by Russia and Ukraine (UN Comtrade, 2025).

Domestic remelting infrastructure remained small, with Ecotitanium representing the only significant EU investment in this capacity over the past decade (Buesa, Georgitzikis, et al., 2025). Finally, between 2000 and 2019, the in-use stock is estimated at 22.4 kt, while 7 kt were collected and stored as hibernating stock, in hangars or aircraft graveyards awaiting dismantling. The upstream import coefficient (α), which is the ratio of gross imports to use-phase inflow, is quantified as 23.3. While the share of reprocessed pre-consumer scrap to gross import (ϕ_{rep}) is quantified as 15%.

Concerning the dynamic MFA results, we find that the stock of titanium in the EU fleet will see a 70% increase in the period 2019–2040. The stock grows from an estimated 10 kt in 2000 to 22.4 kt in 2019 and is projected to reach 38.2 kt by 2040. Future growth is driven by sustained fleet expansion and the progressive entry of titanium-intensive next-generation widebody models.

Historical inflows are strongly shaped by macroeconomic and geopolitical shocks. The upper panel in Fig. 3 shows the post-9/11 slowdown (2001–2002) and the Great Recession (2008–2009) each produced marked inflow contractions. Fleet modernisation led to the 2015–2019 expansion, with the introduction of Airbus neo and Boeing MAX models and low-cost carrier expansion in Eastern Europe (Cirium, 2025; Sabaitytė et al., 2020). The COVID-19 period (2020–2023) imposed a near-complete halt in new deliveries, while outflows rose as especially older long-haul widebody models were retired. The inflow reduction in 2024 corresponds to the contact point of the historical and forecast fleet.

Projected inflows follow a stable delivery based on the DLR fleet forecast which excludes external shocks. However, the variations registered in 2030 and 2035 are linked to the assumption of an aggressive introduction of D239 and D300 new generation models which increase from 0% of the fleet in 2025 to 35% in 2040 (Supplementary 1). As explained in section 2.2.1, these models have a titanium intensity of 17%.

The contraction of in use stock in the COVID-19 period years is not only affected by the flow dynamics explained above, but it is also a consequence of fleet restructuring. Figure SI2 shows the EU fleet composition by class of titanium tonnage. In the years leading up to 2019, the 5–10 t class, dominated by neo and MAX models, starts rising, eventually replacing the older models in 2032. Meanwhile, the decline in 10–15 t class in the 2020–2023 period leads to a drop in the average titanium intensity of the stock, explaining the corresponding decline. One modelling caveat applies: the model assigns outflows according to cohort lifetime distributions, so aircraft grounded but not formally deregistered remain in stock, dampening the apparent retirement signal and likely understating true outflows.

In the steps above we first defined titanium supply structure in 2019, quantifying the upstream import coefficient (α), which is the ratio of gross imports to use-phase inflow. Then we found the yearly titanium inflow to the use phase from 2000 to 2040. This provides all necessary variables for assessing the Import Reduction potential of our three circular strategies, namely intensity reduction, lifetime extension and recycling.

We found that, in the baseline scenario in 2025–2040 across the supply chain, 693 kt of titanium is imported in various forms (sponge, ingots, milled products). Table 2 shows the import reduction of each scenario over the same time period. The small reduction yielded by LTE is due to modelling choices. The survival curve shift from 25 to 30 years only affects cohorts entering service in 2025 whose retirement falls beyond the analysed timeframe. As a result the full import reduction potential of LTE likely extends well beyond 2040, meaning the present analysis underestimates its long-term effect. Titanium intensity reduction replaces 8% of baseline imports by 2040. The effect is delayed, remaining negligible until 2031 and accelerating only as next-generation flagship models begin to dominate new deliveries. The combined scenario (LTE + Reduction) replaced 9% of baseline imports. Since under LTE fewer aircraft are retired and replaced, titanium intensity reduction has a marginally smaller base to act on each year. Therefore combining the two strategies delivers less than adding their separate effects.

Recycling is the dominant intervention, replacing 18% of baseline imports. This is mainly due to reprocessing of pre-consumer scrap, which accounts for 15% of baseline imports and can be immediately retained by domestic industry. End-of-life recycling contributes to just 3% of imports. It is composed by a hibernating stock, estimated at 7 kt in 2019, which has accumulated in hangars and aircraft graveyards since 2000; and the annual flow of newly retired aircraft, which continues to replenish that stock each year. As the dismantling and recycling capacity increases, annual withdrawals exceed annual replenishment, leading to a complete depletion of the stock by 2040.

All interventions together can lower imports by 25% compared to baseline. Interestingly, the combination of demand side and supply side interventions has a marginally lower reduction than the simple sum of each. In fact, by lowering the demand of titanium at use phase, there is less secondary material available for recycling. Both because of a shrinking pool of retired aircraft, which linger longer in the use phase, and because of less upstream inflow to component manufacturing.

Table 2
Import reduction potential of the seven scenarios from
2025 till 2040

Baseline	Total imports (kt)	
	693	
	kt reduced	% reduced
All interventions	175	25%
Reduction and Recycling	166	24%
LTE and Recycling	133	19%
Recycling	123	18%
LTE and Reduction	65	9%
Reduction	53	8%
LTE	12	2%

4. DISCUSSION

Our results show that circular strategies can reduce EU titanium import dependence by up to 25%, with important caveats concerning timing and magnitude.

Pre-consumer scrap reprocessing is the quickest intervention as it could immediately yield around 5 kt of titanium for remelting. As it is proportional to inflow to use phase, based on the 9:1 buy to fly ratio, it steadily grows with titanium demand. Current buyback agreements with the United States limit its potential. The EU exports 60% of the scrap and imports 30% of its primary sponge in return (UN Comtrade, 2025). Phasing out these agreements through collaborative EU-US trade negotiations and joint infrastructure development might build supply chain resilience without triggering trade tensions (Buesa et al., 2025). However, any renegotiation should consider the metallurgical constraint of scrap-to-additive ratio at melting stage, which for aerospace components requires at least an even split of scrap and primary material (Takeda & Okabe, 2019).

End of life scrap would affect only 3% of cumulative imports while the hibernating stock is drawn down faster than retiring aircraft can replenish it, and is exhausted by 2040. Two factors may make this estimate too optimistic. First, we model recycling as simple linear growth, without accounting for market development rates, capital constraints, or alloy contamination. Second, post-dismantling sorting limits high-purity recovery in practice, because scrap contains various alloys whose additive elements affect the quality of recycled material (Tebaldo et al., 2023). Economic, technical, and regulatory barriers further limit these impacts (Buesa et al., 2025). On the other hand, we modelled the EU as a closed system for end-of-life recycling, but local dismantling infrastructure could unlock additional feedstock by attracting imported foreign aircraft.

Demand-side interventions that slow or narrow the titanium loop yield little initial results but increase over time. In our model, LTE achieves a near-term import reduction of just 2%, but its full effect extends beyond 2040. This delay is the result of our choice of shifting the survival curve exclusively for newly built aircraft. In practice, enhanced MRO operations would extend the lifespan of existing fleets as well. At the same time though, it would require secondary inflows of new or remanufactured titanium components during major overhauls, likely dampening initial reduction potential. Despite these early limitations, the demonstrated profitability of aviation component repair and remanufacturing and the retention of control over component service life by operators provide strong drivers for LTE adoption (Baldassarre, 2025; Hoff et al., 2025).

Design stage interventions for titanium intensity reduction appear promising for reducing import demand, while it also creates trade-offs outside the scope of this study. Driven by sustainability and competitiveness targets, the aviation industry is prioritizing airframe lightweighting and higher engine efficiency, for which titanium has currently no viable substitute (Najafizadeh et al., 2024). Nonetheless, technical advancements in steel alloys and thermoplastics present realistic opportunities to reduce component-level intensity (Akter et al., 2026). Finally, additive manufacturing is emerging as a key solution to mitigate heavy pre-consumer scrap generation, lowering buy-to-fly ratios to 3:1 while enabling direct powder recycling (Airbus, 2026; Baldassarre, 2025).

Within the literature reviewed, only Hoff et al. (2025) permits direct comparison with our results. Buesa, Piñero, et al. (2025) model trade through Input Output analysis, reporting economy-wide monetary and material effects rather than physical use-phase flows, so their scenario outputs are not expressed in units comparable to ours. Baldassarre (2025) maps barriers and drivers qualitatively and reports no quantified scenario results. Both remain essential background for the supply chain structure and policy context we model. Comparison with Hoff et al. (2025) is still limited by different method and system boundaries, but it reveals insights concerning CRMA mandated recycling targets and synergies between strategies. First, they focused on global use-phase inflows across two aircraft families. Our model evaluates the full European supply chain across 61 aircraft types. Second, their 2040 projection relied on proven industry orders and a simple regression. We adopted a state of the art projection instead (DLR, 2026). Even though we looked at import reduction potential rather than annual use-phase consumption, the limited effect of recycling alone on imports supports Hoff et al. (2025)'s claim that such intervention cannot meet the 25% EU target of annual titanium consumption. A possible shortcoming of our import reduction metric is that it propagates use-phase inflows to the rest of the supply chain through a fixed coefficient. While this provides an effective synthesis of the overall material cycle, it aggregates imports across different value-chain stages, treating titanium sponge, wrought metal, and scrap under a single label. This aggregation obscures qualitative differences among trade relationships. It treats trade deals with international partners identically to import dependencies on non-partner third countries.

Unpacking the import replacement rate by stage and trade partner is necessary to determine which specific actors along the supply chain benefit from import reduction versus targeted trade diversification. It can be seen, however, that our model contradicts Hoff et al. (2025)'s reported LTE and

recycling synergy and we suppose the discrepancy to stem from our full supply-chain boundary, rather than a different LTE model. A longer aircraft lifespan entails a delay in new builds which reduces manufacturing inflows as well as end-of-life scrap pool. In our model, secondary material has to re-enter the cycle through sorting and melting with related losses, downcycling and scrap generation. Consequently, expanding system boundaries from the use phase to the entire material cycle eliminates the expected synergy.

5. CONCLUSION

Modern civil aviation relies on CRMs to meet consumer demand and decarbonization targets, yet primary supply chains remain vulnerable to trade shocks that threaten these ambitions. This paper provides a quantitative assessment of the potential of CE strategies in mitigating the EU's import dependence for aviation-grade titanium. Using a dynamic MFA, we track titanium stocks and flows through 2040 to evaluate the import reduction potential of combined circular interventions.

By establishing a unified metric to evaluate seven scenarios against a baseline, this study shows that combined circular interventions can reduce EU titanium imports by up to 175 kt, or 25%, by 2040. Beyond broader systemic trade-offs, recycling pre-consumer (15% reduction) and post-consumer (3%) scrap proves to be the most impactful lever, followed by intensity reduction (8%) and lifetime extension (2%). The main limitation of these reduction percentages lies in our demand-side modelling. Intensity reduction targets only aircraft design, excluding manufacturing advances that reduce buy to fly ratios. Similarly, lifetime extension relies only on survival curve shifts for new builds, ignoring both active fleet MRO and overhauls demand for titanium in replacement parts.

To address these boundaries, future research should pursue three specific directions. On the techno-economic side, studies could evaluate the scalability of manufacturing advances, such as additive manufacturing and direct powder recycling, that bypass conventional remelting and fabrication. Socio-economically, research can address consumer demand reduction, including flight frequencies, to lower fleet requirements. Also, the model's scope should expand to military aviation; as EU rearms, defence demand for dual-use titanium will likely further strain civil supply chains. Finally, future studies should transition from a narrow focus on import dependency to a comprehensive resilience framework. Within this broader lens, import dependency represents only one aspect of supply vulnerability, and circularity just one of many possible solutions. Explicitly operationalizing resilience will allow researchers to evaluate the full portfolio of policy and industrial levers needed to ensure long-term resource security.

Two implications for the strategic autonomy agenda follow from the results. First, import reduction potential is greater for circularity strategies that act upstream of the use phase. This includes pre-consumer scrap retention at the manufacturing stage and intensity reduction at the design stage. Demand-side interventions also compound beyond our 2040 horizon, regardless of where in the cycle they act. Second, three-quarters of baseline imports remain untouched by any combination of modelled

interventions. Circular strategies narrow import dependence, but a further reduction likely lies in domestic primary processing capacity and diversified trade partnerships.

Declarations

CRedit authorship contribution statement

Stefano Ghirlandi: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization

Tim Hoff: Writing – review & editing, Validation, Resources, Methodology, Formal analysis, Conceptualization

Catrin Böcher: Writing – review & editing, Validation, Methodology, Formal analysis, Conceptualization

Benjamin Sprecher: Writing – review & editing, Supervision, Formal analysis.

Ahmad Ali Pohya: Writing – review & editing, Supervision, Funding acquisition, Formal analysis.

David Peck: Writing – review & editing, Supervision, Formal analysis.

Corresponding Author: * stefano.ghirlandi.26@ucl.ac.uk, Chadwick Building, Gower Street, London, WC1E 6BT, UK

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Footnotes

1. The EU criticality assessment distinguishes between titanium (dioxide) and titanium metal. Titanium dioxide is the precursor to titanium metal, but is 95% used for pigment production which is noncritical. Here, titanium is used as shorthand for titanium metal.

Figures

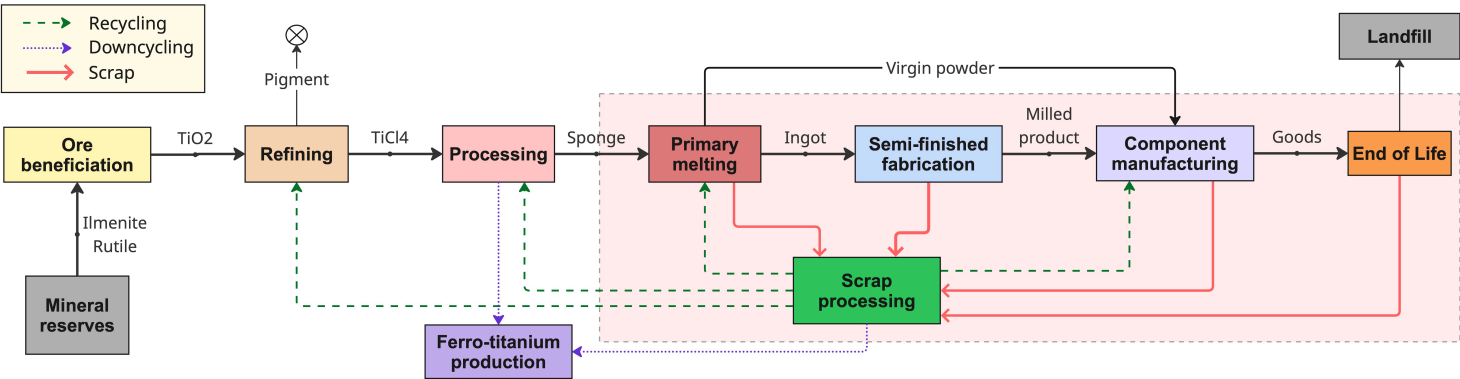


Figure 1

Titanium metal life cycle diagram

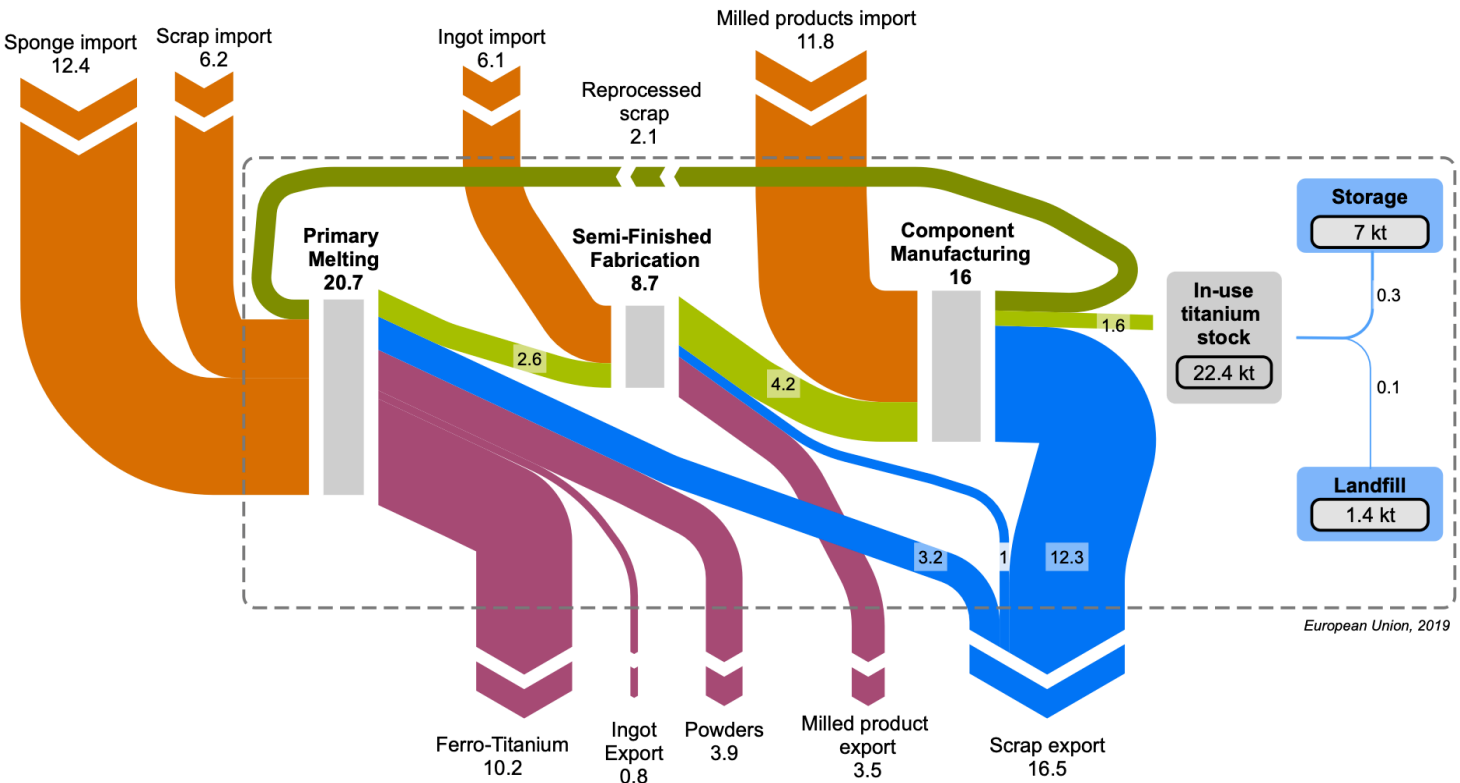


Figure 2

Sankey diagram representing the flow of aviation grade titanium from sponge to post-consumer scrap within the EU in 2019. Values are in kilotonnes. Stocks are accumulated since 2000. Flow colours denote

imports (orange), domestic flows (light green), exports (purple), scrap exports (blue), End-of-life management (light blue).

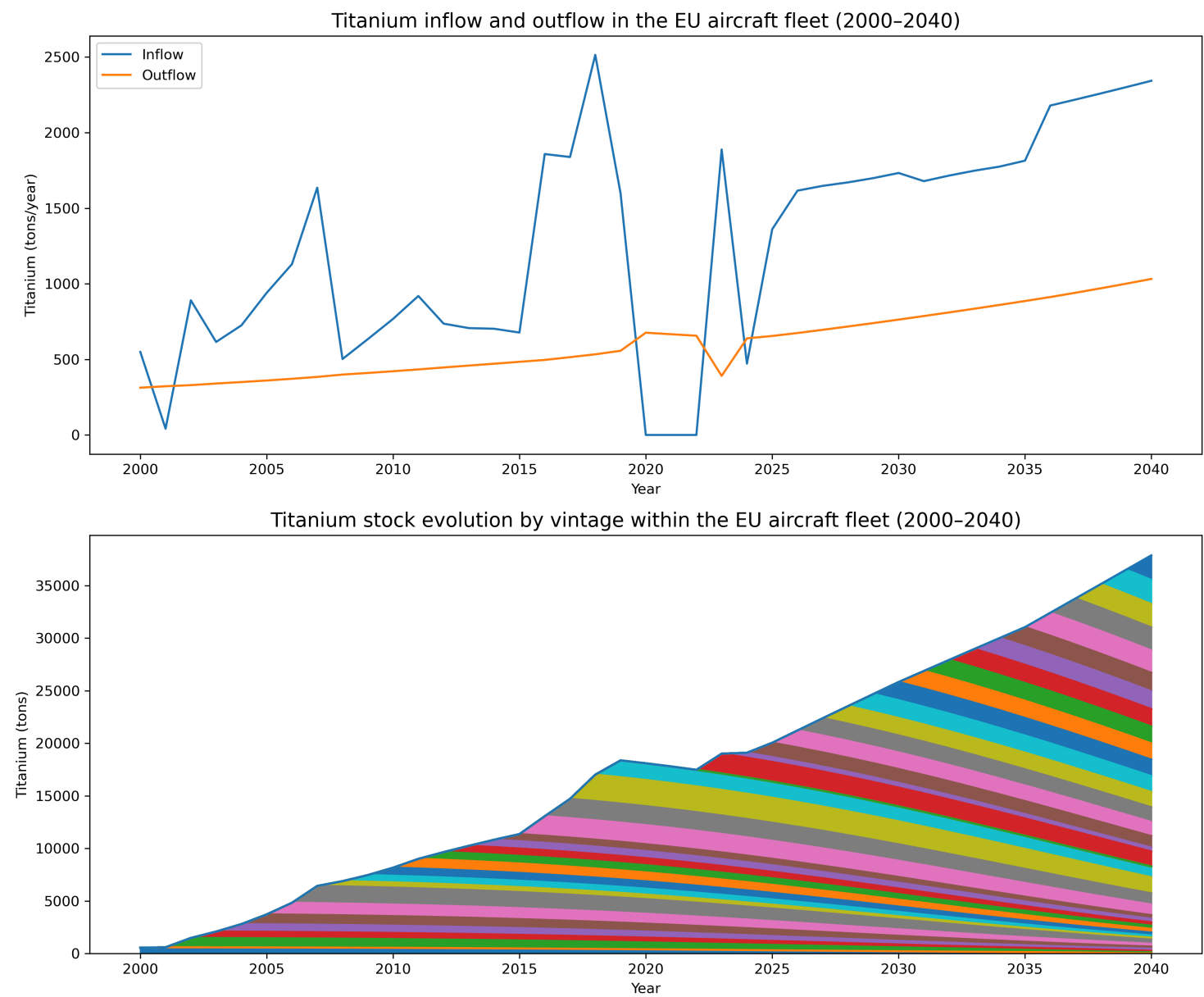


Figure 3

Titanium inflows, outflows, and in-use stock in the EU aircraft fleet (2000–2040). The top panel shows annual flows, while the bottom panel illustrates stock evolution by aircraft vintage.

Supplementary Files

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