Can circularity in Titanium metal improve EU strategic autonomy? Scenario modelling with heterogeneous data

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Executive summary

Titanium metal, though essential for aeronautics and other high-tech applications, is mostly sourced from outside the EU due to the region's lack of domestic reserves and production capacity for critical stages like titanium sponge manufacturing. The EU is heavily reliant on imports from Russia and other non-EU suppliers, highlighting the need for more self-sufficiency in titanium production.

This study investigates the role of circularity in titanium metal to improve the European Union's (EU) strategic autonomy. Circular economy practices, such as recycling, are proposed as a means to reduce dependence on external sources. The paper uses scenario modelling to assess the economic and environmental impacts of two enhanced circularity scenarios in the titanium supply chain, using heterogeneous data from interviews, trade statistics, and industry reports.

The first scenario explores reducing the buyback agreements with the United States, which currently limits the EU's ability to retain and process titanium scrap domestically. By retaining this high-quality scrap for internal remelting, the EU could reduce its reliance on sponge imports and increase local production of titanium ingots and milled products, adding up to 20 million euros in value and creating approximately 380 jobs. The reduction of buyback agreements could improve the EU's trade balance in titanium products by 11.5%.

The second scenario focuses on improving the collection and recycling of end-of-life (EoL) aircraft scrap. The current recovery rates for old titanium scrap are low, but by increasing collection efforts, especially for high-grade material from aircraft, the EU could further reduce its titanium imports. However, this scenario's economic impact is modest compared to the first scenario, with only a small increase in recycling activities and minimal effects on employment and value added.

Both scenarios demonstrate that greater circularity in the titanium supply chain could significantly reduce the EU's dependency on external titanium sources, particularly in the aeronautical sector, enhancing strategic autonomy. However, achieving economic viability also requires increased investment in domestic processing capacity and technology. The environmental impact of circularity was also modelled, indicating that while reducing imports and exports might lower greenhouse gas emissions, increased industrial production in Europe could lead to a rise in emissions.

In conclusion, circularity measures in the titanium value chain, especially reducing export dependencies and improving local recycling infrastructure, offer a pathway to boost EU strategic autonomy, albeit with necessary economic and environmental trade-offs. The study emphasizes the importance of aligning these circularity initiatives with broader industrial capacity expansion to maximize benefits.

Can circularity in Titanium metal improve EU strategic autonomy? Scenario modelling with heterogeneous data*

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ABSTRACT

Strategic autonomy can be bolstered by applying circularity strategies such as reducing primary inputs and recycling critical raw materials in key technologies. However, effective actions require high definition at the material or technology level, leading to a non-systematic and often tedious data collection process. This paper extracts information from heterogeneous data sources attaining sufficient detail to conceive circularity scenarios and gauge their potential impact on global supply chains. Using titanium metal in the EU as a showcase, we start by merging qualitative, macroeconomic and micro-level trade information to disaggregate secondary (i.e., titanium scrap) flows depending on their production stage, sector of origin and quality. Subsequently, we design two enhanced circularity scenarios with marked strategic autonomy implications: a reduction of scrap buyback agreements in the EU with the US, and an increase in scrap collection from end-of-life aircraft. Finally, these scenarios are fed into an inter-country input-output model to compute their economic and employment impact. The results of our simulations show that the EU would benefit from valorising secondary titanium flows domestically, most notably if domestic processing capacity is also increased, by up to 20 million euros in value added and around 380 jobs.

Keywords: Circular economy, open strategic autonomy, critical raw material, global value chains, titanium scrap, granular data, input-output.
JEL Codes: Q53, L61, D57.

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1. Introduction

Strategic autonomy is defined as the capacity to implement policies that are not dependent on third countries. In this context, the European Union (EU) has become increasingly aware of the need to decouple from external actors or reshuffle its country partnerships (Miró, 2023; Helwig and Sinkkonen, 2022). Recent global developments have made this necessity more apparent; for instance, the Russian invasion of Ukraine stressed the risks posed by concentrating energy commodity imports in few trade partners.

Access to critical raw materials (CRMs) and technologies has become one major point of debate in the EU. In the last decade, the European Commission worked on addressing these concerns through several initiatives (Gehrke, 2022): a methodology for identifying CRMs along with material lists, foresight studies on critical materials in key technologies (Carrara et al., 2023), and the setup of the European Raw Materials Alliance, gathering stakeholders from critical supply chains. The bulk of this content has recently been consolidated onto the Critical Raw Materials Act, adopted in March 2024. This regulation aims to align the EU's green and digital transition with a sustainable supply of CRMs through import diversification and strategic trade partnerships, reduced administrative burden and enhanced monitoring of strategic supply chains (European Commission, 2023).

A catalyst to enhanced strategic autonomy is the circular economy: reducing primary CRMs inputs by reusing and repairing products, as well as by recycling insofar possible (Ellen MacArthur Foundation, 2013); a consequence is the reduction of import dependencies. European policymakers have long acknowledged the importance of circularity for sustainable development through the Circular Economy Action Plans in 2015 and 2020 (Akgüç and Pochet, 2023; Romanova, 2023), tackling circularity hotspots along the lifecycle of products and technologies. The linkages with strategic autonomy have also been the object of several policy research studies (Mathieux et al., 2017; Baldassarre et al., 2023).

The intersection of circularity and use of CRMs is a fundamental part of the twin (green + digital) transition, as many of the technologies encompassed require heavy use of such materials. Therefore, the demand for CRMs might grow exponentially just as the technologies requiring them as inputs do, and global supply chains may not be ready to cope up with the ramp-up at such speed (Sprejer and Kleijn, 2021). In this vein, while circularity can help satisfy the increasing demand, it is usually a costly strategy at initial stages if the appropriate infrastructure is not in place; substitution by other technologies requiring a smaller amount of CRMs could equally be more expensive (Pommeret et al., 2022). At any rate, applying circularity strategies to critical value chains is a difficult endeavour. Each product or material is subject to a unique set of drivers and barriers to more circularity (Baldassarre et al., 2022); as a result, generating meaningful policy recommendations frequently requires reaching a high level of detail.

In our paper, we explore how merging different information sources can provide a sharp view of one strategic value chain allowing for policy simulations. We illustrate the procedure using the titanium metal global value chain, with a focus on aeronautical applications, owing to its relevance for the European industrial skeleton. We start by presenting our information sources: insights from interviews and industry data, macroeconomic statistics on trade and production, and micro-level datasets from customs agencies. First, we illustrate how to combine all three to gain an accurate picture of the linkages in the value chain, also disaggregating secondary material flows depending on their sectoral origin, quality and production stage. Second, we use the processed information to design circularity scenarios which can be fed onto economic models. Third, we conduct a modelling exercise to gauge the economic and environmental impact of increased circularity and global value chains reconfiguration.

2. The titanium metal value chain

2.1. Overview

We provide an overview of the titanium metal value chain as sketched in Figure 1, based on existing academic and policy studies, namely Buesa et al. (2023), Georgitzikis et al. (2022), or Takeda et al. (2020), among others. The first stage is mining, where titanium-containing minerals are extracted and processed to remove impurities and separate the titanium dioxide (TiO_2) from the other elements. Most of it -around 95%- will be devoted to the manufacturing of whitening pigments. The other 5% will be used in titanium metal manufacturing (USGS, 2023). The next step towards obtaining titanium metal is the Kroll process, which entails chlorinating TiO_2 into titanium tetrachloride ($TiCl_4$), which will then be reduced with magnesium in a vacuum or inert atmosphere. This results in the formation of sponge, which is a porous mass of pure titanium. Out of all the sponge produced, a modest share will be devoted to ferrotitanium, used as a cleansing agent in steelmaking and a lower-end application. The rest will become titanium metal.

Titanium sponge is then remelted in furnaces to produce ingots or powder, usually together with clean scrap from later stages of the value chain as well as alloying elements (e.g., aluminium, vanadium). Ingots are forged, rolled, extruded or machined to reach milled products such as bars, rods, and plates, which constitute the starting point for manufacture of titanium parts. These find their niche in economic activities ranging from the chemical industry to medical applications (International Titanium Association, 2022); a large part is devoted to manufacturing in the aeronautical sector.

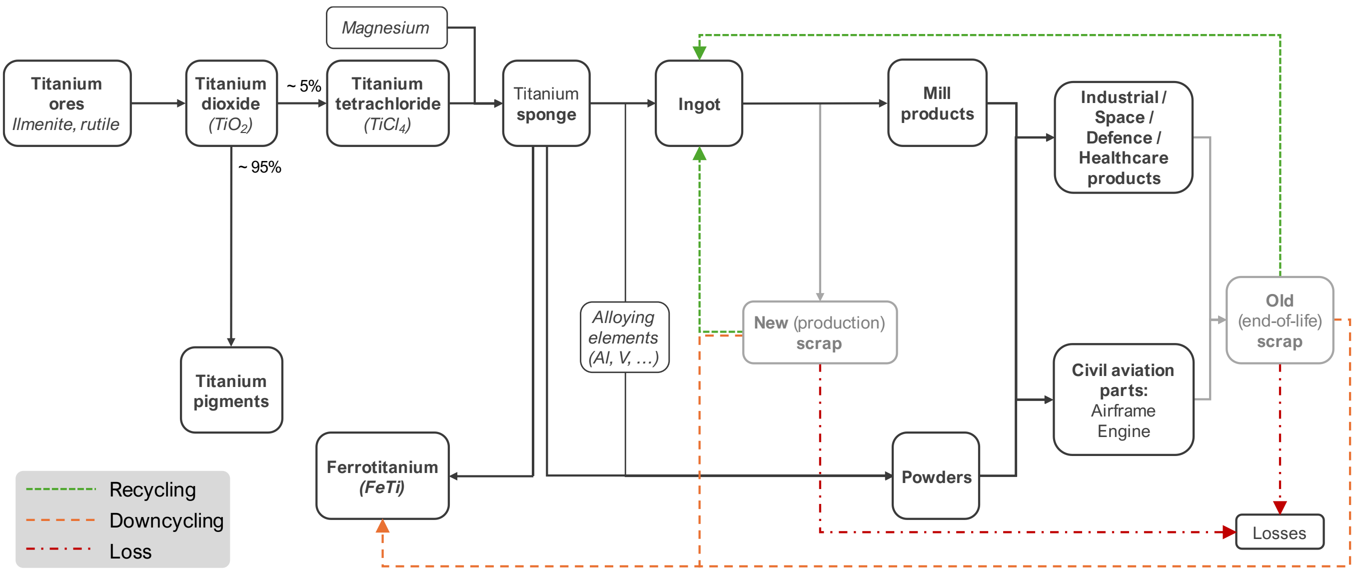

Figure 1. Overview of the value chain for titanium metal. Source: Adapted from Buesa et al. (2023).

Secondary material flows play a fundamental role in this value chain. A significant amount of titanium scrap originates at different stages: *new scrap* refers to the unused titanium metal generated during production; it typically consists of machining scrap, turnings, and other waste. *Old scrap*, on the other hand, comes from end-of-life products, such as aircraft parts that have reached the end of their service life. Crucially, scrap can be remelted together with sponge for ingot production, reducing the amount of primary material needed (Takeda et al., 2020). The percentage of scrap that can used in remelting – the *scrap ratio*- depends on two factors:

- The furnace technology: In conventional ingot fabrication, the maximum ratio is roughly 30%. Newer technologies tolerate up to 75% (Louvigné, 2021).[2]
- The scrap quality: Scrap containing impurities is unsuitable for high-end applications, unless contamination can be removed; it will be lost or down-cycled into ferro-titanium production.

2.2. Titanium in the aeronautical sector

Titanium metal is ubiquitous in civilian and military aeronautical products. For a commercial jetliner, titanium is found in many airframe parts (e.g., pylons, landing gear) and engine components (e.g., blades and disks). Moreover, because of its compatibility with composite materials which are increasingly used, the total share of titanium in the weight of these products has grown steadily in the last decades (Peters et al., 2003)[3].

Due to the stringent shape requirements on many components to minimize weight, titanium alloy parts have a buy-to-fly ratio of 9 to 1, meaning that manufacturing one ton of components generates 8 tons of (new) scrap (Inagaki et al., 2014). When possible, new scrap is cleansed from contaminants and used for remelting. As regards old (end-of-life) scrap, titanium engine components frequently enter a separate re-use loop for such assembly[4], while the remainder in the airframe is processed in different ways: large parts can be cut and downcycled (i.e., recycled into a product of lower value than the original one) into ferro-titanium production; however, only a negligible fraction of scrap from the airframe is used for remelting due to high economic costs or, in some cases, the impossibility to process it.

Looking ahead, two circularity hotspots are visible: On one hand, the high buy-to-fly ratio implies high volumes of new scrap, which will become larger as the titanium content in modern aircraft increases. On the other, as these aircraft reach the end of their lifespan, larger volumes of old scrap will become available. Given that circa 40% of the cost of an aerospace titanium part is the cost of sponge used in ingot fabrication (U.S. Department of Commerce, 2019), component manufacturers will have an increasingly strong incentive to valorise scrap. An additional possibility is Additive Manufacturing (AM) of aircraft parts through powder, thus reducing the buy-to-fly ratio and the material needed. Although the main companies in the sector have started to explore this path, parts and assemblies eligible to be 3D-printed remains strictly confidential; At present, it appears that non-critical parts are candidates to be manufactured through AM, making up for a negligible percentage of total weight. That is why we choose not to explore this option in our paper.

2.3. The EU position

The EU's position in the titanium metal global value chain is not optimal from a strategic autonomy perspective as it lacks domestic reserves of titanium ore, nor does it have any sponge production infrastructure; for ingots, it only accounts for 5% of world capacity. As a result, titanium metal entered the EU's critical raw materials list in 2020, and it remained listed in the 2023 edition (European Commission, 2020b). Aeronautical applications account for 80% of titanium metal consumption in the EU, with a large

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[2] Also, the actual scrap ratio might be lower than its technical limit because cleaning and sorting the scrap could be more costly than purchasing more sponge.

[3] As an illustration, the titanium content in older commercial aircraft like the A320 was around 7%, while new-generation models are closer to 15%. This effect is more pronounced in the defence segment: airframes entering service after 2000 have an average 30% titanium content, as opposed to 9% for legacy models.

[4] Rotating parts of the engine are considered *life-limited* parts (LLPs), which have a known degradation profile, are safety-critical and will be discarded after a certain number of flight hours or cycles. These parts might be re-used but will be discarded at end-of-life, as safety regulations prohibit their recycling.

share of imports concentrated in Russia: At the start of the war in Ukraine, Airbus relied on the Russian conglomerate VSMPO-AVISMA to supply 50% of its titanium needs; in fact, titanium imports were excluded from the European Commission's sanctions to not hamper the EU aeronautical industry (Georgitzikis et al., 2022).

A number of features are apparent when analysing the EU's import and export structures of titanium products sketched in Figure 2 (An overview in value terms is available in Appendix A of Supporting Information S1). First, the largest share of extra-EU imports is wrought products. Second, the latter are considerably diversified from a geographical standpoint. Third, the EU is a net importer of titanium metal products, with an import-to-export ratio of 2:1. Finally, there is a notable asymmetry: scrap makes up for 12.5% of the import mass, against 67% of exports.

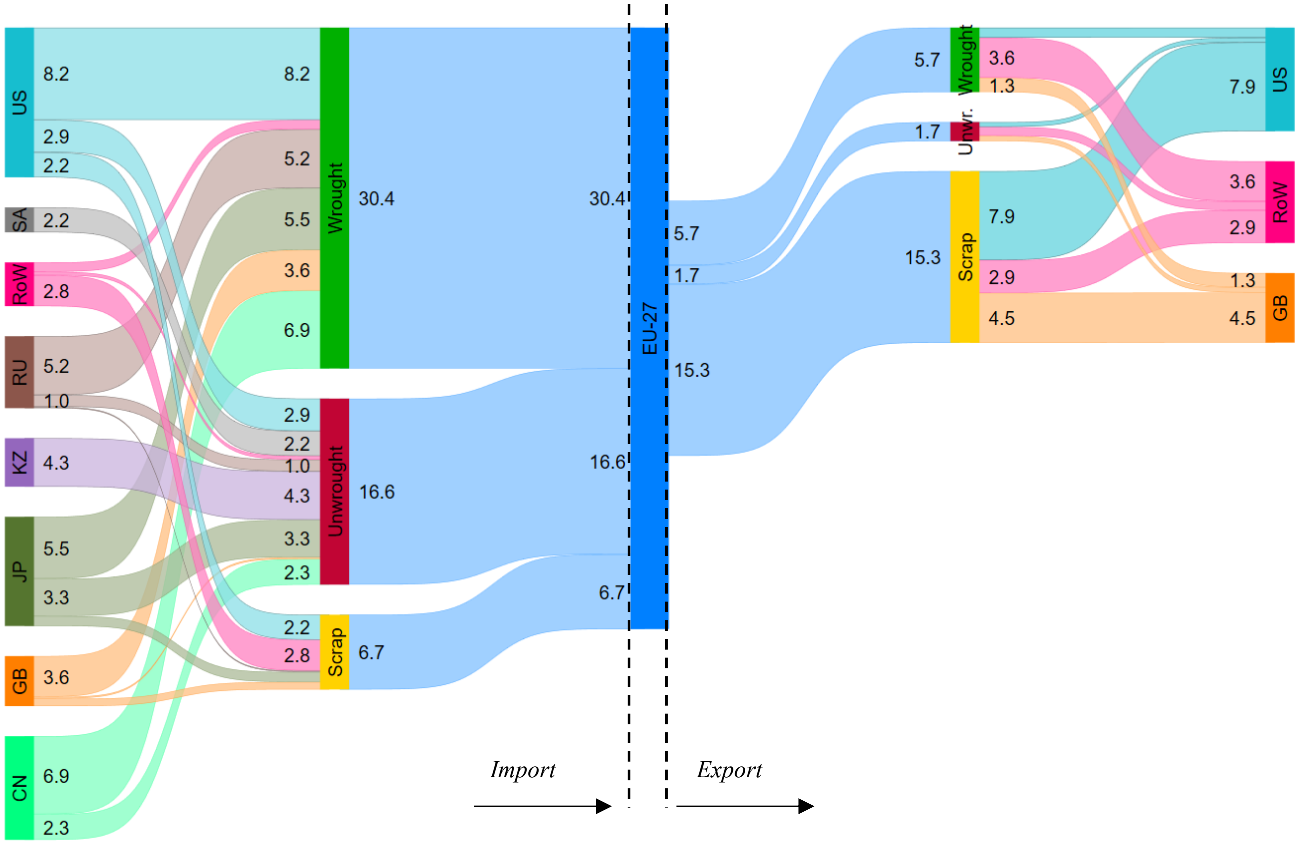

Figure 2. Overview of extra-EU international trade volumes (in kt) of titanium products in 2023. Source: Eurostat dataset "EU trade since 1988 by HS2-4-6 and CN8" (ds-045409).

Why does the EU export so much scrap overseas? The absence of sponge and ingot manufacturing renders valorising scrap less interesting. EU-generated scrap is often subject to *buyback* agreements, whereby third-country suppliers require production scrap to be shipped back for remelting. Most EU scrap is channelled to the US, with strong processing capacity, and the UK, hosting subsidiaries of US suppliers.

Retaining more titanium scrap domestically would reduce import dependencies and enhance the EU's strategic autonomy: buyback agreements could be reverted or discarded in future trades. However, the EU needs to conceive a feasible alternative for scrap use. The two most natural paths are increasing domestic production capacity of titanium products, and circularity initiatives. Circularity already takes place in this value chain though largely outside of the EU, where existing projects are limited in scope and started only in recent times. The aeronautical sector is at a more advanced stage: for instance, an EU-funded project in France aims to process old aviation scrap to be remelted onto aero-grade ingot (Georgitzikis et al., 2022).

3. Data sources

The study of strategic autonomy requires understanding international economic linkages with third countries, which might influence domestic policymaking. These can take the form of foreign investment or linkages in trade of goods and services. Applying circular economy strategies can mitigate dependencies; however, these strategies require accurate information on specific products and technologies to identify circularity hotspots, as well as relevant drivers and barriers. It may also occur that both fields intersect, as illustrated by the fact that circularity in titanium metal takes place mostly outside the EU realm. The required information on both fields is often spread between different sources of heterogeneous forms and content.

In this section, we describe how to combine data sources towards an accurate understanding of the titanium metal global value chain, with a particular emphasis on its circularity and strategic dependencies. These insights will later be used to build policy scenarios and impact simulations. We will concentrate on titanium scrap in the aeronautical sector: therefore, we need as much information as possible on scrap flows from three different angles:

- Its *value chain* origin (new/production vs. old/end-of-life)
- Its *sectoral* origin (aeronautical vs. non-aeronautical)
- Its *quality* (vacuum grade vs. subprime grade downcycled for ferrotitanium production)

We will use three information sources: qualitative information from industry reports and stakeholder interviews, quantitative data at the macro (country) level from international trade and production statistics, and quantitative microdata from customs agencies. We choose to present them in that order to render the narrative easier to follow: qualitative and non-systematic data first as its content is fundamental to identify drivers and barriers to circularity, upon which the circularity scenarios described in Section 4 will build. As a second step, we introduce macroeconomic data as it is readily available and with widespread usage, and finally we illustrate how its limitations can be partially overcome by using micro-level customs information: the two quantitative sources are the cornerstones of scenario calibration. Also, this ordering facilitates understanding the complementarity between all three sources, and although they should all be combined when extrapolating the procedure to products or materials other than titanium metal, it need not be the case that it is optimal to analyse them in the same order.

3.1. Qualitative and non-systematic data

We scanned the information recovered from a consultation of selected stakeholders (Baldassarre, 2024) covering all parts of the value chain inside and outside the EU, which allowed us to identify drivers and barriers to titanium circularity in Europe. We cross-validated these findings using proprietary, non-systematic industry data from reports or presentations, understood as any quantitative data point extracted from granular sources within which data dissemination is not the main objective. The main outputs from this phase are summarized in Table 1. The main drawbacks of this dataset are possible geographical or judgement biases at collection, and the issue of industrial confidentiality, which might force participants to withhold facts and figures to external actors.

Titanium metal value chain		
Sectoral distribution of titanium consumption in Europe (2019)	*Commercial aerospace: 70%* *Industrial applications: 26%*	*Defence: 3%* *Consumption goods: 1%*
Aero-grade sponge in global production	*43%* (2021)	
Aero-grade ingot in global production	*54%* (2019)	
Titanium scrap		
Global scrap availability forecast	*Index for 2021- 2025: 1.00 - 1.35 - 1.40 - 1.60 - 1.85*	
% scrap (new + old) downcycled for FeTi	*27%*	
% world scrap supply eligible for remelting	*54% - 56%*	
EoL aero scrap w.r.t. new scrap in ingot production	*Negligible (interviews), 25% (literature)*	
Scrap flow between sectors	*Negligible*	
Consumption areas of scrap in the US (2017)	*84% Ti industry and superalloy (recyclable)* *14% Steel industry (downcycled)* *2% Other*	
Titanium scrap: Recyclable-to-loss ratio	*New (Manufacture of wrought products from ingot): 5:1* *New(Manufacture of aero parts from wrought products): 2:1* *Old (end-of-life): 1:5*	
Destination of scrap in different value chain stages	*- New (manufacturing of milled products from ingot):* *60% recyclable, 16% downcycled, 24% lost* *- New (manufacturing of parts from milled products):* *61% recyclable, 18% downcycled, 21% lost* *- Old (end-of-life): 40% recyclable, 46% downcycled, 15% lost*	
Titanium scrap: Recyclable-to-loss ratio	*New (Manufacture of wrought products from ingot): 5:1* *New(Manufacture of aero parts from wrought products): 2:1* *Old (end-of-life): 1:5*	
Aeronautical sector		
Titanium consumption in the EU	*Index for 2022 - 2023 - 2025: 1.0 - 1.0 - 1.5*	
Buy-to-fly ratio for Ti alloy components	*9:1 - 7:1 (aero), 5:1 - 4:1 (other)*	
Destination of new scrap from aero in the EU	*Most of it shipped to the US for processing*	
Market share of new-gen airliners	*20% in 2021, 95% in 2041*	
Ti content in civil aircraft (forecast)	*12% (narrow-body), 15% (wide-body) in 2040*	
Ti alloy content in commercial aircraft	*A320: 3% (struct), 7.2% (total)* *A350: 15% (struct), 14% (total)* *A330-340: 7% (struct), 36% (engine)*	*B747: 3-4% (total, old), 5% (struct)* *B777: 8.5% (1994)* *B787: 18% (struct), 15% (total)*
Weight distribution in a commercial aircraft	*Fuselage: 30-35% vs 21%* *Landing gear: 5-10% vs. 10%* *Avionics and systems: 5-10% vs. 8%* *Furnishings: 14%*	*Wings: 20-25% vs 27%* *Tail section: 10-15% vs. 3.6%* *Engine: 15-20% vs 17%*
Ti alloy content in aircraft engines	*20 - 30%*	
% engines in Ti alloy parts in commercial aircraft	*60 - 70% (interview), 20 - 42% (computed from other sources)*	

In addition to insights obtained from the stakeholder consultation in Buesa et al. (2023), the main sources for this table are: For the titanium metal value chain, Georgitzikis et al. (2022), Louvigné (2021), and Takeda et al. (2020) ; for the scrap figures, Feng et al. (2023), Inagaki et al. (2014), International Titanium Association (2022), Takeda et al. (2020), and Wang and Wu (2023). Lastly, most data on the aeronautical sector was extracted from Al-Shamma and Ali (2013), Inagaki et al. (2014), Louvigné (2021), Peters et al. (2003), and Uhlmann et al. (2015).

Table 1. Qualitative and non-systematic data on titanium metal and aeronautical applications.

3.2. Quantitative data: macro

International trade and production statistics are the starting point to study material dependencies between countries. However, aggregate statistics have several downsides: firstly, they do not account for re-exports, that is, goods in transit to their final destination, which can distort the real origin and destination of goods. Secondly, they fail to capture the underlying production networks, or value added at each stage of the value chain, merely providing a static picture where trade codes for the different goods "float" with no linkages. The titanium value chain in the EU from the standpoint of macro-level statistics is shown in Figure 3. Noticeably, unwrought products are not disaggregated into ingot and sponge. More importantly, there is no detail on the flows in terms of scrap quality, the sector of origin, or the stage of the value chain at which it is generated. Therefore, macroeconomic data needs to be enriched with other compatible sources.

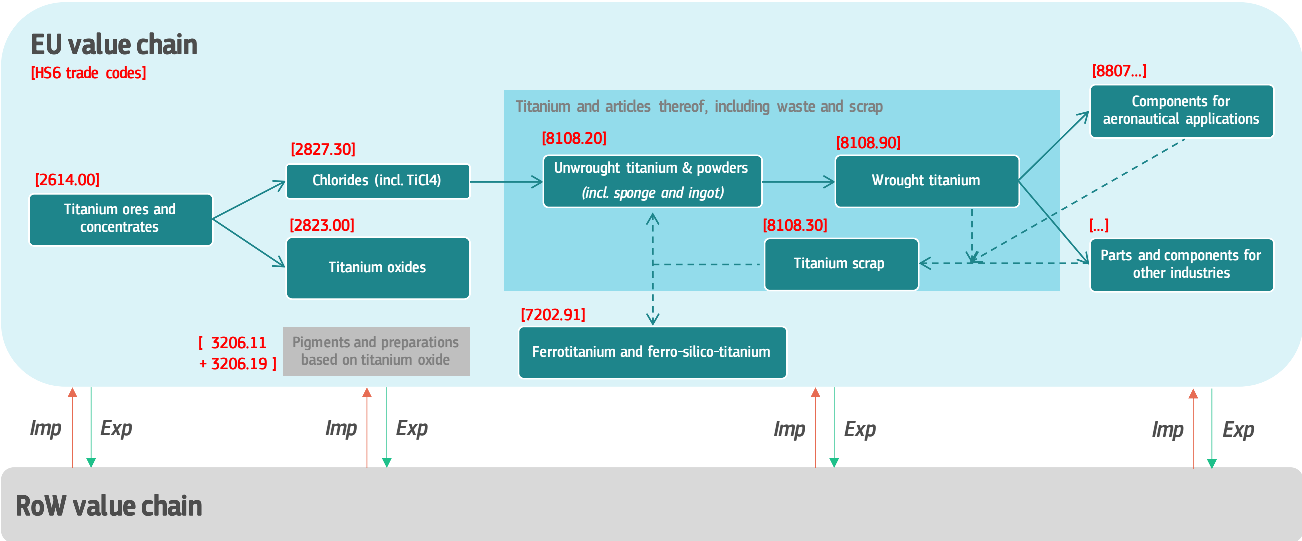

Figure 3. Titanium value chain as viewed from international trade data. Arrowed lines represent theoretical primary (continuous line) and secondary (dashed line) product flows. Source: Authors' elaboration from Eurostat dataset "EU trade since 1988 by HS2-4-6 and CN8" (ds-045409).

3.3. Quantitative data: micro

The most suitable complement to aggregate trade statistics is micro-level data from customs agencies. Country figures are usually constructed from customs data, which is however not widely available because of data protection issues or restrictive dissemination policies; at best, private third-party data providers buy the right to incorporate these statistics to their databases. The main advantage of customs data is that it provides information on each individual shipment. This level of detail allows for a more nuanced understanding of flows between sectors. For our exercise, there are many useful features:

- The description of the contents, which allows to identify scrap types.
- Shipper/consignee firm names facilitate the sectorial (e.g., aeronautical) mapping of scrap.
- Shipments containing multiple goods (e.g., titanium scrap together with other metals) can be informative about scrap quality.

We use a sample of circa 100,000 shipments of titanium products in the period 2018-22 obtained from S&P Panjiva[5]. An extensive data cleaning and imputation process allows us to recover information from shipments with missing fields; the details are given in Appendix B of Supporting Information S1. Subsequently, we extract shares of the most notable scrap flows according to the sector of origin, quality, and type of scrap; the results are shown in Figure 4.

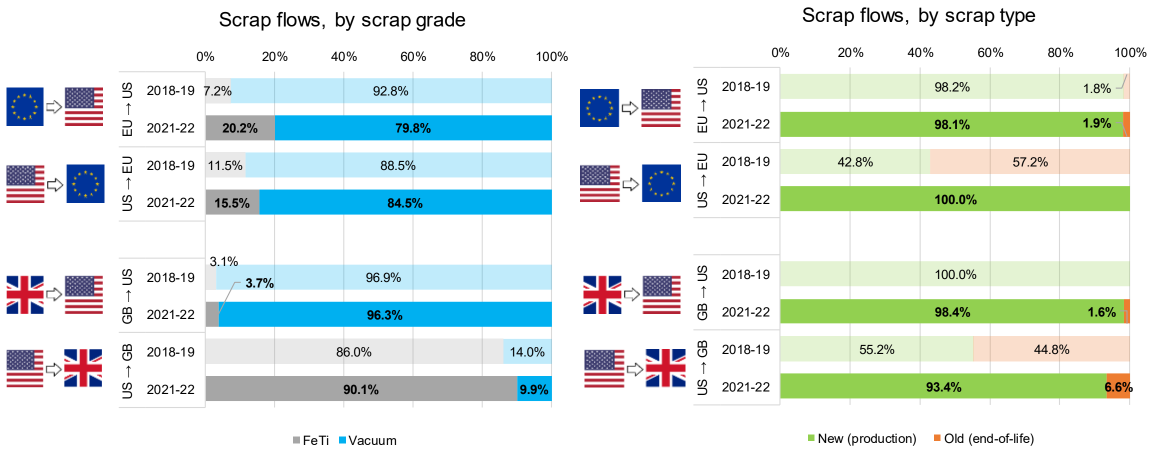

Figure 4. Disaggregation of titanium scrap trade flows using shipment-level information. Source: Authors' calculations using the customs dataset extracted from S&P Panjiva.

From a scrap quality standpoint, the EU and the UK send mostly vacuum scrap to the US, while the US ships a larger amount of ferrotitanium-grade scrap to Europe. Over time, however, the EU seems to have reduced the amount of vacuum scrap shored to the US; one possible explanation is the advancement of domestic recycling initiatives. Similarly, from a scrap type perspective, Europe almost exclusively sends new (production) scrap to the US, likely because it is not valorised domestically. Remarkably, the US *used to* send back a larger share old (end-of-life) scrap in the past but seems to retain it in recent times; this can be a signal of developing capacity for end-of-life scrap use. Although the relative size of mass trade is not visible in Figure 4, flows *to* the US are much larger than flows *from* the US (see Figure 2).

Customs-level data is also subject to several limitations: First, not all countries provide shipment-level data, and even among those that do, data may not cover all trade flows. This can lead to incomplete or biased estimates. Second, some countries may restrict data availability for some goods due to concerns about confidentiality or national security; this might be the case for titanium metal, especially on the defence segment. Third, data processing by third parties might introduce misclassification and measurement errors.

4. Methods

4.1. Circularity scenario design

Our study depicts two scenarios of enhanced circularity and global value chain reconfiguration for titanium in the EU: a reduction in buyback agreements with the US that results in higher retention rates of high-quality scrap in the EU, and an improvement in the collection of old (end-of-life) scrap from aeronautical applications suitable for remelting into primary material. The following paragraphs provide a stylized overview, while the full details are available in Appendix C of Supplementary Information S1.

[5] Panjiva aggregates customs datasets from 17 countries accounting for 40% of global merchandise trade.

Scenario #1: Reduction in buyback agreements for titanium scrap with the US

We concentrate on scrap flows from and to the United States, which constitute the largest share of extra-EU trade in scrap (see Figure 2). Second to it is trade with the UK, where many US subsidiaries are located. However, computing indirect flows passing through the UK would unnecessarily increase uncertainty as public UK trade data is much less disaggregated.

In the first step, the EU retains vacuum-grade aeronautical titanium scrap subject to buyback agreements instead of sending it to the US, resulting in a reduction in exports with the latter. Our calculations show that approximately 83% of scrap flows to the US in value terms (roughly 5.8 kt in mass) are vacuum-grade and likely subject to buyback agreements. In the second step, were the EU to retain scrap domestically, it is reasonable to assume that scrap imports would shrink. Vacuum grade aeronautical scrap constitutes circa 79% of US imports in value.

Next, we want to know what happens if the EU uses the scrap retained from buyback agreements to manufacture aeronautical ingot. To that end, we quantify how less scrap dependencies might affect trade in unwrought titanium (sponge, ingot and powder). Using a 60% scrap ratio for remelting, in the lower/conservative end of estimates for new procedures, the maximum volume of ingot that could be produced with the additional scrap retained is 9.65 kt. This would require importing the remaining 40% of the mass in sponge, that is, 9.7 - 5.8 = 3.9 kt. Because of the war in Ukraine, it is reasonable to assume that priority will be given to decoupling from Russia: hence, this effect will be mapped as an increase in imports of unwrought titanium from Japan and Kazakhstan, the other two countries with qualified producers of aeronautical-grade sponge.

However, ingot production capacity is about one third below melting capacity as multiple remelting can take place to remove impurities; therefore, melting 9.7 kt will result in approximately 6.4 kt of ingots produced in the EU, which could no longer be sourced from abroad. We map this effect by reducing the value of ingot import flows proportionally to the share of each trade partner (China, Russia, Kazakhstan, and the United States). An open question remains whether the EU can produce this additional volume of ingot annually. According to the latest available figures, EU ingot production is close to 5 kt with maximum capacity in the range of 8 to 12 kt (Marscheider-Weidemann et al., 2021): a ramp-up to 11.4kt appears reasonable.

The additional 6.4 kt of ingot produced would translate into milled products at a ratio of 3:2 (Wang and Wu, 2023), resulting in 4.3 kt which would in turn become finished titanium products at a ratio of 2:1, that is, 2.15 kt. The EU could stop importing that quantity from abroad: if decoupling from the US were the preferred alternative, a 26% fall in the value of import flows is to be expected. Finally, could the EU produce this quantity? The latest production statistics for 2022 yield 24.7 kt, concentrated in France, Italy, and Germany. We assume that the additional 2.15 kt from this step are a manageable ramp-up and introduce a positive shock to titanium production activities in the latter three countries.

Figure 5 summarizes the steps involved in the construction of our scenario, as well as the direct effects of Steps 1 to 4 in the EU trade balance for titanium (wrought, unwrought, and scrap). In value terms, the EU is a net importer. The aforementioned steps can have a beneficial effect on the trade balance (reduction of imports) or a detrimental one (reduction of exports). Overall, the net effect of Scenario 1 is positive as it reduces the trade deficit of the EU by 11.5%.

International trade in titanium *(HS6 code)*				Production of Ti products (CPA code 24.45.30.42)
Scrap (8108.30)	*Unwrought (8108.20)*		*Wrought (8108.90)*	
Step 1: **-83.1%** US exports **Step 2:** -**79.2%** US imports	**Step 3a** (+ sponge**):** **+33.0%** KZ imports **+41.5%** JP imports	**Step 3b** (- ingot**):** **-52.4%** CN imports **-41.5%** KZ imports **-95.1%** RU imports **-48.2%** US imports	**Step 4:** **-26%** US imports	**Step 5:** **+20.2%** in FR, IT, DE

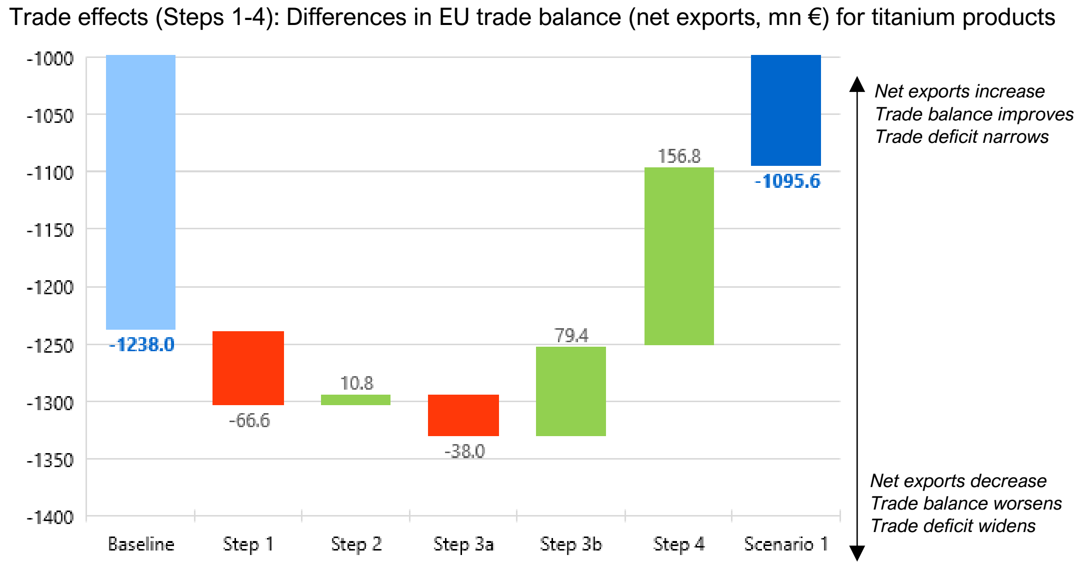

Figure 5. Summary of Scenario 1 effects on EU international trade and production. Source: Authors' calculations based on Eurostat dataset ds-045409.

Scenario #2: Increased collection of aero end-of-life scrap suitable for remelting

In our second scenario, we will estimate the amount of post-consumer scrap that could be recovered from decommissioned commercial aircraft and remelted into ingot after processing. The first step is to model the *status quo*: how much scrap is available with current retirement flows and collection rates.

We start our definition at the aircraft level, relying on model-specific data from Uhlmann et al. (2015) and Al-Shamma and Ali (2013) such as the number of retired aircraft per year, the geographical distribution of decommissioned planes, and the weight and titanium content in each model. The full details are available in Appendix C of Supplementary Information S1. We also assume that titanium in the airframe becomes scrap because recertification procedures make it impossible to re-use it, whereas engine components may become spare parts. Finally, our estimate is that only 40% of all the available titanium in the airframe at end of life remains eligible for remelting. Under these conditions, a total of 0.24 kt of aircraft post-consumer scrap are ready to enter the remelting loop in the EU. This constitutes a small amount which will not be subject to buyback agreements, nor will it impact the size of the titanium recycling industry. Our choice is to link the modest increase in domestic titanium scrap as a reduction in scrap imports from the US.

Alternatively, we design an enhanced circularity case with elements from the future: a greater number of decommissioned aircraft based on market forecasts, a larger share of titanium in their airframe, and a higher recovery rate of old scrap. In this case, 1.31 kt of scrap will be available for ingot manufacturing loop, five times as much as in the baseline, translating into a 45.3% reduction in US scrap imports. Additionally, as the volumes of available post-consumer scrap are larger, we also increase the relevance of titanium recycling activities in the EU (+15.2%), proportionally distributed in those Member States where the lion's share of metal recovery takes place. Figure 6 depicts the direct effect of our second scenario. The *status quo* (resp. enhanced) alternative would entail a 0.11% (0.50%) reduction in the trade deficit, considerably smaller in magnitude than Scenario 1.

Stock of scrap ready for remelting in the EU	**Trade of titanium scrap (HS6 code 8108.30)**	**Value added of titanium recycling activities**
Status quo **+ 0.24 kt** available	**Step 1:** **-10.7%** US imports	**No change,** additional scrap processed w/ existing infrastructure.
Enhanced circularity **+ 1.31 kt** available	**Step 1:** **-45.3%** US imports	**Step 2:** **+15.23%** in FR, IT, DE

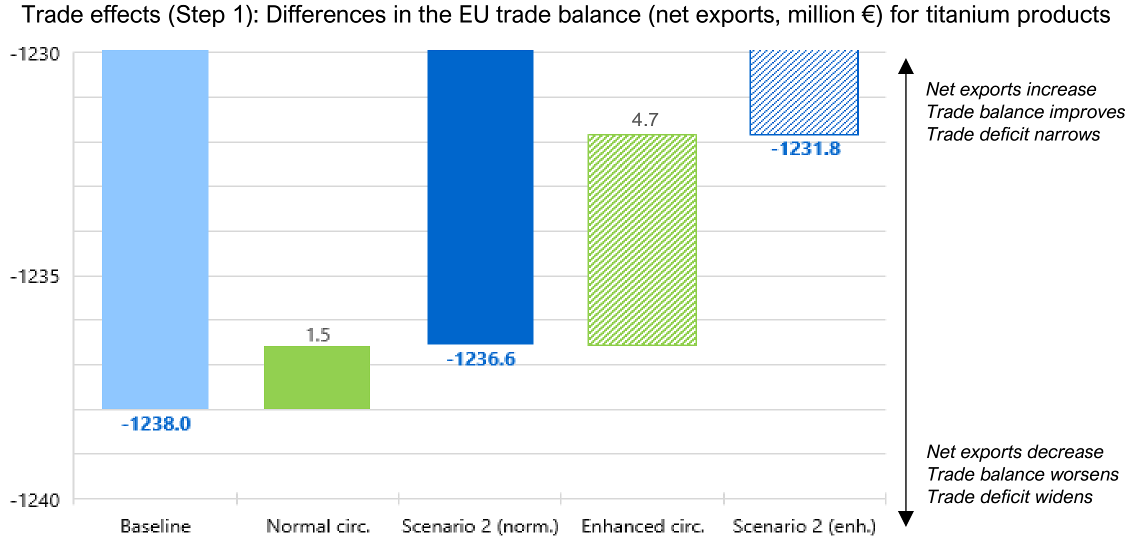

Figure 6. Summary of Scenario 2 effects on EU international trade and production. Source: Authors' calculations based on Eurostat dataset ds-045409.

4.2. The modelling framework: the FIGARO input-output model

We will evaluate the potential impact of our circularity scenarios using the EU Inter-Country Supply, Use and Input-Output Tables (EU IC-SUIOTs), also called the FIGARO (*Full International and Global Accounts for Research in Input-Output analyses*) database (Remond-Tiedrez and Rueda-Cantuche, 2019). Since 2022, FIGARO tables are published as official statistics by Eurostat, linking national Supply, Use and Input-Output data with National Accounts main aggregates, and international trade statistics for the EU Member States and its trading partners.[6]

However, product and industry resolutions in the FIGARO tables are too low for assessing the impacts of our scenarios on the global titanium metal value chain; therefore, a more granular input-output system needs to be developed. We employed the FIGARO-E3 experimental dataset[7] (Usubiaga et al., 2023) that extends the FIGARO coverage to 213 products and 176 industries for the year 2015, including employment

[6] Argentina, Australia, Brazil, Canada, China, India, Indonesia, Japan, South Korea, Mexico, Norway, Russia, Saudi Arabia, South Africa, Switzerland, Türkiye, the UK, and the US, along with a 'rest of the world' (RoW) region.

[7] FIGARO-E3 is available at the Join Research Centre Data Catalogue.

data in number of workers, and climate change emissions in CO_2 equivalents (CO_2e). This database was the starting point of a specific model for tracing flows of titanium and aeronautical products along global value chains (see Annex C).

The exercise can be divided into two steps. First, we estimate the negative impact on production of cutting off trade with non-EU countries, via exports and/or imports of related titanium products. For such purpose, we use the hypothetical extraction method (HEM) to carry out partial extractions according to the qualitative and quantitative data. This methodology was originally proposed by Paelinck (1965), reviewed thoroughly in Miller and Lahr (2001), and extended in Dietzenbacher et al. (2019) to the global economy.

Secondly, we increase the EU production capacity of related titanium products according to the same qualitative and quantitative information, thus obtaining new positive effects in the EU after applying bi-proportional adjustment methods to re-balance supply, demand and trade of the global economy. We use the balancing method recommended by United Nations (2018), namely GRAS (Günlük-Senesen and Bates, 1988; Junius and Oosterhaven, 2003; and Temursho et al., 2013). As a result, we obtain a new set of inter-country input-output tables with which we re-estimate value added, employment and CO_2e multipliers (Miller and Blair, 2009) that are eventually compared (in levels) with those of the original inter-country input-output database (baseline), as described in Eq. 1 (see Annex C for details on the economic interpretation):

$$\boldsymbol{\alpha} = \mathbf{v}\bar{\mathbf{L}}\mathbf{f} - \mathbf{v}\mathbf{L}\mathbf{f} = \mathbf{v}(\bar{\mathbf{L}} - \mathbf{L})\mathbf{f} \qquad (1)$$

In Equation (1), $\mathbf{v}$ is a row vector of the value added (also employment or CO_2 equivalent) per unit of sectoral output, $\mathbf{L}$ is the Leontief inverse matrix and $\mathbf{f}$ is a column vector of the demand of goods and services for final use (final demand), including gross exports to the rest of the world. Effects of the circularity policies are modelled endogenously in the Leontief inverse, denoted by $\bar{\mathbf{L}}$. As a result, $\boldsymbol{\alpha}$ indicates changes in value added and employment by Member State in each step and scenario, which can be negative (HEM) or positive (rebalanced inter-country input-output tables).

5. Results

We present the results of our input-output exercise for the reduction in EU buyback agreements for titanium scrap with the US in Table 2. Starting with Scenario 1, the most significant impact from the EU perspective on international trade comes from Step 1. The reduction in scrap exports to the US results in a decrease in value added of around seven million euros and the loss of approximately 120 jobs; less exports lead to a natural deterioration in the trade balance (i.e., a decrease in net exports; see Figure 5) which mathematically decreases total output. Conversely, the reduction in scrap imports also yields a negative economic impact, though of a much smaller order of magnitude (a mere 100,000 euros) and through a different channel: to the eyes of our input-output infrastructure, reducing imports can be understood system-wise as a moderation of economic activity. The smaller impact compared to the first step is reasonable, as imports of scrap are notably smaller than exports in volume and value, and because the focus is on the impact in the EU and not the US.

Steps 3a and 3b cover the rise in sponge imports and the reduction in ingot brought from outside the EU. Similarly to Step 2, importing more (3a) has a marginally positive net effect (almost 1 million euros and 13 full-time equivalents) due to compensation effects related to upstream interlinkages, when EU industries produce inputs for titanium goods produced elsewhere. The last trade effect originates in Step 4 from the reduction in imports of wrought titanium, which is also negligible like Step 2. The final step of the scenario depicts how the larger domestic supply of scrap affects the metal manufacturing industry, increasing its production capacity and propagating to the rest of the economy through sectorial linkages. This latter effect is positive, at around 20 million euros and nearly 380 jobs along the whole supply chain with respect to the baseline, accounting for approximately 54,000 euros worth of value added per worker/year.

From an environmental standpoint, certain trends are anticipated, as a decrease in trade is likely to have a positive effect by reducing greenhouse gas (GHG) emissions, while an increase in trade flows or domestic production is expected to result in higher emissions. This anticipation is grounded in the principle that reduced economic activity generally leads to a decrease in total emissions. Table 1 shows that Step 1 reduces GHG emissions by 6.5 CO_2 equivalent kilotons, whereas Step 3(a) (resp. b) increase (decrease) emissions by 0.4 kilotons. Finally, Step 5 implies more industrial production in the metallurgical sector, leading to an increase in GHG emissions larger in magnitude that any preceding step: 16.4 CO_2e kilotonnes more than the baseline.

In contrast, Scenario 2 focuses on increasing the collection of aeronautical end-of-life scrap suitable for remelting, highlighting the economic potential of recycling activities within the EU. The *status quo* alternative, where existing flows of decommissioned aircraft are used to recover scrap at a modest collection rate, does not have a visible impact. Better scrap collection rates and entrant flows of aircraft with a higher titanium content, as in our enhanced case, might increase this figure by a factor of 4, but the economic and environmental effect remains negligible; the potential push in titanium recycling activities (Step 2) yields a rise in value added of around 100,000 euros, and a surge in emissions of about 0.1 CO_2 equivalent kilotons. Employment would remain virtually unchanged.

Scenario #1: Reduction in EU buyback agreements for titanium scrap with the US						
	Value added (mn €)	*(marg.)*	Employment (# workers)	*(marg.)*	GHG emissions (CO_2e kt)	*(marg.)*
Step 1 (↓ US exports)	-7.3		-119.8		-6.5	
Step 1 to 2 (↓ US imports)	-7.4	*-0.1*	-120.9	*-1.1*	-6.5	*0.0*
Step 1 to 3a (↑ KZ, JP sponge imports)	-6.5	*+0.9*	-107.5	*+13.4*	-6.1	*+0.4*
Step 1 to 3b (↓ US, CN, KZ, RU ingot imports)	-7.6	*-1.1*	-124.8	*-17.4*	-6.5	*-0.4*
Step 1 to 4 (↓ US imports)	-7.7	*-0.1*	-126.4	*-1.6*	-6.5	*0.0*
Step 1 to 5 (↑FR, IT, DE production)	20.4	*+28.1*	377.1	*+496.9*	16.4	*+22.9*

Scenario #2: Increased collection of aeronautical end-of-life scrap suitable for remelting			
	Value added (mn €)	Employment (# workers)	GHG emissions (CO_2e kt)
Status quo			
Step 1 (↓ imports from the US)	-0.0012	0.0	-0.0004
Enhanced circularity			
Step 1 (↓ imports from the US)	-0.0052	-0.1	-0.0019
Step 1 to 2 (↑ recycling activities in the EU)	0.1015	0.2	0.113

Table 2. EU-wide effect of scenarios #1 and #2 on value added, employment, and emissions.

6. Discussion

Our paper attempts to reconcile heterogeneous data sources and render them usable for policy simulation purposes in a systematic and fashion, ideally allowing for replication with other strategic materials and technologies; the case of titanium metal is particularly relevant because of its strategic nature for the EU and the large circularity potential, especially on the recycling front.

We have followed the exploratory work by Buesa et al. (2023); to the best of our knowledge, the latter is the first study of its kind. Within material flow analyses, the focus has been on constructing future demand scenarios at the product/technology level, with no associated impact evaluation (Carrara et al., 2023). For titanium metal, a limited number of studies discuss recycling (Takeda et al., 2020; Feng and Wang, 2023), and they constitute valuable sources of non-systematic data for our study. Besides, Wang and Wu (2023) map titanium scrap flows in China, albeit without sectorial detail and not considering the end-of-life stage. All in all, titanium circularity has not been investigated in depth, partly due to limited data availability and lack of disclosure by major industry actors (US Dept. of Commerce, 2016).

To understand the plausibility of our scenarios, we work backwards and benchmark the economic impacts described above with actual data for the EU titanium industry. Starting with Scenario 1, we extract company information[8] for the three largest EU manufacturers of titanium ingot in the EU in 2022: Timet Savoie in France, TiFast in Italy, and Zirom in Romania. Overall, these companies hold total assets valued at almost 175 million euros (120, 42, and 12, respectively) and employ 360 workers (120 each, approximately). Were the last step of Scenario 1 to materialize, the EU economy would add 377 workers to the titanium supply chain, including direct and indirect contributions from suppliers, and 20 million euros to its total output. Putting both dimensions together implies that eliminating buyback agreements could double the employment in the titanium economy at the EU level; the positive impact in value added is close to the total assets of an existing medium-sized titanium factory.

As for Scenario 2, our results hint at a very modest sectorial gain from additional scrap recycled, but the existing infrastructure suffices to cope with the increased flows in any case and does not require additional labour or capital expenditure. Company information confirms this intuition: The French EcoTitanium recycling plant employs 40 workers, and its total assets amount to 30 million euros, and both metrics are considerably larger than the impacts from our exercise.

Regarding environmental impacts, we resort to emissions accounts by economic activity from Eurostat (dataset *env_ac_ainah_r2*) and extract actual figures to compare against. Combining EU GHG emissions from the metal manufacturing sector (C24) with the share of titanium metal production within C24, we estimate 14.4 CO_2 equivalent tonnes emitted in 2022. Steps 1 to 4 in Scenario 1 would result in a reduction comparable to a 45% cut in GHG emissions from that figure, while the last step would double them (+114%). In addition, interpreting the results for Steps 1 to 4 requires recalling that over 90 percent of global trade in titanium takes place through maritime transportation. Therefore, any reduction in imports or exports will lead to a decrease in CO_2 emissions as shipping companies will transport less cargo. Additionally, the magnitude of the changes in emissions will be proportional to the *mass* (not the value) traded, which is proportional to cargo volume; as depicted in Figure 2 and developed in the scenario description, the bulk of mass changes takes place in Step 1 (less scrap exported), and to a large extent in Step 3a (less wrought

[8] Extracted from the ORBIS database.

imports) and Step 3b (more unwrought imports). For Scenario 2, no data is available at the required disaggregation to benchmark emissions.

6.1. Policy implications

There are two noteworthy lessons to draw from a policy standpoint. On one hand, while circularity measures can cause drastic changes in the titanium metal global value chain, and contribute to bolstering strategic autonomy, relying solely on trade effects may not suffice to ensure economic viability. A substantial ramp-up in production capacity is also necessary to ensure that the net effect of hypothetical scenarios is positive in employment and output terms. On the other hand, despite yielding much smaller economic benefits in our setup compared to ending buyback agreements, increasing end-of-life collection of titanium scrap in the aeronautical sector may offer smoother navigation from an international relations standpoint: This consideration is particularly salient given historical precedents, such as the imposition of tariffs on aluminium by the US in response to perceived trade imbalances (Jakimow et al., 2024).

Finally, our combination of data sources including stakeholder insights reiterates that, in order to enhance the credibility and effectiveness of any policy action, data disclosure or validation from industry actors is essential. It allows policymakers to make more informed decisions on the amount, distribution and form of any public support mechanisms such as industry subsidies or R&I funding opportunities.

6.2. Limitations and future research

Merging data sources that do not necessarily share the same structure, depth, or geographical coverage is subject to a degree of uncertainty. First, as detailed in Appendix B of Supplementary Information S1, the total flows of titanium scrap computed from customs-level information do not perfectly match macroeconomic statistics. Aside from re-exports, the most likely explanation for this discrepancy is the existence of shipments containing several goods, which is not fully accounted for in our methodology when computing the totals, and the more limited geographical coverage of the micro-level dataset (see footnote 3).

Second, the inter-country input-output database FIGARO-E3 is based on data from 2015. Any deviations between that year and any other are not considered, and the impact of this assumption was not evaluated. Third, as explained in Appendix D of Supplementary Information S1, FIGARO-E3 is based on official statistics disaggregated using the input structure of the EXIOBASE database (Stadler et al., 2018). Aggregating EXIOBASE to official FIGARO does not yield the same figures, and deviations are noticeable (Cazcarro et al., under review). Therefore, despite the known differences between both input-output databases, the input structure of one was employed for disaggregating the other. In conclusion, the twofold disaggregation from FIGARO at a 64-product level to FIGARO-E3 of 213 products using EXIOBASE, and further extended to FIGARO-E3 for the titanium economy, is an important source of uncertainty. These factors should be considered when interpreting our results.

Fourth, CO_2 emission figures were included as supplementary data for the value added and employment estimates, to demonstrate that trade policies can also affect climate goals. However, it is important to note that the comparison with the EU metal industry discussed above was based on industry averages, which may not accurately represent the titanium industry. Furthermore, modelling CO_2 emissions using input-output analysis introduces new sources of bias due to the integration of physical data from national inventories into the input-output framework (Tukker et al., 2020).

Finally, we have some doubts concerning how accurately recycling activities are represented in national accounts, and whether there is a risk of misclassification. For example, in NACE Revision 2, division C24 encompasses smelting and/or refining metals from scrap, while E38 includes materials recovery but not the manufacture of new final products from secondary raw materials, such as the production of metal from scrap, which we believe should be included in C24. Additionally, scenario 2 includes sewerage (div. 37) and remediation activities (div. 39), which could potentially lead to a certain aggregation bias.

7. Conclusions

Strategic autonomy from an EU standpoint can be facilitated by fostering circularity strategies in strategic value chains. Our paper attempts to systematise the procedure to evaluate the potential of greater circularity in mitigating dependencies from third countries. To this end, we use the supply chain of titanium with a focus in aeronautical applications. We show how reconciling non-systematic -sometimes qualitative- insights and structured data sources can succeed in mapping production and trade flows beyond the usual disaggregation level; for instance, we obtain higher definition on how secondary raw materials circulate within the value chain. As a next step, we create hypothetical economic scenarios of enhanced circularity from the combined data. Finally, using input-output modelling we show that these scenarios are easily translatable into inputs for analytical frameworks, allowing us to evaluate the potential impact of greater circularity in economic and environmental terms.

The results of our simulations show how the impact of greater circularity in critical value chains can be significant and positive for the EU, boosting employment and value added. However, while reducing dependencies by curtailing trade alone might enhance strategic autonomy, it will not suffice to render circularity economically viable; a ramp-up in domestic infrastructure at the EU level is also necessary. In broader terms, our study also stresses how timely and comprehensive information by industry actors can better inform ex ante policy evaluation through quantitative exercises.

References

Akgüç, M, and P. Pochet (2023). European single market 2.0: Striving for a more social and environmental market aligned with open strategic autonomy. *EconPol Forum* 24(5): 19-22.

Al-Shamma, O. and R. Ali (2013). Aircraft weight estimation in interactive design process. Presented at the 72nd Annual International Conference on Mass Properties Engineering. St. Louis, MO, USA.

Baldassarre, B., Maury, T., Mathieux, F., Garbarino, E., Antonopoulos, I., and S. Sala (2022). Drivers and Barriers to the Circular Economy Transition: the case of Recycled Plastics in the Automotive Sector in the European Union. *Procedia CIRP* 105: 37–42.

Baldassarre, B., Buesa, A., Albizzati, P F., Jakimow, M., Saveyn, H. and S. Carrara (2023). Analysis of Circular Economy Research and Innovation intensity for critical products in the supply chains of strategic technologies, Publications Office of the European Union, Luxembourg, JRC 134253.

Baldassarre, B. (2024). Circular economy for resource security in the European Union (EU): Case study, research framework, and future directions. *Ecological Economics* 227: 108345.

Buesa, A., Baldassarre, B., Garbarino, E., and H. Saveyn (2023). Circular economy in EU critical value chains: the case of titanium metal in defense and civil aviation. *Proceedings of the 5th PLATE Conference (2023)*: 149-154.

Carrara, S., Bobba, S., Blagoeva, D., Alves Dias, P., Cavalli, A., Georgitzikis, K., Grohol, M., Itul, A., Kuzov, T., Latunussa, C., Lyons, L., Malano, G., Maury, T., Prior Arce, A., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., Pennington, D.

and M. Christou (2023). Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, Publications Office of the European Union, JRC132889.

Cazcarro, I., Usubiaga, A., Román, M.V., Piñero, P., Dietzenbacher, E., Rueda-Cantuche, J.M., and I. Arto. FIGARO-e: a highly disaggregated extended multi-regional input-output database consistent with official statistics. Under consideration in *Scientific Data*.

Dietzenbacher, E., B. van Burken, and Y. Kondo (2019). Hypothetical extractions from a global perspective. *Economic Systems Research* 31: 505-519.

Ellen MacArthur Foundation (2013). Towards the circular economy (Vol. 2).

European Commission (2020). Circular Economy Action Plan. Publications Office of the European Union.

European Commission (2023). Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations EU 168/2013, EU 2018/858, 2018/1724 and EU 2019/1020, COM/2023/160 final. March.

Feng, E., Gao, D., W, Y., Yu, F., Wang, C., Wen, J., Gao, Y, and S. Xu (2023). Sustainable recovery of titanium from secondary resources: A review. *Journal of environmental management* 339: 117818.

Gehrke, T. (2022). 'EU Open Strategic Autonomy and the Trappings of Geoeconomics'. *European Foreign Affairs Review* 27, Special Issue: 61–78.

Georgitzikis, K., D'Elia, E. and U. Eynard (2022). Titanium metal: Impact assessment for supply security, European Commission, JRC129594.

Günlük-Senesen, G., and J.M. Bates (1988). Some Experiments with Methods of Adjusting Unbalanced Data Matrices. *Journal of the Royal Statistical Society (Series A)* 151: 473–490.

Helwig, N., and V. Sinkkonen (2022). Strategic Autonomy and the EU as a Global Actor: The Evolution, Debate and Theory of a Contested Term. *European Foreign Affairs Review* 27, Special Issue: 1–20.

Inagaki, I., Takechi, T., Yoshihisa, S., and N. Ariyasu (2014). Application and Features of Titanium for the Aerospace Industry. *Nippon Steel & Sumitomo Metal Technical Report* 106: 22–27.

International Titanium Association (2022). Titanium Conference proceedings. Documents available at https://titanium.org/general/custom.asp?page=ti_Proceedings.

Jakimów,M., Samokhalov, V., and Baldassarre, B. (2024). Achieving European Union strategic autonomy: circularity in critical raw materials value chains, *International Affairs* 100(4): 1735–1748,

Junius, T. and J. Oosterhaven (2003): The solution of updating or regionalizing a matrix with both positive and negative entries. *Economic Systems Research* 15: 87–96.

Louvigné, P. F. (2021). Étude de veille sur le marché du titane 2018 – 2020. Groupe de travail 'Titane', Ministère de la Transition Ecologique et Solidaire, République Française.

Marscheider-Weidemann, F.; Langkau, S.; Baur, S.-J.; Billaud, M.; Deubzer, O.; Eberling, E.; Erdmann, L.; Haendel, M.; Krail, M.; Loibl, A.; Maisel, F.; Marwede, M.; Neef, C.; Neuwirth, M.; Rostek, L.; Rückschloss, J.; Shirinzadeh, S.; Stijepic, D.; Tercero Espinoza, L., and M. Tippner (2021): Raw materials for emerging technologies 2021. – DERA Rohstoffinformationen 50. Berlin.

Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G. A., Dias, P. A., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F., and S. Solar (2017). Critical Raw Materials and the Circular Economy. Background report. In Report EUR 28832 EN.

Miller, R.E. and M.L. Lahr (2001). A Taxonomy of Extractions. In: M.L. Lahr and R.E. Miller (eds.) Regional science perspectives in economic analysis. Amsterdam: Elsevier Science, 407–441.

Miller, R.E. and P.D. Blair (2009). *Input–Output Analysis: Foundations and Extensions*, 3rd ed. Cambridge, Cambridge University Press.

Miró, J. (2023). Responding to the global disorder: the EU's quest for open strategic autonomy. *Global Society* 37(3): 315–335.

Paelinck, J., J. de Caevel and J. Degueldre (1965). Analyse quantitative de certaines phénomènes du développement régional polarisé: Essai de simulation statique d'itéraires de propogation. In: Bibliothèque de l'Institut de Science

Économique (No. 7) Problèmes de Conversion Economique: Analyses Théoretiques et Études Appliquées. Paris, M.-Th. Génin, 341–387.

Peters, M., Kumpfert, J., Ward, C.H. and C. Leyens (2003). Titanium Alloys for Aerospace Applications. *Advanced Engineering Materials* 5: 419-427.

Pommeret, A., Ricci, F., and K. Schubert (2022). Critical raw materials for the energy transition. *European Economic Review* 141: 103991.

Remond-Tiedrez, I. and J.M. Rueda-Cantuche (2019). EU Inter-country Supply, Use and Input-output Tables: Full International and Global Accounts for Research in Input-output Analysis (FIGARO): 2019 Edition. Publications Office of the European Union.

Romanova, T. (2023). A choice between neoliberal engagement and strategic autonomy? The impossibility of EU's green cooperation with Russia between 2019 and 2021. *Energy Policy* 172: 113329.

Sprecher, B. and R. Kleijn (2021). Tackling material constraints on the exponential growth of the energy transition. *One Earth* 4(3): 335-338.

Stadler, K., Wood, R., Bulavskaya, T., Södersten, C.-J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernández, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, N., Erb, K.-H., de Koning, A., and A. Tukker (2018). EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. *Journal of Industrial Ecology* 22: 502-515.

Takeda, O., Ouchi, T., and T. H. Okabe (2020). Recent progress in titanium extraction and recycling. *Metallurgical & Materials Transactions B: Process Metallurgy & Materials Processing Science* 51(4): 1315–1328.

Temursho, U., Miller, R.E., and M. C. Bouwmeester (2013). A note on the GRAS method. *Economic Systems Research* 25(3): 342-361.

Tukker, A., Wood, R., & Schmidt, S. (2020). Towards accepted procedures for calculating international consumption-based carbon accounts. *Climate Policy*, 20(sup1), S90–S106.

Uhlmann, E., Kersting, R., Klein, T. B., Cruz, M. F., and A. V. Borille (2015). Additive Manufacturing of Titanium Alloy for Aircraft Components. *Procedia CIRP* 35: 55–60.

United Nations (2018). *Handbook on supply, use and input-output tables with extensions and applications.* Department of Economic and Social Affairs. Statistics Division. Series F No.74, Rev.1. United Nations Publication.

USGS (2023). Mineral commodity summaries: titanium mineral concentrates. United States Geological Survey.

U.S. Department of Commerce Bureau of Industry and Security Office of Technology Evaluation. (2016). *U.S. Strategic Material Supply Chain Assessment: Titanium.*

U.S. Department of Commerce Bureau of Industry and Security Office of Technology Evaluation. (2019). *The Effect Of Imports Of Titanium Sponge On The National Security.*

Usubiaga, A., Arto, I., Cazcarro, I., Dietzenbacher, E., Pinero, P., Román, M.V., and J. M. Rueda-Cantuche (2023). Expanding Eurostat's FIGARO MRIO database: industry disaggregation, and environmental and labor extension. 29th IIOA Conference in Alghero, Italy.

Wang, W. and Wu, F. (2023). Dataset of annual metal scrap circularity of titanium industry in China from 2005 to 2020. *Nature: Scientific Data* 10: 435.

Supporting information

Appendix A. Extra-EU titanium metal international trade in value terms

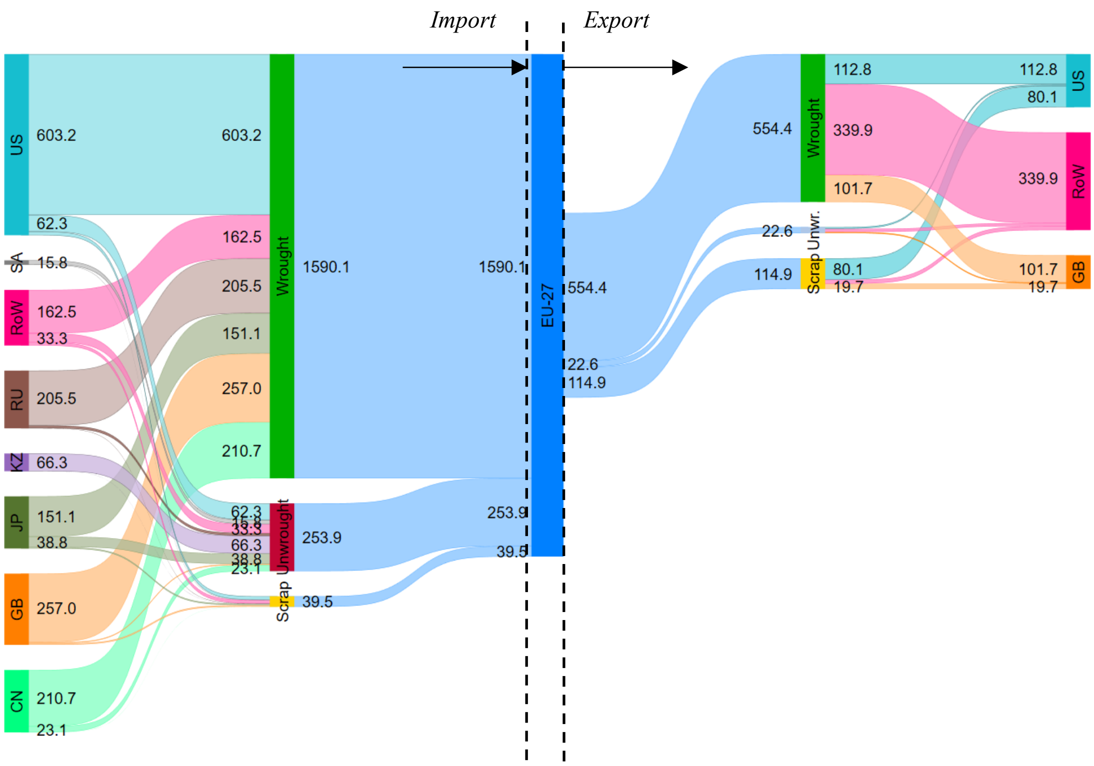

Figure A.1. Value (€ mn) of extra-EU trade flows for titanium in 2023. Source: Eurostat dataset "EU trade since 1988 by HS2-4-6 and CN8" (ds-045409).

Appendix B. Customs-level dataset: Data cleaning, processing and detailed results

Data cleaning and processing: General aspects

We start with a data extraction from our customs-level dataset (*S&P Panjiva*) between January 2018 and December 2022, restricted to shipments containing titanium metal trade codes (HS6 8108.20, .30 and .90, or their equivalent in previous editions of the HS nomenclature). This initial dataset comprises 108,144 shipments and 26 variables, which are listed in Table B.1.

Variable	Description	Variable	Description
date	Date of shipment	g_origin	Goods: Country of origin
c_name	Consignee: Firm name	g_destination	Goods: Country of destination
c_country	Consignee: Country of origin	g_portload	Goods: Port of lading
c_industry	Consignee: Sector of activity	g_portload_ctry	Goods: Port of lading (country)
c_traderoles	Consignee: Trade roles	g_portunload	Goods: Port of unlading
c_sic	Consignee: SIC codes	g_portunload_ctry	Goods: Port of unlading (country)
c_parent_name	Consignee: Ultimate parent company	g_hs6	Goods: HS6 codes
s_name	Shipper: Firm name	g_desc	Goods: Description
s_country	Shipper: Country of origin	g_vol_teu	Goods: Volume in TEU (twenty-foot equivalent units)
s_industry	Shipper: Sector of activity	g_wgt_kg	Goods: Weight (kg)
s_traderoles	Shipper: Trade roles	g_val_usd	Goods: Declared value (US$)
s_sic	Shipper: SIC codes	data_source	Data: Original source
s_parent_name	Shipper: Ultimate parent company	data_dot	Data: Original direction of trade

Table B.1. Variables included in the dataset. Prefixes [c_], [s_] and [g_] denote information on the consignee, shipper and goods traded, respectively.

We discard shipments for the year 2020 to remove the structural break in trade derived from the Covid-19 pandemic. As a next step, we try to impute missing values for the variables across shipments by exploiting the within-shipment available information:

- *Missing shipment origin/destination:* Use country from port of lading and/or unlading; if unavailable, use shipper and/or consignee countries; else, use names of shipper and/or consignee firms that include their legal form (e.g. SpA in Italy) to proxy country of origin/destination.
- *Missing HS6 code:* Extract keywords from shipment content that can be mapped with an HS6 code. For instance:
    - *"Billet, bar, pipe, sheet"* are wrought titanium products (8108.90)
    - "*Sponge, ingot, powder*" would be mapped onto unwrought titanium (8108.20)
    - "*scrap*" implies contents in code 8108.30.
    - As we allow for multiple HS6 codes in one shipment (see below), the former can overlap.
- *Missing shipper/consignee industry*: Where the Standard Industrial Classification (SIC) codes[9] are present, we recover the industry from them. If no SIC codes exist for the shipment, we extract information from the shipper/consignee firm names to derive it. For instance, a firm name containing "logistics" or "freight" would be classified into the logistics industry. Originally, industry is missing for 69.7% of existing firms. After our processing, the figure lowers to 39.8%.
- *Multiple HS codes:* If more than one code is present, we discard shipments with codes linked to non-titanium-intensive activities (e.g., anything with HS2 code 25-*Vegetables, animals, foodstuffs*). For the remaining shipments, we convert codes to their HS4 equivalent (which results in broader categories for goods), then compute the mode of HS4 in each shipment. This information is mapped onto sectors of activity in case the steps in the previous points do not suffice to infer the consignee/shipper industry if missing.

Subsequently, we attempt to clean the shipper/consignee firm names -as well as their parent companies- from duplicates, spelling mistakes and typos. The main procedures are:

- Uncapitalize, remove symbols, remove leading/trailing/duplicate spaces.
- Remove parentheses/brackets and their content, as well as "*and*".
- Correct spelling mistakes spotted by visual inspection (e.g., "*aibrus*" instead of "*airbus*").
- Use of regular expressions (*regex*) to unify similar words (e.g., "*manufacturing*" and "*manufacturer*") and combine multiple divisions from the same firm (e.g., "*airbus final assembly line*" and "*airbus"*)
- Use of *regex* to remove firm types or legal form (e.g., "ltd", "inc", "co", "gmbh", …).
- Manual fine-tuning to remove any inconsistencies not captured by the previous steps.

After the name-cleaning stage, from 13,538 distinct firm names we are left with 10,977 unique names (-19%).

Data cleaning and processing: Titanium scrap disaggregation

We now concentrate on titanium scrap flows (HS6 code 8108.30), our primary subject of analysis, for which circa 10,300 shipments are available. The first disaggregation we perform is on the scrap quality, which can be "vacuum" or "FeTi":

- <u>Vacuum</u> if the shipment description contains "*clean*", "*vacuum*" or equivalent words.
- <u>Vacuum</u> if the shipment description contains "*Ti 6-4*", "*only for remelting*", "*commercially pure*", "*bulk weldable*", "*grade 1*" or equivalent terms.
- <u>FeTi</u> if the shipment description contains "*low grade*", "*contaminated*", "*ferrotitanium*", "*mixed*" or equivalent words.
- <u>FeTi</u> if the shipment contains multiple HS6 codes and titanium scrap is shipped together with other metals.
- Finally, we extract the titanium scrap grade from the shipment description using regex. Anything over 90% is <u>vacuum</u> while the rest is considered <u>FeTi</u>.

Next, we try to distinguish new (production) scrap from old (end-of-life) scrap:

[9] Although Standard Industrial Classification (SIC) codes were replaced by North American Industry Classification System (NAICS) in 1997, some actors in the U.S. Government still use SIC.

- New if the shipment description contains "*turnings*", "*bulk*", "*solid*", "*castings*", "*cobble*", "*chip*", "*disc*" or equivalent terms.
- Old if the shipment description contains "*turbine*", "*blade*", "*rotor*", "*airframe*", "*turbo*", "*propeller*", "*aircraft*", "*component*", "*obsolete*" or equivalent words.

Lastly, we attempt to disentangle aeronautical titanium scrap flows from the rest of sectors:

- Do not classify any shipment between airlines or logistics companies, as their true sectoral origin is unclear.
- Non-aeronautical if the shipment contains commercially pure (CP) titanium -very rarely used in aerospace.
- Non-aeronautical if either the description or the consignee/shipper names contain keywords from other sectors (e.g., "healthcare", "plastic", "electronics").
- Aeronautical if consignee/shipper industry is "Aeronautical" or if the names of trading firms belong to the aerospace sector.
- Aeronautical if the shipment description contains keywords from aerospace (e.g., "aircraft", "turbine", "rotor").

We choose not to use the aero vs. non-aero disaggregation in our main results as the number of shipments eligible is relatively small and there might be room to sharpen our filters much further.

As a last step, we use time series on scrap prices to approximate the mass of those shipments for which the volume traded (in kg) is not available but the monetary value (in USD) is reported. Since there are probably significant lags between the contract formation and the shipment, as well as long- run contracts and market imperfections (e.g., imperfect foresight.), we use the average annual prices. Besides, given the variety of scrap types present in the shipments, we combine a number of price indicators extracted from Argus Metals depending on the scrap classification. The details are shown in Table B.2.

	EU → US			US → EU			UK → US			US → UK		
	Customs	Macro	*Ratio*	**Customs**	Macro	*Ratio*	**Customs**	Macro	*Ratio*	**Customs**	Macro	*Ratio*
2018	**12.65**	9.98	*127%*	**1.10**	2.29	*48%*	**5.65**	6.27	*90%*	**3.03**	1.70	*179%*
2019	**16.78**	12.54	*134%*	**2.72**	4.43	*61%*	**5.35**	7.52	*71%*	**2.65**	2.04	*130%*
2021	**5.79**	4.43	*131%*	**2.81**	3.06	*92%*	**1.33**	1.92	*69%*	**1.83**	1.67	*110%*
2022	**5.94**	5.81	*102%*	**1.98**	2.47	*80%*	**2.22**	2.93	*76%*	**1.12**	0.96	*116%*

Table B.2. Combinations of price time series used to extrapolate mass value of shipments with missing information. Source: Argus metals.

Data integrity: Comparison with macro statistics

Total cross-country titanium scrap flows derived from our customs-level information will not coincide with the figures reported in international trade statistics due to a number of factors: On one hand, some shipments contain multiple HS6 codes, the share of which in total mass is unknown or, at best, very difficult to extract from the shipment description. Besides, there might exist duplicate entries for the same shipment. At any rate, we need to ensure a sufficient coverage of customs entries with respect to the total amount. Table B.3. compares total volumes of trade from macro-level data (UN Comtrade and national statistical institutes) and our micro-level dataset. In most cases, customs data covers a large fraction of total trade; in some other, though, the micro-level figure is larger than the macro-level volume, hinting at the aforementioned data issues.

Table B.4. displays the full results of the disaggregation of titanium scrap flows that was summarized in Figure 6 in the body of the paper.

Quality	Type	Sector	Price indicator used
FeTi	New	Aero	Average of (1) + (2)
FeTi	New	Non-aero	Average of (1) + (2)
FeTi	Old	Aero	Average of (1) + (2)
FeTi	Old	Non-aero	Average of (1) + (2)
Vacuum	New	Aero	(3)
Vacuum	New	Non-aero	(4)
Vacuum	Old	Aero	(5)
Vacuum	Old	Non-aero	(6)
FeTi	New	-	Average of (1) + (2)
FeTi	Old	-	Average of (1) + (2)
FeTi	-	Aero	Average of (1) + (2)
FeTi	-	Non-aero	Average of (1) + (2)
Vacuum	New	-	Average of (3) + (4)
Vacuum	Old	-	Average of (5) + (6)
Vacuum	-	Aero	Average of (3) + (5)
Vacuum	-	Non-aero	Average of (4) + (6)

Quality	Type	Sector	Price indicator used
-	New	Aero	Average of (1) + (2) + (3)
-	New	Non-aero	Average of (1) + (2) + (5)
-	Old	Aero	Average of (1) + (2) + (4)
-	Old	Non-aero	Average of (1) + (2) + (6)
FeTi	-	-	Average of (1) + (2)
Vacuum	-	-	Average of (3) + (4) + (5) + (6)
-	-	Aero	Average of (1) + (2) + (3) + (5)
-	-	Non-aero	Average of (1) + (2) + (4) + (6)
-	New	-	Average of (1) + (2) + (3) + (4)
-	Old	-	Average of (1) + (2) + (5) + (6)
Unknown	-	-	Average of (1) + (2) + (3) + (4) + (5) + (6)

(1) Ferro-titanium 30% Ti ex-works China $/kg
(2) Ferro-titanium 70% scrap grade ex-works China $/kg
(3) Titanium scrap 6Al-4V turnings aero quality US dealer/processor $/kg
(4) Titanium scrap grade CP1 solids del US dealer/processor $/kg
(5) Titanium turnings 90/6/4 max 0.5% Sn ddp UK $/kg
(6) Titanium scrap min 85% Ti non-tin-bearing mixed turnings US dealer/processor $/kg

Table B.3. Comparison of macro aggregates and totals from customs-level data.

2018-19		**Scrap grade**				**Scrap sector**				**Scrap type**			
		Export view		Import view		Export view		Import view		Export view		Import view	
Origin	Destination	FeTi	Vacuum	FeTi	Vacuum	Aero	Non-aero	Aero	Non-aero	Old	New	Old	New
EU	US	7.10%	92.90%	7.39%	92.61%	21.73%	78.27%	21.73%	78.27%	1.79%	98.21%	1.79%	98.21%
GB	US	3.09%	96.91%	3.09%	96.91%	15.48%	84.52%	15.48%	84.52%	0.00%	100.00%	0.00%	100.00%
US	EU	15.52%	84.48%	7.46%	92.54%	0.00%	100.00%	0.00%	100.00%	57.88%	42.12%	56.43%	43.57%
US	GB	86.00%	14.00%	86.00%	14.00%	0.00%	100.00%	0.00%	100.00%	47.25%	52.75%	42.43%	57.57%

2021-22		**Scrap grade**				**Scrap sector**				**Scrap type**			
		Export view		Import view		Export view		Import view		Export view		Import view	
Origin	Destination	FeTi	Vacuum	FeTi	Vacuum	Aero	Non-aero	Aero	Non-aero	Old	New	Old	New
GB	US	20.15%	79.85%	20.15%	79.85%	0.13%	99.87%	0.13%	99.87%	1.85%	98.15%	1.85%	98.15%
EU	US	3.73%	96.27%	3.73%	96.27%	16.50%	83.50%	16.50%	83.50%	1.63%	98.37%	1.63%	98.37%
US	EU	13.72%	86.28%	17.31%	82.69%	0.00%	100.00%	0.00%	100.00%	0.00%	100.00%	0.00%	100.00%
US	GB	80.12%	19.88%	100.00%	0.00%	-	-	-	-	8.49%	91.51%	4.80%	95.20%

Table B.4. Detailed results of scrap flows disaggregation performed with customs-level dataset.

Appendix C. Detailed calculations for circularity scenarios

Scenario #1: Reduction in buyback agreements for titanium scrap with the US

8108.30: Titanium waste & scrap	Volume (kt)	Value (million €)	Implicit export price (€/kg)
Total extra-EU **exports**, 2023	15.3	114.9	7.51
to the United States	*7.92*	*80.11*	*10.11*

(S1.1) X_{scrap}^{US} = 7.92/15.3 = 51.8% of EU scrap exports in mass are directed to the US. (*macro, Eurostat data for 2023*)

(S1.2) *Scrap grade*: According to our estimates, $w_{X,scrap,vacuum}^{US}$ = 79.8% of EU exports to the US are vacuum-grade and almost entirely come from production. (*customs data*)

(S1.3) *Sectorial distribution:* $w_{aero,cons}^{EU}$ = 67.0% of titanium metal consumption in Europe is in the commercial aerospace sector (*Louvigné, 2021*).

Given that aeronautical titanium parts have a much higher buy-to-fly ratio than other sectors, we use the figure of 9:1 for aero and 5:1 for the rest (see table 1). This means that the proportion for the aero sector on the total scrap output will be higher, $\boldsymbol{w_{scrap,aero}^{EU} \approx 91.6\%}$.

aero demand	scrap 9:1		other demand	scrap 5:1		
67	60.3		33	5.5		60.3/(60.3+5.5) = 0.916

Thus, $w_{X,scrap,buyback}^{US} = w_{X,scrap,vacuum}^{US} \cdot w_{scrap,aero}^{EU}$ = **73.1%** of flows to the US are vacuum-grade aero scraps, likely subject to buyback agreements. In mass terms, $Q_{vacuum,buyback} = w_{X,scrap,buyback}^{US} * 7.92 =$ **5.**79 kt is the total weight of vacuum aero scraps subject to buybacks with the US, or 37.8% of total extra-EU exports in mass. In our scenario, the EU retains this scrap, which is not traded anymore. **This is Step 1 of the scenario.**

From the implicit price for EU exports of scrap to the US, we know that $p_{vacuum}w_{vacuum} * p_{other}(1 - w_{vacuum}) = 10.11$. Using the value of $w_{vacuum} = 79.8\%$ we have $0.798 * p_{vacuum} + 0.202 * p_{other} = 10.11$, subject to $p_{vacuum} > p_{other}$ and $p_{other} > 0$.

Taking the 2022 Q3 average price of "*Titanium scrap 6Al 4V bulk weldable del US dealer/processor USD/kg*", which is 11.5, for $p_{vacuum} = 11.5$ we obtain $p_{other} = 4.62$,which is close to the series of *Ti-6-4 unprocessed turnings* (USGS, MCS 23Q3), a good proxy for lower-quality.

Finally, the value of vacuum aero scrap subject to US buybacks is 11.5*5.79 = 66.59 mn €, or 83.1% of exports to the US in value. This is 58% of total extra-EU exports in value.

In parallel, were the EU to retain scrap domestically, it is reasonable to assume that imports would be reduced.

8108.30: Titanium waste & scrap	Volume (kt)	Value (million €)	Implicit import price (€/kg)
Total extra-EU **imports**, 2023	6.7	39.5	5.90
from the United States	*2.23*	*13.64*	*6.12*

(S1.4) M_{scrap}^{US} = 2.23/6.7 = 33.2% of EU titanium scrap imports in mass come from the US. (*Eurostat data for 2023*)

(S1.5) *Scrap grade*: According to our estimates, $w_{M,scrap,vacuum}^{US}$ = 84.5% of EU imports from the US are vacuum-grade and almost entirely come from production stages (*Customs data*)

(S1.6) *Sectorial distribution:* $w_{aero,cons}^{US}$ = 80% of titanium metal consumption in the US is in the commercial aerospace sector (*Louvigné, 2021*). Once again, due to the higher buy-to-fly ratio, the proportion on total scrap supply will be higher, say $w_{scrap,aero}^{US} \approx 85\%$.

Thus, $w_{M,scrap,aero,vacuum}^{US} = w_{M,scrap,vacuum}^{US} \cdot w_{scrap,aero}^{US} = 71.8\%$, which is the share of vacuum-grade, aeronautical EU scrap imports from the US. In mass terms, $Q_{vacuum} = w_{M,scrap,aero,vacuum}^{US} * 2.23 =$ 1.60 kt is the total weight of vacuum aero scraps imported from the US, or 23.9% of total extra-EU exports in mass.

From the implicit price for EU imports of scrap to the US, we know that $p_{vacuum}w_{vacuum} * p_{other}(1 - w_{vacuum}) = 6.12$. Using the value of $w_{vacuum} = 84.5\%$ we have $0.845 * p_{vacuum} + 0.155 * p_{other} = 6.12$. Taking the 2022 end-value available on the price of "*Titanium scrap 6Al 4V bulk weldable del US dealer/processor USD/kg*", which is 6.75, for $p_{vacuum} = 6.75$ we obtain $p_{other} = 2.69$, which is close to the series of *Titanium scrap min 85% Ti tin-bearing mixed turnings del US*, a good proxy for lower-quality.

Finally, the value of vacuum aero scrap imports from the US is 6.75*1.6 = 10.8 mn €, or 79.2% of imports to the US in value. This is 27.3% of total extra-EU exports in value. **This is Step 2 of the scenario.**

As a next step, we quantify how these effects on scrap might affect trade in unwrought titanium (sponge, ingot and powder).

8108.20: Unwrought titanium & powders	**Volume (kt)**	**Value (mn €)**	**Implicit import price (€/kg)**
Total extra-EU **imports**, 2023	**16.6**	**253.9**	***15.32***
among which, from:			
Japan	3.33	38.78	*11.65*
Kazakhstan	4.32	66.32	*15.36*
Russian Federation	1.05	10.22	*9.74*

(S1.7) *EU unwrought titanium imports:* $M_{unw}^{TOT} = 16.6$ kt in 2023, with the main countries of origin being Kazakhstan (26.1%), Japan (20.1%), the US (17.4%), China (13.8%), and Saudi Arabia (13.4%). (*Eurostat 2023 data*)

Aero-grade sponge is produced solely in Russia, Kazakhstan, and Japan. (*qualitative*).

We want to know what happens if the EU used the scrap retained from buyback agreements to manufacture aeronautical ingots.

Using a scrap ratio of $s_{EU} = 60\%$, in the lower/conservative end of estimates for new remelting procedures, the maximum volume of ingot that could be produced is:

$$Y_{ingot}^{EU} = \frac{Y_{scrap,buyback}^{EU}}{s_{EU}} = \frac{5.79kt}{0.6} = 9.65 \text{ kt.}$$

This would require importing the remaining 40% of the mass in sponge, that is, $9.65 - 5.79 = 3.86$ kt. Because of the Russian invasion of Ukraine, it is reasonable to assume that priority will be given to decouple from Russia, meaning that we source 3.86 kt from Japan and Kazakhstan. We maintain the relative shares of both in the sum of their production (43.5% JP and 56.5% KZ) and apply it to the extra sponge needed. **This will be Step 3a in our scenario**:

- 3.86*0.435 = +1.68 kt from JP. At an average of 9.58€/kg of sponge, this means +16.09 mn € imports of unwrought from JP, which means +41.5% in value.
- 3.86*0.565 = +2.18 kt from KZ. At an average of 10.05€/kg of sponge, this means +21.9 mn € imports of unwrought from KZ, which is +33% in value.

Bear in mind that ingot *production* capacity is about 1/3 less than *melting* capacity (some stuff can be molten more than once to remove impurities). This means that melting 9.65kt will result in approximately 6.43kt of ingots produced. We could reduce imports of ingots by 6.43kt. **This is step 3b of the scenario**.

	IMPORT		% vol			Avg price	% reduction
	kt	*%vol*	w/o RoW			(TAXUD)	in value
China	2.29	*13.8%*	21.75		1.40	8.64	**-52.4**
Japan	3.33	*20.1%*		Ingot:			
Kazakhstan	4.32	*26.1%*	40.93	-> Reduce	2.63	10.46	**-41.5**
Russian Federation	1.05	*6.3%*	9.95	6.43kt	0.64	15.18	**-95.1**
Saudi Arabia	2.22	*13.4%*					
United States	2.89	*17.4%*	27.36		1.76	17.06	**-48.2**
Rest of the world	0.47	*2.8%*					
	16.6						

An open question remains whether the EU has the capacity to produce another 6.43 kt of ingot annually. According to the latest available figures, EU ingot production is close to 5 kt, split between France (62.8%), Italy (18.3%), Romania (10.5%), and Sweden (8.4%); maximum production capacity lies between 8 kt and 12 kt (*Roskill, 2018*). This would entail a ramp-up to 11.43kt, which does not appear crazy given the outdated figures and the push for circularity and strategic autonomy.

However, providing an estimate for the ingot production needed and when it will be installed is a challenging exercise because of temporal factors – a new plant takes up to 10 years to set up[10]–, and changes in demand, which is expected to rise substantially in the next decade for the aerospace sector.

Finally. The additional 6.43 kt of ingots produced would probably translate into milled products at a ratio of 3:2[11], meaning 4.28 kt of additional milled products, which in turn would become (2:1 ratio) 2.14kt of finished titanium products.

The EU could stop importing that quantity from abroad: it is 2.14/30.4=7% of total imports of 8108.90, more precisely -26% if it all came from the US. **This is Step 4 of the scenario.**

Could it produce this amount of Ti products domestically? In 2022, the last period available, Prodcom code 24.45.30.42 (*Titanium and articles thereof; bars and rods, profiles, wire, plates, sheets, strip and foil, tubes and pipes, other*) yields 24.73 kt produced, among which 7.84kt in France, 1.7 in Italy and 1.06 in Germany. Let us split the 2.14kt (+20.18% in total) proportionally to these three countries so that: France produces 2.14*0.74 = +1.58kt of Ti finished products, Italy produces 2.14*0.16 = +0.34kt, and Germany produces 2.14*0.1= +0.214kt (+20.18%). **This is step 5 of the scenario.**

The full depiction of Scenario #1 in terms of international trade and production is presented in Table C.1.

Scenario #1: Reduction in EU buyback agreements for titanium scrap with third countries					
Trade in Ti scrap (HS6 code 8108.30)		**Trade in unwrought Ti (8108.20)**		**Trade in Ti products (8108.90)**	**Production of Ti products (24.45.30.42)**
Step 1: **-83.1%** US exports	**Step 2:** -**79.2%** US imports	**Step 3a (+sponge):** **+33.0%** KZ imports **+41.5%** JP imports	**Step 3b (-ingot):** **-52.4%** CN imports **-41.5%** KZ imports **-95.1%** RU imports **-48.2%** US imports	**Step 4:** **-26%** US imports	**Step 5:** **+20.2%** in FR, IT, DE

Table C.1. Summary of Scenario 1 effects on EU international trade and production.

Scenario #2: Increased collection of aero end-of-life scrap suitable for remelting

In our second scenario, we will estimate the amount of post-consumer scrap that could be recovered from decommissioned commercial aircraft; after appropriate processing, this scrap could be remelted into titanium ingots. We start our baseline definition at the aircraft level:

(S2.1) *Number of retired aircraft per year:* The last pre-Covid value was $x_{EoL}^{TOT} = 666$ aircraft globally in 2019. (*qualitative*)

(S2.2) *Geographical distribution of decommissioning:* The share of retired aircraft in the EU is unknown. We will use the EU share on the global aircraft fleet in 2021, $s_{Fleet}^{EU} = 19.3\%$. *(macro*)

(S2.3) *Aircraft total weight:* Among medium and large commercial airliners, around 10-15% of the weight is in the engines, where closed-loop recycling is already functional; we concentrate on the remaining $w_{airframe} = 85\%$ of the mass comprising the airframe. (*qualitative*)

(S2.4) *Aircraft titanium content:* We use model-specific data on titanium content and decommissioning. See Table C.2. (*qualitative + micro;* Al-Shamma and Ali, 2013)

At the global level, we compute a total amount of titanium scrap generated in our baseline of roughly $y_{EoL}^{TOT} = 3.18$ kt, out of which $y_{EoL}^{EU} = s_{Fleet}^{EU} \cdot y_{EoL}^{TOT} = 0.6$ kt in the EU.

An implicit assumption is that titanium parts in the airframe become scrap because recertification procedures make it impossible to re-use them in another aircraft. We now turn to quality-specific information on the scrap:

(S2.5) *Uses of aircraft old scrap:* $s_{EoL}^{Remelt} = 40\%$ remains eligible for remelting, 45% is downcycled to ferrotitanium production, and 15% is lost. (*qualitative*)

[10] The French EcoTitanium project was launched in 2013, the factory was inaugurated in 2017 and we assume that it will reach full capacity in 2023.

[11] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10325961/pdf/41597_2023_Article_2351.pdf

Therefore, in our baseline scenario, a total of $y_{EoL}^{Remelt,EU} = s_{EoL}^{Remelt} \cdot y_{EoL}^{EU}$ = **0.24 kt** of aircraft post-consumer scrap are ready to enter the remelting loop in the EU. This constitutes a quite small amount which will not be subject to buyback agreements, nor will it impact the size of the titanium recycling industry. With such small additional scrap available, we map it as a direct reduction in scrap imports from the US: **-10.76% scrap imports (in mass/value) from the US.**

Aircraft model	Aircraft specifications			Decommissioned aircraft, 2022		Decommissioned aircraft, 2019	Titanium EoL scrap		
	Type	Weight (OEW, t)	Titanium content	Number (2)	% (2)	Number (2)	% of airframe Ti in aircraft weight (1)	Mass of airframe Ti (t)	Titanium scrap per aircraft model (t)
A320CEO	NB	43	5%	62	22.90%	153	4.25%	1.83	279.6
737NewGen	NB	37	10%	55	20.37%	136	8.50%	3.15	427.7
737Classic	NB	33	5%	19	7.03%	47	4.25%	1.40	65.9
MD80	NB	78	5%	15	5.55%	37	4.25%	3.32	122.7
757	NB	61	5%	7	2.59%	17	4.25%	2.59	44.1
A330	WB	122	5%	15	5.55%	37	4.25%	5.19	191.8
767	WB	90	5%	13	4.81%	32	4.25%	3.83	122.4
777-200/300	WB	275	10%	11	4.07%	27	8.50%	23.38	631.1
A340/200-300	WB	275	6%	8	2.97%	20	5.10%	14.03	280.5
747-400	WB	178	5%	7	2.59%	17	4.25%	7.57	128.6
Rest of models	-	119	6.10%	58	21.48%	143	5.19%	6.18	883.8
Total				**270**		**666**		**72.44**	**3178.3**

NB: Narrow-body; WB: Wide-body; OEW: Operating empty weight.

(1) Assuming 85% of aircraft weight in airframe.

(2) Data for Jan-Oct 2022. Shares are applied to 2019 figures, which are not affected by Covid-19..

Table C.2. Circularity scenario #2 (baseline): Aircraft-specific calculations for titanium content. Source: own elaboration from granular sources.

Alternatively, we design an enhanced circularity alternative to our baseline scenario with elements from the future: a greater number of decommissioned aircraft, a larger share of titanium in their airframe, and a higher recovery rate of old scrap eligible for remelting:

(S2.1 bis) *Number of retired aircraft per year:* Using a linear trend with coefficients based on the period 2001-19 yields a forecast of around 1,000 retired aircraft in 2031; industry reports yield 1,500 – 2,000 at that date, so we take the midpoint of $x_{EoL,circ}^{TOT}$ = 1,500. (*qualitative + macro*)

(S2.4 bis) *Aircraft titanium content:* New-generation planes retiring lead to a higher supply of end-of-life scrap from their airframes. We apply the shares of new aircraft deliveries in 2022-31 by model obtained from industry data to the predicted decommissioning volume $x_{EoL,circ}^{TOT}$, together with information on titanium content for each model (Table C.3).

This implies that now roughly 9.02 kt of titanium post-consumer scrap from aircraft are available worldwide, out of which $y_{EoL,circ}^{EU}$ = 1.75 kt lie in the EU. We add one more layer to the alternative scenario by assuming a higher collection of plane scrap:

(S2.5 bis) *Uses of aircraft old scrap:* $s_{EoL,circ}^{Remelt}$ = 75% remains eligible for remelting, 20% is downcycled to ferrotitanium production, and 5% is lost. *(qualitative)*

Aircraft model	Type	Weight (OEW, t)	Titanium content	New aircraft delivery forecast, 2022-31 Number	%	Decommissioned aircraft forecast Number [2]	Titanium EoL scrap % of airframe Ti in aircraft weight [1]	Mass of airframe Ti (t)	Titanium scrap per aircraft model (t)
A320neo	NB	44	12%		41%	615	10.20%	4.5	2760.1
737max	NB	45	12%		29%	435	10.20%	4.6	1996.7
A220	NB	36	8%		6%	90	6.80%	2.4	220.3
787	WB	117	15%		5%	75	12.75%	14.9	1118.8
A350	WB	115	13%		4%	60	11.05%	12.7	762.5
767	WB	90	5%		1%	15	4.25%	3.8	57.4
777X	WB	188	13%		1%	15	11.05%	20.8	311.6
A330neo	WB	135	10%		1%	15	8.50%	11.5	172.1
Rest of models	-	96	11.0%		12%	180	9.35%	9.00	1619.9
Total						**1500**		**84.22**	**9019.4**

NB: Narrow-body; WB: Wide-body; OEW: Operating empty weight.

(1) Assuming 85% of aircraft weight in airframe.

Table C.3. Circularity scenario #2 (enhanced): Aircraft-specific calculations for titanium content. Source: own elaboration from granular sources.

Consequently, $y^{Remelt,EU}_{EoL,circ} = s^{Remelt}_{EoL,circ} \cdot y^{EU}_{EoL,circ} = \mathbf{1.31\ kt}$ of scrap will enter the ingot manufacturing loop, i.e., over five times as much as in the baseline case. : This implies **-45.32% in scrap imports (in mass/value) from the US.**

Furthermore, as the volumes of available post-consumer scrap are larger than in the baseline, we increase the relevance of titanium recycling activities in the EU. Taking the latest value for (Export – import) of scrap in the EU in 2023 (8.6kt), we assume an additional 1.31kt entail a 15.23% increase in recycling activities, so we increase the sectorial value added by the same proportion in the three countries where titanium production takes place, from Scenario 1.

The full depiction of Scenario #2 in terms of international trade and production is presented in Table C.4.

Scenario #2: Increased collection of aeronautical end-of-life scrap suitable for remelting		
Stock of scrap ready for remelting in the EU	**Trade of titanium scrap (HS6 code 8108.30)**	**Value added of titanium recycling**
Baseline		
+ 0.24 kt available	**Step 1:** **-10.7%** US imports	**Step 2:** (No change) Additional scrap volume can be processed with current infrastructure.
Enhanced circularity		
+ 1.31 kt available	**Step 1:** **-45.3%** US imports	**Step 2:** **+15.23%** in FR, IT, DE

Table C.4. Summary of Scenario 2 effects on EU international trade and production.

Appendix D. Extended inter-country input-output database to trace titanium flows

The Supply and Use framework

The starting point for developing the Extended Inter-Country Input Output Database for tracing Titanium and key aeronautical product flows is the Supply and Use Tables (SUT) framework. Figure D.1. shows a simplified SUT framework for two regions, the EU, and the Rest of the World (RW). The main elements of the SUT framework are $\mathbf{U}^{r,s}_{i,j}$, $\mathbf{Y}^{r,s}_{i,j}$, $\mathbf{W}^{s}_{i}$, $\mathbf{V}^{s}_{i,j}$, $\mathbf{g}^{s}_{j}$ and $\mathbf{q}^{r}_{i}$. $\mathbf{U}^{r,s}_{i,j}$ describes the intermediate use of product $\mathbf{i}$ produced in country $\mathbf{r}$ by industry $\mathbf{j}$ in country $\mathbf{s}$. It worth noting that when $\mathbf{r} = \mathbf{s}$ the flow refers to domestic production, while $\mathbf{r} \neq \mathbf{s}$ indicates exports from country $\mathbf{r}$ to country $\mathbf{s}$. Similarly, $\mathbf{i} = \mathbf{j}$ indicates that $\mathbf{i}$ is the main product of industry $\mathbf{j}$, while $\mathbf{i} \neq \mathbf{j}$ refers to secondary production. Further, $\mathbf{Y}^{r,s}_{i,j}$ describes the final use of product $\mathbf{i}$ produced in country $\mathbf{r}$ by final user $\mathbf{j}$ (e.g., households) in country $\mathbf{s}$, whereas $\mathbf{q}^{r}_{i}$ describes total use of product $\mathbf{i}$ in country $\mathbf{r}$. Using the simplified example of two regions, these elements determine total product use in the EU as $\mathbf{U}^{EU,EU}\mathbf{i} + \mathbf{Y}^{EU,EU}\mathbf{i} + \mathbf{e}^{EU,RW} = \mathbf{q}^{EU}$, where $\mathbf{e}^{EU,RW} = \mathbf{U}^{EU,RW}\mathbf{i} +$

$\mathbf{Y^{EU,RW}i}$ represents EU exports to the RW. One basic identity of the SUT framework is that total product use should equal total product supply, which is obtained applying $\mathbf{S^{EU}i} = \mathbf{q^{EU}}$ where $\mathbf{S^{s}_{i,j}}$ is the supply matrix, which describes supply of product $\mathbf{i}$ produced in country $\mathbf{s}$ by industry $\mathbf{j}$. In Figure D.1, the make matrix $\mathbf{V^{s}_{i,j}}$, obtained simply by $\mathbf{V^{s}_{i,j}} = \mathbf{S^{s}_{i,j}}'$ is shown instead, so the SUT system can be represented more compactly.

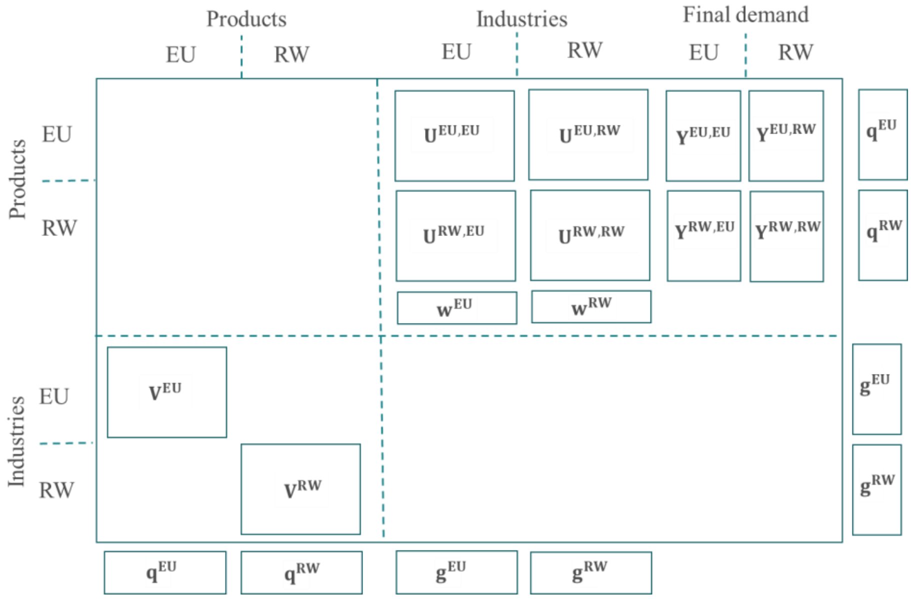

Figure D.1. Graphical depiction of the SUT (supply and use) framework.

Another basic identity of the SUT framework is that total output $\mathbf{g^{s}_{j}}$ of industry $\mathbf{j}$ in country $\mathbf{s}$ should equal total industry supply. Thus, total industrial output $\mathbf{g^{EU}}$ in the EU, calculated following $\mathbf{i'U^{EU,EU}} + \mathbf{i'U^{EU,RW}} + \mathbf{i'W^{EU\prime}} = \mathbf{g^{EU\prime}}$, should equal total industry supply obtained following $\mathbf{V^{EU}i} = \mathbf{g^{EU}}$, where $\mathbf{W^{s}_{i}}$ describes the value added component $\mathbf{i}$ (e.g. compensation to employees) produced in country $\mathbf{s}$. Equivalent considerations apply for RW. In the following, we describe the data needed for developing all elements of a SUT framework specifically for Titanium and aeronautical products.

Data

The main data source for this study is the FIGARO-E3[12] database, which was developed by combining official FIGARO tables with technological blueprints from the more disaggregated EXIOBASE database (Stadler et al., 2018). Put simply, FIGARO-E3 can be seen as a more detailed version of the official FIGARO tables for primary and manufacturing products. However, the Titanium economy is not specifically described in FIGARO-E3, and further extension was needed to assess circularity scenarios.

We achieved this by using the micro data described in subsection 3.3 along with other data sources to split more aggregated monetary flows in FIGARO-E3. Specifically, we disaggregated six products into 24 to represent better the Titanium and aeronautical economy. This group includes both Titanium products and non-Titanium products within the original FIGARO-E3 product category, resulting in 8 specific products related to the Titanium economy, and 10 key aeronautical products in the model. The concordance between FIGARO-E3 and the new database for Titanium and aeronautical product flows is offered in Table D.1. In terms of industries, the original six industries were further divided into 13 of which six describe the Titanium economy, and one to manufacturing of aerospace equipment.

[12] Available in the Joint Research Centre Data Catalogue https://data.jrc.ec.europa.eu/collection/id-00403

	Economic activity codes (NACE Rev.2)	CPA + PRODCOM codes	Trade codes (HS6)
Mining and extraction	07.29: Mining of other non-ferrous metal ores	07.29.19.30 Titanium ores and concentrates	2614.00
Chemical products	20.12: Manufacture of dyes and pigments	20.12.11.50 Titanium oxides	2823.00
		20.12.24.15 Pigments and preparations based on titanium dioxide containing ≥ 80 % by weight of TiO_2	3206.11
		20.12.24.19 Pigments and preparations based on titanium dioxide (excluding those containing ≥ 80 % by weight of TiO_2)	3206.19
	20.13: Manufacture of other inorganic basic chemicals	20.13.31.39 Other chlorides n.e.s (Including titanium tetrachloride)	Part of 2827.20
Metal manufacturing	24.10: Manufacture of basic iron and steel and of ferro-alloys	24.10.12.55 Ferro-titanium and ferro-silico-titanium	7202.91
	24.45: Other non-ferrous metal production	24.45.30.43 Titanium and articles thereof (excluding waste and scrap)	8108.20 + 8108.90 + 8108.30 (new scrap)
Aerospace: Components	30.30: Manufacture of air and spacecraft & related machinery	30.30.12.00 Turbo-jets and turbo-propellers, for civil use	8411.11 + 8411.12 + 8411.21 + 8411.22
		30.30.13.00 Reaction engines, for civil use	8412.10
		30.30.16.00 Parts of turbo-jets or turbo-propellers, for use in civil aircraft	8411.91
		30.30.50.30 Propellers and rotors and parts thereof for non-powered aircraft, helicopters and aeroplanes, for civil use	8803.10
		30.30.50.50 Undercarriages and parts thereof for non-powered aircraft, helicopters, aeroplanes, spacecraft and spacecraft launch vehicles, for civil use	8803.20
		30.30.50.90 Parts for all types of aircraft excluding propellers, rotors, undercarriages, for civil use	8803.30 + 8803.90
Aerospace: Final assemblies		30.30.31.00 Helicopters, for civil use	8802.11 + 8802.12
		30.30.32.00 Aeroplanes and other aircraft of an unladen weight ≤ 2 000 kg, for civil use	8802.20
		30.30.33.00 Aeroplanes and other aircraft of an unladen weight > 2 000 kg but ≤ 15 000 kg, for civil use	8802.30
		30.30.34.00 Aeroplanes and other aircraft of an unladen weight > 15 000 kg, for civil use	8802.40
Titanium scrap: Recycling	38.32: Recovery of sorted materials	38.32.20.00 Metal secondary raw materials	8108.30 (old scrap)

Table D.1. Mapping of industry (NACE r2) onto production (PRODCOM) and trade (HS6) codes.

In Appendix C, we quantified our two circularity scenarios using trade codes from the HS6 classification (Tables C.2. and C.4.). However, the FIGARO database employs the European statistical Classification of Product Activities (CPA) for goods and services; the converted scenarios are depicted in Table D.2.

Scenario #1: Reduction in EU buyback agreements for titanium scrap with third countries					
Effect on the share of CPA code 24.45.30.43 linked to titanium					
Step 1: **-33.7%** US exports	**Step 2:** -**13.1%** US imports	**Step 3a (+sponge):** **+32.9%** KZ imports **+8.2%** JP imports	**Step 3b (-ingot):** **-5.2%** CN imports **-41.4%** KZ imports **-4.5%** RU imports **-4.4%** US imports	**Step 4:** **-23.1%** US imports	**Step 5:** **+20.2%** prod. FR, IT **+12.2%** prod. DE

Scenario #2: Increased collection of aeronautical end-of-life scrap suitable for remelting		
Stock of scrap ready for remelting in the EU	*Effect on the share of CPA code 24.45.30.43 linked to titanium*	*Effect on the share of CPA code 38.32.29.10 linked to titanium*
Baseline		
+ 0.24 kt available	**Step 1:** **-0.2%** US imports	**Step 2:** (No change) Additional scrap volume can be processed with current infrastructure.
Enhanced circularity		
+ 1.31 kt available	**Step 1:** **-0.9%** US imports	**Step 2:** **+15.23%** in FR, IT, DE

Table D.2. Mapping of circularity scenarios converted into the CPA classification.

Supply

Supply of Titanium products need to be specifically described in $\mathbf{V^{EU}}$. This was done splitting the original FIGARO-E3 monetary flows using information available in PRODCOM and other sources. The disaggregation was performed at EU level, that is, the same splitting shares were applied to all EU countries. For the non-EU countries ($\mathbf{V^{RW}}$), and due to the lack of a similar industrial production statistics such as PRODCOM for all non-EU countries, international trade data was employed. That is it was assumed that same shares can be applied to domestic and exports production of the Titanium and aeronautical products for all industries (see next subsection for details on the international trade data employed). For splitting by industry, no secondary production was assumed for non-EU countries.

Table D.3 shows the split between Titanium and non-Titanium products for the EU, US and the RW for comparison, while Table D.4 summarises production and total shares of the eight different Titanium products considered in this study. Tables D.5 and D.6 inform on the aerospace economy.

	EU	US	RW	World
Non-Titanium	557.5	358.1	3,399.5	4,315.1
Titanium	3.1	0.2	42.7	46.0
Total	**560.6**	**358.3**	**3,442.2**	**4,361.1**
Non-Titanium	99.4%	99.9%	98.8%	98.9%
Titanium	0.6%	0.1%	1.2%	1.1%

Table D.3. Titanium and non-titanium total production for the EU, US, RW in 2015 (bn € and %).

Code	EU		US		RW		World	
B07_H_Ti	0.0	0%	0.0	0%	0.4	0%	0.4	0%
C20_C_Ti_20121150	1,068.2	35%	59.8	24%	679.4	2%	1,807.5	4%
C20_C_Ti_20122415	577.4	19%	59.8	24%	679.4	2%	1,316.6	3%
C20_C_Ti_20122419	482.8	16%	59.8	24%	679.4	2%	1,222.0	3%
C20_C_Ti_20133139	78.4	3%	43.4	18%	404.9	1%	526.8	1%
C24_A_Ti	12.5	0%	24.2	10%	222.6	1%	259.3	1%
C24_K_Ti	847.0	27%	0.4	0%	26,283.8	62%	27,131.2	59%
E37T39_A_Ti	22.9	1%	-	0%	13,751.0	32%	13,773.9	30%
Total	**3,089.3**	**100%**	**247.5**	**100%**	**42,701.0**	**100%**	**46,037.7**	**100%**

Table D.4. Total production of titanium products for the EU, US and RW in 2015, by CPA (mn €).

	EU	US	RW	World
Non-Space	89.4	24.6	398.3	512.3
Space	85.2	254.6	177.4	517.2
Total	**174.6**	**279.1**	**575.7**	**1,029.5**
Non-Space	51.2%	8.8%	69.2%	49.8%
Space	48.8%	91.2%	30.8%	50.2%

Table D.5. Space and non-space total production for the EU, US, RW in 2015 (bn €).

Code	EU		US		RW		World	
C30_Space_30301200	8,615.3	10%	26,218.2	10%	28,435.3	16%	63,268.8	12%
C30_Space_30301300	13,202.5	15%	328.5	0%	988.4	1%	14,519.4	3%
C30_Space_30301600	6.8	0%	45,427.2	18%	31,591.1	18%	77,025.1	15%
C30_Space_30303100	4,025.6	5%	6,935.7	3%	4,913.1	3%	15,874.3	3%
C30_Space_30303200	326.6	0%	4,343.4	2%	8,783.9	5%	13,453.9	3%
C30_Space_30303300	2,707.5	3%	996.0	0%	994.7	1%	4,698.2	1%
C30_Space_30303400	13,537.4	16%	113,554.7	45%	36,114.5	20%	163,206.6	32%
C30_Space_30305030	131.6	0%	2,245.2	1%	820.5	0%	3,197.4	1%
C30_Space_30305050	1,570.6	2%	7,160.1	3%	5,969.3	3%	14,700.0	3%
C30_Space_30305090	41,063.1	48%	47,381.1	19%	58,794.1	33%	147,238.4	28%
Total	**85,187.0**	**100%**	**254,590.1**	**100%**	**177,404.9**	**100%**	**517,182.0**	**100%**

Table D.6. Total production of space products for the EU, US and RW in 2015, by CPA (mn €).

International trade

FIGARO covers 27 EU Member States, 18 main trade partners, and a Rest of the World region. However, to compile these tables, more detailed international trade statistics were used, which we also applied in this research to break down Titanium and aeronautical product flows in international supply chains. It is worth noting that this trade database is fully balanced at the global level, which means that trade asymmetries in mirror trade flows were corrected. Additionally, quasi-transit and re-export flows were adjusted to national accounting principles to correct discrepancies between the country of origin and the country of consignment.

This database contains international information at a Harmonized System (HS) resolution of six digits, which adequately matches the requirements of the model. To disaggregate the data, we developed a concordance table between the 24 Titanium and aeronautical products and 475 HS codes, with most of the codes referring to non-Titanium/other transport products. More precisely, the 18 specific products related to the Titanium and aerospace economy correspond to 24 HS6 codes, with only three cases with n-to-1 concordance (turbojets and propellers, parts of aircrafts, and helicopters). These trade flows appropriately aggregated were employed for splitting FIGARO-E3 flows between Titanium/aeronautical and non-Titanium/other transport products. Finally, for metal waste and scrap, the procedure was slightly different: share for Titanium scrap vs. other scrap was calculated using one HS6 product (810830), and assuming the rest to be other scrap.

Use

International trade data was use for splitting product flows in $\mathbf{U}^{\mathbf{EU,RW}}$ and in $\mathbf{U}^{\mathbf{RW,EU}}$, while for splitting by column (i.e. by industry), shares from $\mathbf{g}^{\mathbf{EU}}$ and $\mathbf{g}^{\mathbf{RW}}$ from the supply matrices were employed. Similarly, for splitting by product and industry in domestic matrices $\mathbf{U}^{\mathbf{EU,EU}}$and $\mathbf{U}^{\mathbf{RW,RW}}$, $\mathbf{q}^{\mathbf{EU}}$ and $\mathbf{q}^{\mathbf{RW}}$ and $\mathbf{g}^{\mathbf{EU}}$ and $\mathbf{g}^{\mathbf{RW}}$, were used respectively. This implies that the same input structures and market shares were assumed for the rows and columns to be split. Finally, it worth noting that no final demand of Titanium/aeronautical products was assumed.

Balancing and development of the Input-Output table

Due to the combination of different data sources for splitting rows and columns in Figaro-E3, we used again the GRAS balancing method. This was applied for each EU and non-EU country, respecting the original Supply and the Use matrix of imports, and adjusting the domestic part of the Use matrix and the value added components, which were considered less reliable. Once both Supply and Use matrices were fully balanced, the product-by-product input-output matrix was obtained using the 'industry technology assumption (model B)', which assumes that products can be produced with different technologies depending on the industry where it is actually produced.

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