Resources Policy 111 (2025) 105793

Contents lists available at ScienceDirect

Resources Policy

journal homepage: www.elsevier.com/locate/resourpol

The benefits of enhanced circularity on strategic autonomy: Titanium metal in the EU☆

Alejandro Buesa [a,b,*], Pablo Piñero [a], Luis Pedauga [a,c], José Manuel Rueda-Cantuche [a], Brian Baldassarre [a]

[a] European Commission, Joint Research Centre (JRC), Seville, Spain
[b] E.T.S. de Ingeniería y Sistemas de Telecomunicación, Universidad Politécnica de Madrid, Madrid, Spain
[c] Departamento de Economía y Estadística, Universidad de León, León, Spain

ARTICLE INFO

JEL classification:
Q53
L61
D57

Keywords:
Circular economy
Open strategic autonomy
Critical raw material
Global value chains
Titanium scrap
Granular data
Input–output

ABSTRACT

Strategic autonomy can benefit from circular economy initiatives, such as reducing primary inputs and recycling critical raw materials in key technologies. Using titanium metal in the EU as a showcase, we start by combining information from heterogeneous sources: non-systematic data, macroeconomic statistics and micro-level information from Customs agencies. This procedure allows us to disaggregate secondary (i.e., titanium scrap) flows depending on their production stage, sector of origin and quality. Building upon this novel dataset, 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 retaining and valorizing secondary titanium flows domestically instead of routing it to third countries, most notably if domestic processing capacity is also increased, by up to 40 million euros in value added and around 620 jobs.

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 to address these concerns through several initiatives (Gehrke, 2022): a methodology to identify CRMs along with material lists, foresight studies on the role of critical materials in key technologies (Carrara et al., 2023), and the establishment of the European Raw Materials Alliance, bringing together stakeholders from critical supply chains. The bulk of this content has recently been consolidated in the Critical Raw Materials Act, adopted in March 2024. This regulation aims to align the green and digital transition of the EU 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 for improved strategic autonomy is the circular economy: reducing primary CRM inputs by reusing and repairing products, as well as recycling insofar as possible (Ellen MacArthur Foundation, 2013); a consequence is the reduction of import dependencies. Moreover, the intersection of circularity and use of CRMs is a fundamental part of the green and digital transitions, as many of the technologies encompassed require heavy use of such materials (Carrara et al., 2023),

☆ A previous version of this work was published with the title "*Can circularity in Titanium metal improve EU strategic autonomy? Scenario modelling with heterogeneous data*" in the JRC Working Papers in Economics and Finance (number 2024/06). We thank three anonymous referees and participants of the 1st IRTC Conference (Lille, Feb'23) and the *Journées Technologiques Titane* of the French Titanium Association (Lyon, Oct'23) for their insightful comments and suggestions, as well as Luis Tercero and Denis Stijepic from Fraunhofer ISI for their help mapping worldwide scrap flows. The views expressed in this article are solely the authors' and do not represent those of the European Commission.

* Corresponding author at: European Commission, Joint Research Centre (JRC), Seville, Spain.
E-mail address: alejandro.buesa-olavarrieta@ec.europa.eu (A. Buesa).

https://doi.org/10.1016/j.resourpol.2025.105793
Received 17 November 2024; Received in revised form 11 August 2025; Accepted 11 November 2025
Available online 15 November 2025

and demand for CRMs might grow exponentially just as the technologies requiring them as inputs do, leaving supply chains unprepared to cope with the ramp-up at such speed. 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 throughout the life cycle of products and technologies.

Several policy studies with different methodologies have examined the linkages between circularity and strategic autonomy. For example: a material flow analysis (MFA) with policy scenarios for electric vehicle batteries quantifying how reuse, recycling and substitution reduce primary CRM demand but may shift dependencies to another material (Baars et al., 2021); an analysis of supply chain integration for steel combining case evidence with quantitative modelling to retain resources domestically (Pinto and Diemer, 2020); and EU-level literature/policy mappings that synthesize circular options and constraints for CRMs highlighting waste management, local sourcing and infrastructure stockpiling as key levers (Mathieux et al., 2017; Fellner et al., 2017). Complementary systematic reviews map implementation tools across EU sectors (De Pascale et al., 2023). Another study, prepared contemporaneously to this article, focuses on the geostrategic dimension and its implications for international affairs (Jakimów et al., 2024).

Applying circularity strategies and generating meaningful policy recommendations for the supply chain of a specific CRM or critical product requires 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 EU 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.

2. The titanium metal value chain

2.1. Overview

We provide an overview of the titanium metal value chain as sketched in Fig. 1, in the spirit of Buesa et al. (2023), drawing from insights in Buesa et al. (2025) 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, 2024). 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. 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 (ITA, 2022); a large part is devoted to manufacturing in the aeronautical sector.

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, 2023).[1]
- 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).[2]

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 tonne of components generates 8 tonnes 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 parts in the engine frequently enter a separate re-use loop for such assembly, while the remainder lying 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 (BIS, 2019), component manufacturers will have an increasingly strong incentive to valorize 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.

[1] 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.

[2] As an illustration, the titanium content in older commercial aircraft like the Airbus 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.

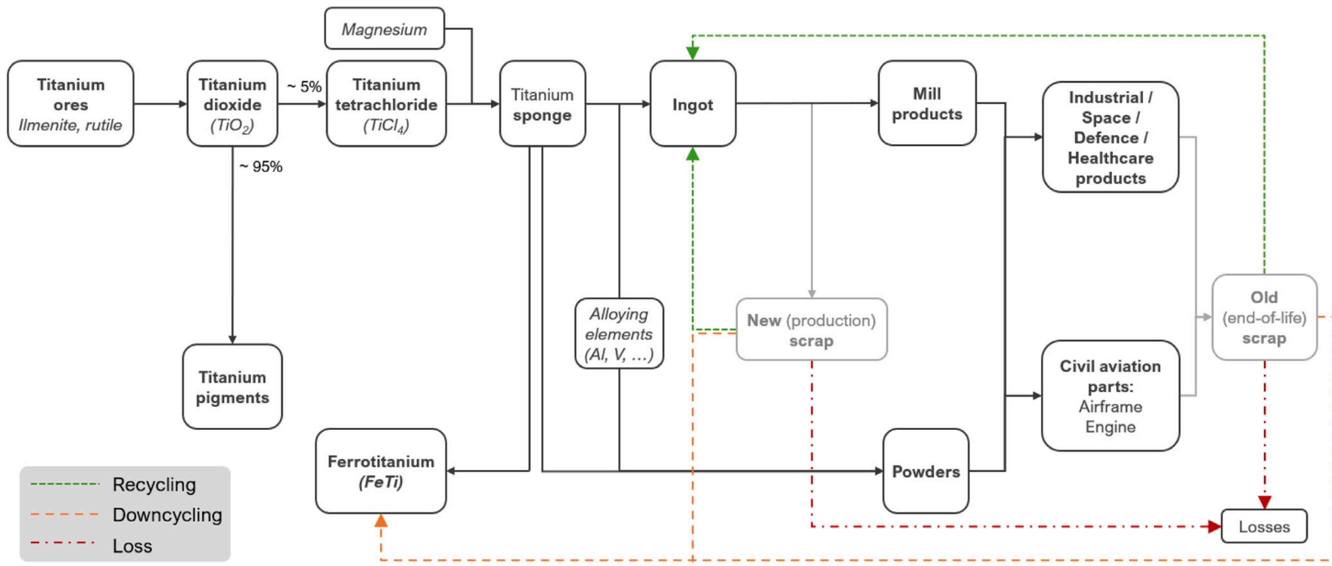

Fig. 1. Overview of the value chain for titanium metal.
Source: Adapted from Buesa et al. (2023).

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, and has no 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 remained listed in the 2023 edition. Aeronautical applications account for 80% of titanium metal consumption in the EU, with a large 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 (Buesa et al., 2025).

A number of features are apparent when analysing the EU's import and export structures of titanium products sketched in Fig. 2 (an overview in value terms is available in Appendix A of Supplementary 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-export ratio of 2:1. Finally, there is a notable asymmetry between the content of imports and exports: scrap makes up for 12.5% of the import mass, against 67% of exports.

Why does the EU export so much scrap overseas? The absence of sponge and ingot manufacturing renders scrap valorization less interesting. EU-generated scrap is often subject to *buyback* agreements, whereby third-country suppliers require that production scrap 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 come up with 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 (Buesa et al., 2025).

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. The application of 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 sources of information: qualitative information from industry reports and stakeholder interviews, quantitative data at the macro (country) level from international trade and production statistics, and quantitative data at the micro level from customs agencies.

3.1. Qualitative and non-systematic data

As a first step, we scanned the information recovered from a consultation of selected stakeholders (Baldassarre, 2025) covering all parts of the value chain and actors from inside and outside the EU. Beyond identifying drivers and barriers to titanium circularity in Europe, the consultation shed light on the value chain to a granularity level unimaginable with aggregate statistics. For instance, we obtained insights on the titanium composition of aeronautical products, or recycling capacities by the main actors. We cross-validated these findings using

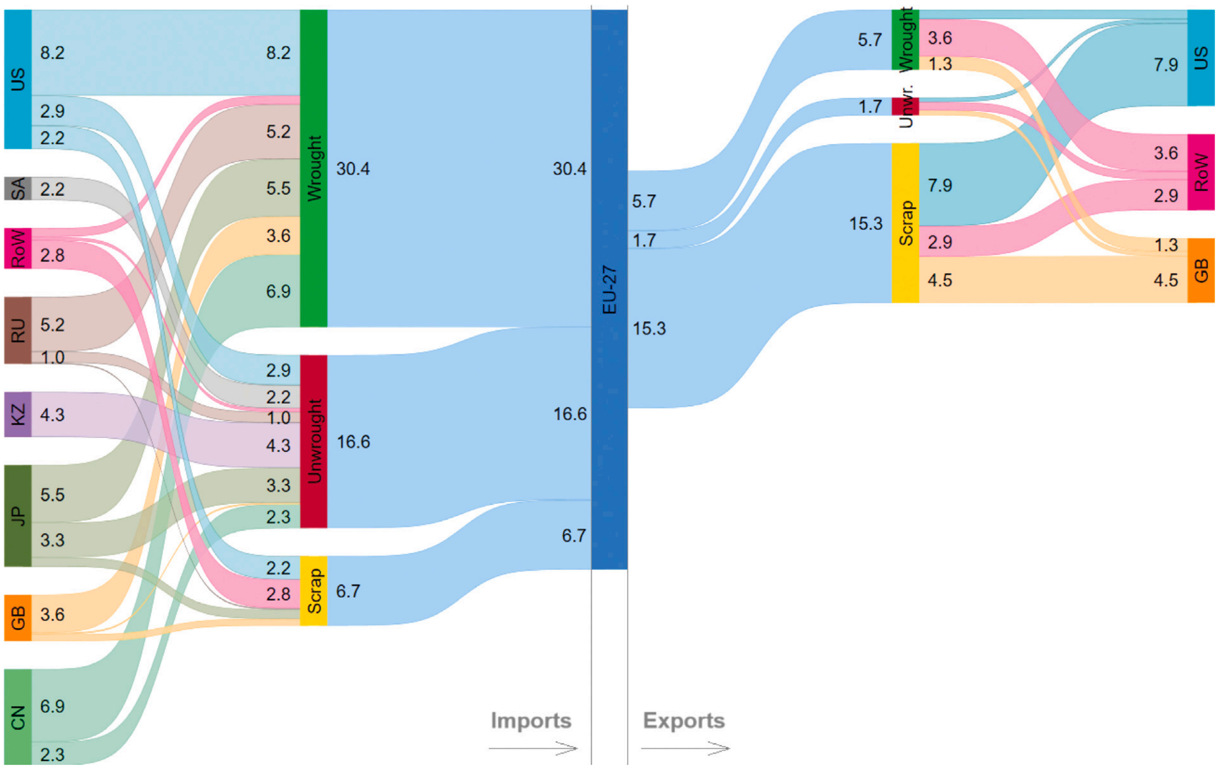

Fig. 2. Overview of extra-EU international trade volumes (in kt) of titanium products in 2023.
Source: Eurostat dataset "EU trade since 1988 by HS2-4-6 and CN8" (ds-045409).

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 of 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.

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 Fig. 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 sectors of origin, or the stage of the value chain at which it is generated. Therefore, macroeconomic quantitative data needs to be enriched with alternative sources.

3.3. Quantitative data: micro

The most suitable complement to aggregate trade statistics are 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 and consignee firm names facilitate mapping scrap flows between sectors (e.g., aeronautical).
- 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 2018–2022 obtained from the S&P Panjiva database.[3] 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 Supplementary 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 presented in Fig. 4.

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 valorized 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 Fig. 4, flows to the US are much larger than flows from the US (see Fig. 2).

Customs-level data is also subject to several limitations: First, not all countries provide shipment-level data, and even among those that

[3] Panjiva aggregates customs datasets from 17 countries in the world accounting for 40% of global merchandise trade.

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

Titanium metal value chain		
Sectoral Ti demand 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 (Mfg. of wrought products from ingot): 5:1 New (Mfg. of aero parts from wrought products): 2:1 Old (end-of-life): 1:5	
Destination of scrap by value chain stage (Recyclable, downcycled, lost)	New (Mfg. of milled products from ingot): 60%, 16%, 24% New (Mfg. of parts from milled products): 61%, 18%, 21% Old (end-of-life): 40%, 46%, 15%	
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 parts 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 (2040 forecast)	12% (narrow-body), 15% (wide-body)	
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: 21 to 35% Landing gear: 5 to 10% Avionics and systems: 5 to 10% Furnishings: 14%	Wings: 20 to 27% Tail section: 3.6 to 15% Engine: 15 to 20%
Ti alloy content in aircraft engines	20–30%	
% engines in Ti alloy parts in commercial aircraft	60%–70% (interview), 20%–42% (other sources)	

In addition to insights obtained from the stakeholder consultation in Baldassarre (2025), the main sources for this table are: For the titanium metal value chain, Buesa et al. (2025), Louvigné (2023), and Takeda et al. (2020); for the scrap figures, Feng et al. (2023), Inagaki et al. (2014), ITA (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 (2023), Peters et al. (2003), and Uhlmann et al. (2015).

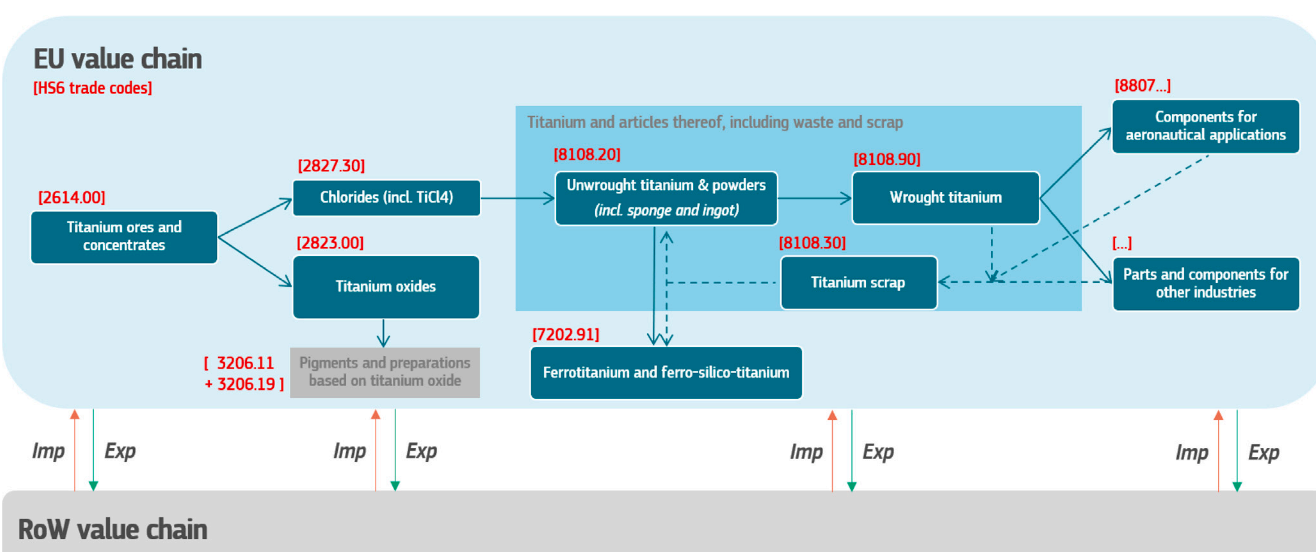

Fig. 3. Titanium value chain as viewed from international trade data. Arrowed lines represent theoretical primary (continuous line) and secondary (dashed line) product flows.
Source: Authors' elaboration from Eurostat dataset "EU trade since 1988 by HS2-4-6 and CN8" (ds-045409).

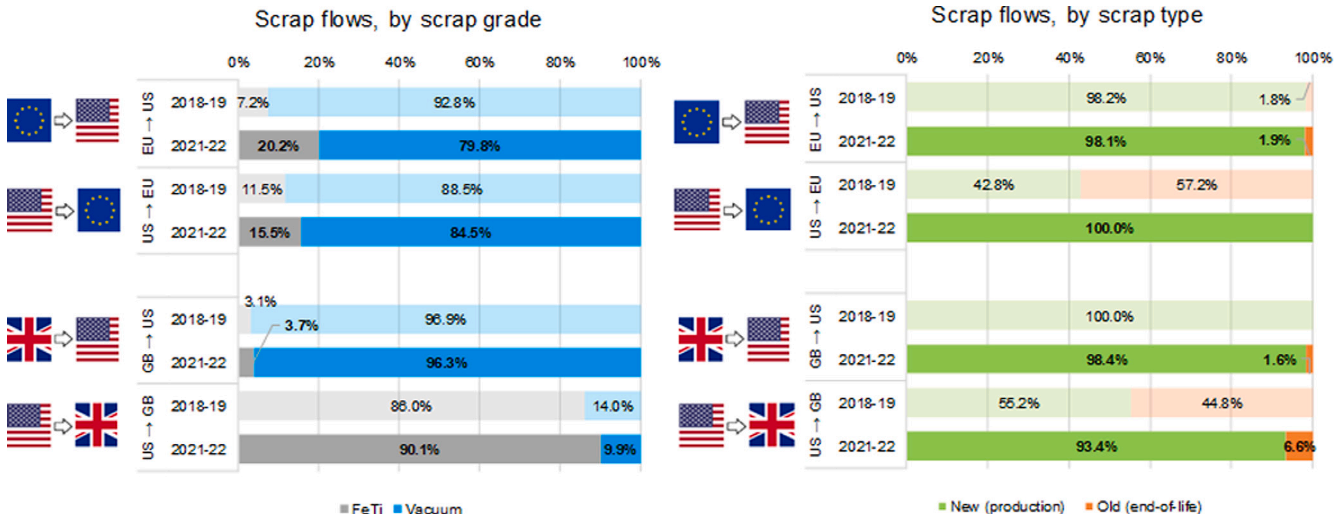

Fig. 4. Disaggregation of titanium scrap trade flows using shipment-level information.
Source: Authors' calculations using the customs dataset extracted from S&P Panjiva.

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.

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 Fig. 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 publicly available UK trade data is much less disaggregated than the EU side.

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). Estimating a 60% scrap ratio for remelting — in the lower/conservative end if the most recent technologies are considered[4] – 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 production capacity in the range of 8 to 12 kt (Marscheider-Weidemann et al., 2021): a ramp-up to 11.4 kt 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.

Fig. 5 summarizes the steps involved in the construction of our scenario in terms of trade and production categories, 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%.

[4] In the EU, the largest ingot manufacturers use older melting technologies which result in a lower scrap ratio (30%–50%). A newly launched factory can reach up to 75%: we adopt 60% as a reasonable aggregate estimate, which is also consistent with figures reported for the US (Buesa et al., 2025).

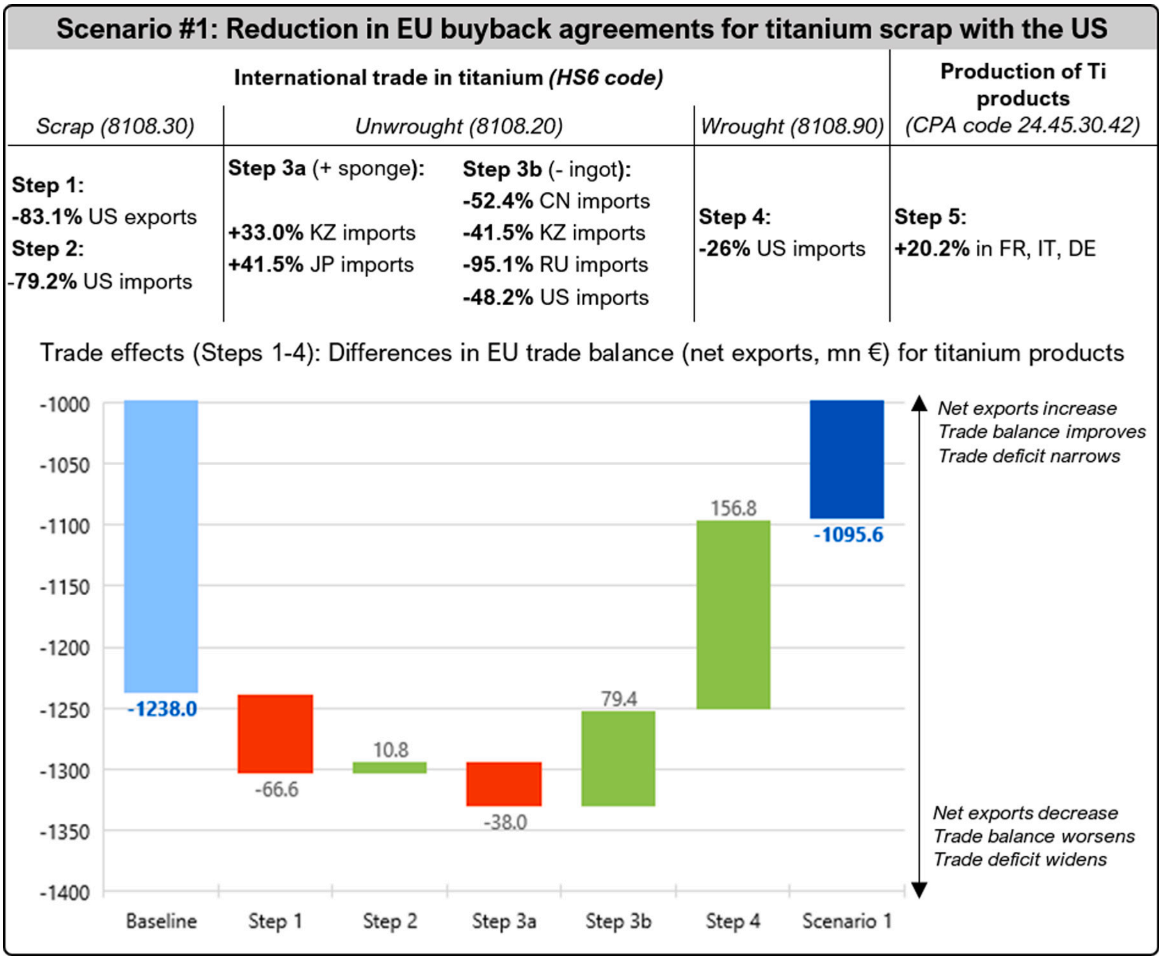

Fig. 5. Summary of Scenario 1 effects on EU international trade and production.
Source: Authors' calculations based on Eurostat dataset ds-045409.

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. Fig. 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.

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 (Mahajan et al., 2018). 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.[5] 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.

[5] 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.

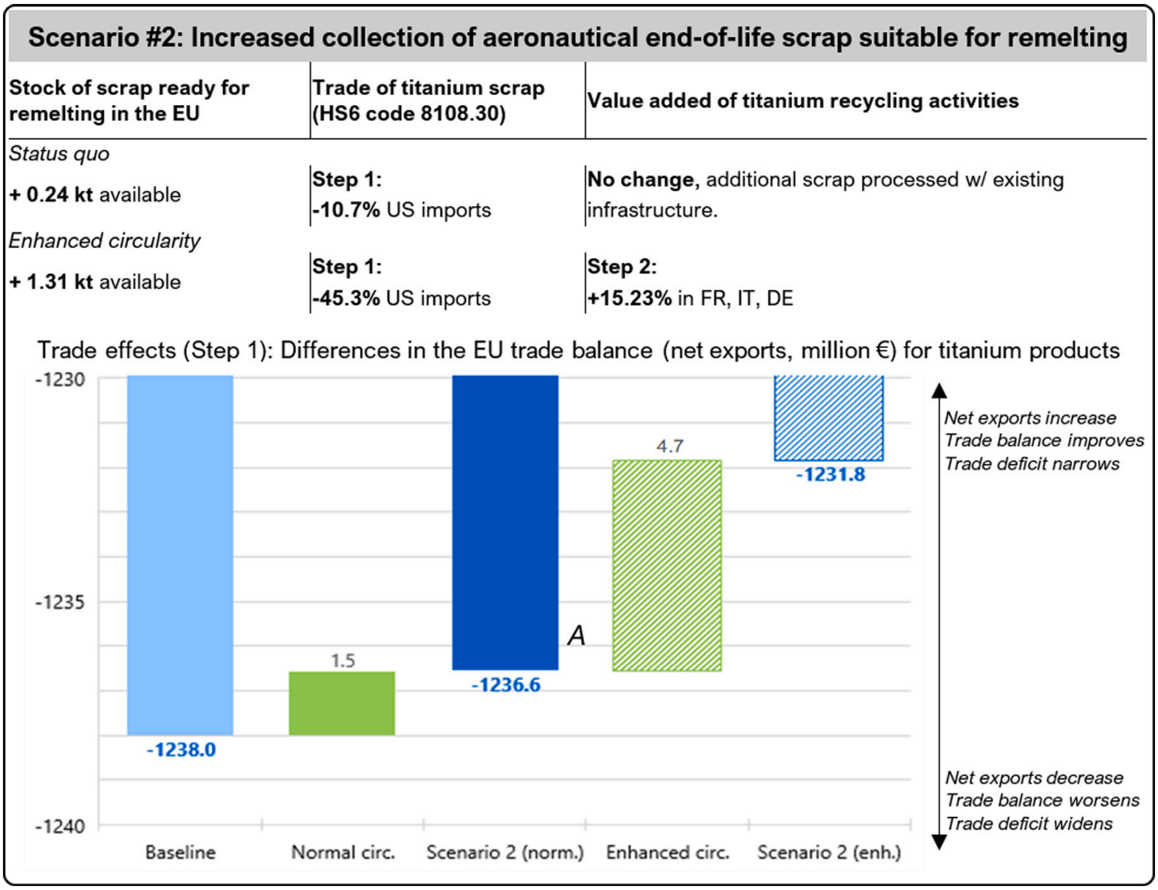

Fig. 6. Summary of Scenario 2 effects on EU international trade and production.
Source: Authors' calculations based on Eurostat dataset ds-045409.

We employed the FIGARO-E3 experimental dataset[6] that extends the FIGARO coverage to 213 products and 176 industries for the year 2015, including employment data in number of workers, and climate change emissions in CO_2 equivalents (CO_2e) (Cazcarro et al., 2025). This database was the starting point of a specific model for tracing flows of titanium and aeronautical products along global value chains (see Appendix C of Supplementary Information S1).

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 is reviewed thoroughly in Miller and Blair (2021), 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 Mahajan et al. (2018), namely GRAS (Gunluk-Senesen and Bates, 1988; Junius and Oosterhaven, 2003; Temurshoev 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, 2021) that are eventually compared (in levels) with those of the original inter-country input–output database (baseline), as described in Eq. (1) (see Appendix C for details on the economic interpretation):

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

In Eq. (1), υ is a row vector of the value added (also employment or CO_2 equivalent) per unit of sectoral output, L is the Leontief inverse matrix and 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 $\bar{L}$. As a result, α 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 7.5 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 Fig. 5) which mathematically decreases total output. Conversely, the reduction in scrap imports also yields no visible negative economic impact; this 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 economy and not on 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

[6] FIGARO-E3 is available at the Joint Research Centre Data Catalogue.

Table 2
EU-wide effect of scenarios on value added, employment, and emissions (marginal effect of each step in italics).

Scenario #1: Reduction in EU buyback agreements for titanium scrap with the US						
	Value added (mn)		Employment (# workers)		GHG emissions (CO_2e kt)	
Step 1 (US exports)	−7.5		−117.0		−6.0	
Step 1 to 2 (US imports)	−7.5	*0.0*	−117.4	*−0.3*	−6.1	*0.0*
Step 1 to 3a (KZ, JP sponge imports)	−6.7	*0.8*	−104.2	*13.2*	−5.6	*0.4*
Step 1 to 3b (US, CN, KZ, RU ingot imports)	−8.5	*−1.8*	−132.6	*−28.4*	−6.5	*−0.8*
Step 1 to 4 (US imports)	−8.8	*−0.3*	−136.9	*−4.3*	−6.7	*−0.2*
Step 1 to 5 (FR, IT, DE production)	30.1	*38.9*	483.7	*620.6*	24.2	*30.9*
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)	−0.0028		0.0		−0.0017	
Enhanced circularity						
Step 1 (imports from the US)	−0.0126		−0.2		−0.0077	
Step 1 to 2 (recycling activities in the EU)	0.2963		2.9		0.6607	

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 has a moderate impact if compared with lower ingot imports. 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 40 million euros and 620 jobs along the whole supply chain with respect to the baseline, accounting for approximately 60,000 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 2 shows that Step 1 reduces GHG emissions by 6 CO_2 equivalent kilotonnes, whereas Step 3(a) (resp. b) increase (decrease) emissions by 0.4 (0.8) kt. 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: 24 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 300,000 euros, and a surge in emissions of about 0.7 CO_2 equivalent kilotonnes. Employment would remain virtually unchanged.

6. Discussion

Our paper is a first attempt to reconcile heterogeneous data sources and render them usable for policy simulation purposes in a systematic and orderly fashion, ideally allowing for replication with other strategic materials and technologies. 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 et al., 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 (BIS, 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[7] 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.[8] 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 620 workers to the titanium supply chain, including direct and indirect contributions from suppliers, and 40 million euros to its total output. Putting both dimensions together implies that eliminating buyback agreements could triple 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, and 25% of the largest one.

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 plant producing ingot mostly from scrap employs 40 workers, 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 quadruple them.

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

[7] Extracted from the ORBIS database.

[8] These three firms, together with EcoTitanium (France), comprise the full set of active ingot-making facilities in the EU, as identified in Buesa et al. (2025). The EU titanium mid-stream segment is therefore extremely concentrated, and the benchmarking exercise reflects the actual population of relevant producers rather than a selective or skewed sample.

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 our hypothetical scenarios is positive in employment and output terms. On the other hand, despite yielding much smaller economic benefits 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. On the side, 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.

Operationalising these scenarios requires a coordinated set of industrial, environmental, and regulatory policy levers at the EU level. The CRM Act mandates that by 2030, at least 40% of strategic raw materials must be processed and 25% recycled domestically — setting binding targets that provide long-term signals for investment in EU melting and scrap processing infrastructure. To facilitate this, the Act simplifies permitting procedures and offers financial backing for strategic projects; notably, the Commission recently endorsed a first batch of 47 initiatives, including 11 in the recycling domain (European Commission, 2025). Other existing policy initiatives in the EU playbook such as the Green Deal Industrial Plan can further channel funding towards capacity expansion, particularly for high-grade aerospace applications which are capital-intensive. However, capacity investment alone is insufficient if regulatory barriers to circularity persist. In the aeronautics sector, stringent recertification and safety rules limit the reuse of titanium parts and EU directives currently classify end-of-life aircraft materials as waste, discouraging domestic recycling. Revising such standards and applying end-of-waste criteria to titanium alloys could unlock a secondary raw materials market and improve the economic viability of circularity. Together, these combined efforts are essential to ensure that strategic autonomy objectives translate into tangible employment and output gains.

Beyond the EU, the economic mechanisms and policy lessons are relevant to other major geopolitical actors in the titanium value chain. For instance, the US remains a net importer of titanium sponge despite hosting the world's largest aerospace industry, and its dependence on a limited set of external suppliers creates similar vulnerabilities to those observed in the EU. China, by contrast, controls a dominant share of global sponge production but relies heavily on exports of semi-finished and finished products to downstream consumers. These asymmetries suggest that policy strategies combining import diversification with domestic capacity ramp-up – such as those modelled in Scenario 1 – can be relevant in multiple geographies. Moreover, the economic viability of end-of-life scrap collection, while limited in isolation, becomes more attractive when integrated into broader industrial policy frameworks aiming to reduce input cost volatility and enhance value added domestically. Our results also highlight the role of global trade frictions: curbing titanium scrap exports, as in the EU–US buyback context, may yield employment and output gains domestically, but could trigger retaliatory measures.

6.2. Limitations of the study

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). We quantify the uncertainty stemming from our disaggregation procedure and assumptions in Appendix F of Supplementary Information S1, where we consider a smaller share of traded vacuum-grade scrap with the US coupled with a more moderate scrap ratio and compute deviations from the baseline figures in Scenario 1 for each step. This exercise yields several useful elasticities: in step 1, a 1 pp decrease in the vacuum-grade share of scrap exports to the US is associated with a 1.26% decrease in the effects on value added, employment, and emissions; in step 3b, a 1 pp decrease in the scrap ratio is associated with 0.5% decreases in the trade-induced effects on GDP and employment and 0.375% on emissions; and in step 5, a 1 pp decrease in the scrap ratio is associated with a 9% increase in the manufacturing-induced effects on GDP, employment, and emissions.

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. Aggregating EXIOBASE to official FIGARO does not yield the same figures, and deviations are noticeable; 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. In addition, it is argued that the disaggregated model employed in this study is a superior choice to using solely FIGARO-E3 and Eurostat's FIGARO at the 64-product level, especially in the case of Eurostat's FIGARO, as the results of the sensitivity analysis in Appendix E of Supplementary Information S1 suggest.

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 on 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 systematize 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 funnel through 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.

CRediT authorship contribution statement

Alejandro Buesa: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Project management. **Pablo Piñero:** Writing – review & editing, Writing – original draft, Methodology, Data curation. **Luis Pedauga:** Methodology, Conceptualization. **José Manuel Rueda-Cantuche:** Writing – review & editing, Methodology, Conceptualization. **Brian Baldassarre:** Writing – review & editing, Conceptualization, Visualization, Project management.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The research was supported by the European Commission – Directorate General Joint Research Centre as part of the bounCE4ward Project of the Centre for Advanced Studies of Unit S.4 (Scientific Development Programmes), hosted by Unit B.5 (Circular Economy and Sustainable Industry).

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.resourpol.2025.105793.

Data availability

The authors do not have permission to share data.

References

Akgüç, M., Pochet, P., 2023. European Single Market 2.0: Striving for a more social and environmental market aligned with Open Strategic Autonomy. EconPol Forum 24 (05), 19–22.

Al-Shamma, O., Ali, R., 2013. Aircraft weight estimation in interactive design process. In: 72nd Annual International Conference on Mass Properties Engineering. St. Louis, MO, USA.

Baars, J., Domenech, T., Bleischwitz, R., Melin, H., Heidrich, O., 2021. Circular economy strategies for electric vehicle batteries reduce reliance on raw materials. Nat. Sustain. 4, 71–79. http://dx.doi.org/10.1038/s41893-020-00607-0.

Baldassarre, B., 2025. Circular economy for resource security in the European Union (EU): Case study, research framework, and future directions. Ecol. Econom. 227, 108345. http://dx.doi.org/10.1016/j.ecolecon.2024.108345.

BIS, 2016. U.S. Strategic Material Supply Chain Assessment: Titanium. U.S. Department of Commerce, Bureau of Industry and Security Office of Technology Evaluation, URL https://www.bis.doc.gov/index.php/documents/technology-evaluation/2094-titanium-supply-chain-assessment.

BIS, 2019. The Effect Of Imports Of Titanium Sponge On The National Security. U.S. Department of Commerce, Bureau of Industry and Security Office of Technology Evaluation, URL https://www.govinfo.gov/content/pkg/FR-2021-10-26/pdf/2021-23301.pdf.

Buesa, A., Albizzati, P., Garbarino, E., Saveyn, H., Baldassarre, B., 2023. Circular economy in EU critical value chains: The case of titanium metal in defence and civil aviation. In: Proceedings of the 5th PLATE Conference. Espoo, Finland, pp. 149–154. http://dx.doi.org/10.13140/RG.2.2.11104.66566.

Buesa, A., Georgitzikis, K., Jakimow, M., Pinero Mira, P., Maury, T., Latunussa, C., Pedauga, L., Samokhalov, V., Baldassarre, B., Mathieux, F., Rueda Cantuche, J., Stijepic, D., Reys, A., Bilous, A., Notom, P., Tercero Espinoza, L., 2025. Titanium Metal in the EU: Strategic Relevance and Circularity Potential. Publications Office of the European Union, Luxembourg, http://dx.doi.org/10.2760/5871804, JRC137082.

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., Christou, M., 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, Luxembourg, http://dx.doi.org/10.2760/386650, JRC132889.

Cazcarro, I., Usubiaga-Liaño, A., Román, M., Piñero, P., Dietzenbacher, E., Rueda-Cantuche, J., Arto, I., 2025. FIGARO-E3: a high-resolution extended multi-regional input-output database consistent with official statistics. Sci. Data 12 (1), 575. http://dx.doi.org/10.1038/s41597-025-04431-z.

De Pascale, A., Giannetto, C., Limosani, M., Ioppolo, G., Szopik-Depczyńska, K., Lanfranchi, M., 2023. The circular economy implementation at the European Union level: Past, present and future. J. Clean. Prod. 423, 138658. http://dx.doi.org/10.1016/j.jclepro.2023.138658.

Dietzenbacher, E., Van Burken, B., Kondo, Y., 2019. Hypothetical extractions from a global perspective. Econ. Syst. Res. 31 (4), 505–519. http://dx.doi.org/10.1080/09535314.2018.1564135.

Ellen MacArthur Foundation, 2013. Towards the Circular Economy (Vol.2). Ellen MacArthur Foundation.

European Commission, 2023. Proposal for a Regulation of the European Parliament and 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.

European Commission, 2025. Commission Decision C(2025) 1904 Final of 25 March 2025 — Recognising Certain Critical Raw Material Projects As Strategic Projects under Regulation (EU) 2024/1252. URL https://single-market-economy.ec.europa.eu/document/download/9b159533-2a45-4d43-bf33-6ca5fa88440d_en?filename=C_2025_1904_1_EN_ACT_part1_v2.pdf.

Fellner, J., Lederer, J., Scharff, C., Laner, D., 2017. Present potentials and limitations of a circular economy with respect to primary raw material demand. J. Ind. Ecol. 21 (3), 494–496. http://dx.doi.org/10.1111/jiec.12582.

Feng, E., Gao, D., Wang, Y., Yu, F., Wang, C., Wen, J., Gao, Y., Xu, S., 2023. Sustainable recovery of titanium from secondary resources: A review. J. Environ. Manag. 339, 117818. http://dx.doi.org/10.1016/j.jenvman.2023.117818.

Gehrke, T., 2022. EU open strategic autonomy and the trappings of geoeconomics. Eur. Foreign Aff. Rev. 27 (Special Issue), 61–78. http://dx.doi.org/10.54648/eerr2022012.

Gunluk-Senesen, G., Bates, J.M., 1988. Some experiments with methods of adjusting unbalanced data matrices. J. R. Stat. Soc. Ser. A (Statistics Society) 151 (3), 473–490. http://dx.doi.org/10.2307/2982995.

Helwig, N., Sinkkonen, V., 2022. Strategic autonomy and the EU as a global actor: The evolution, debate and theory of a contested term. Eur. Foreign Aff. Rev. 27, 1–20. http://dx.doi.org/10.54648/eerr2022009.

Inagaki, I., Takechi, T., Ariyasu, Y., 2014. Application and features of titanium for the aerospace industry. In: Nippon Steel & Sumitomo Metal Technical Report. Vol. 106, pp. 22–27, URL https://api.semanticscholar.org/CorpusID:138460261.

ITA, 2022. Proceedings of the world titanium conferences. Documents available at https://titanium.org/general/custom.asp?page=ti_Proceedings.

Jakimów, M., Samokhvalov, V., Baldassarre, B., 2024. Achieving European Union strategic autonomy: circularity in critical raw materials value chains. Int. Aff. 100 (4), 1735–1748. http://dx.doi.org/10.1093/ia/iiae127.

Junius, T., Oosterhaven, J., 2003. The solution of updating or regionalizing a matrix with both positive and negative entries. Econ. Syst. Res. 15, 87–96. http://dx.doi.org/10.1080/0953531032000056954.

Louvigné, P.-F., 2023. Étude De Veille Sur Le Marché Du Titane 2018 – 2020. Ministère de la Transition Ecologique et Solidaire, République Française, URL https://www.mineralinfo.fr/sites/default/files/documents/2021-10/louvigne_titane_rapport_2018-2020_edition_publique.pdf.

Mahajan, S., Beutel, J., Guerrero, S., Inomata, S., Larsen, S., Moyer, B., Remond-Tiedrez, I., Rueda-Cantuche, J., Simpson, L., Thage, B., Rompaey, C., Verbiest, P., Di Matteo, I., Kolleritsch, E., Alsammak, I., Brown, G., Cadogan, A., Elliot, D., Havinga, I., 2018. Handbook on Supply, Use and Input-Output Tables with Extensions and Applications. United Nations Department of Economic and Social Affairs, Statistics Division, ISBN: 978-92-1-1.

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, L., 2021. Raw Materials for Emerging Technologies 2021. Technical report, DERA - Deutsche Rohstoffagentur, Berlin, Germany, URL https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-50-en.pdf.

Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G.A., et al., 2017. Critical Raw Materials and the Circular Economy: Background report. Publications Office of the European Union, Publications Office of the European Union, Luxembourg, http://dx.doi.org/10.2760/378123, JRC108710.

Miller, R., Blair, P., 2021. Input-Output Analysis: Foundations and Extensions, third ed. Cambridge University Press, ISBN: 978-1-108-72353-4, http://dx.doi.org/10.1017/9781108676212.

Miró, J., 2023. Responding to the global disorder: the EU's quest for open strategic autonomy. Glob. Soc. 37 (3), 315–335. http://dx.doi.org/10.1080/13600826.2022.2110042.

Peters, M., Kumpfert, J., Ward, C., Leyens, C., 2003. Titanium alloys for aerospace applications. Adv. Eng. Mater. 5 (6), 419–427. http://dx.doi.org/10.1002/adem.200310095.

Pinto, J., Diemer, A., 2020. Supply chain integration strategies and circularity in the European steel industry. Resour. Conserv. Recycl. 153, 104517. http://dx.doi.org/10.1016/j.resconrec.2019.104517.

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. http://dx.doi.org/10.1016/j.enpol.2022.113329.

Takeda, O., Ouchi, T., Okabe, T., 2020. Recent progress in titanium extraction and recycling. Met. Mater. Trans. B 51 (4), 1315–1328. http://dx.doi.org/10.1007/s11663-020-01898-6.

Temurshoev, U., Miller, R., Bouwmeester, M., 2013. A note on the GRAS method. Econ. Syst. Res. 25 (3), 361–367. http://dx.doi.org/10.1080/09535314.2012.746645.

Tukker, A., Wood, R., Schmidt, S., 2020. Towards accepted procedures for calculating international consumption-based carbon accounts. Clim. Policy 20 (sup1), S90–S106. http://dx.doi.org/10.1080/14693062.2020.1722605.

Uhlmann, E., Kersting, R., Klein, T., Cruz, M., Borille, A., 2015. Additive manufacturing of titanium alloy for aircraft components. Procedia CIRP 35, 55–60. http://dx.doi.org/10.1016/j.procir.2015.08.061.

USGS, 2024. Mineral Commodity Summaries 2024. United States Geological Survey, http://dx.doi.org/10.3133/mcs2024.

Wang, W., Wu, F., 2023. Dataset of annual metal scrap circularity of titanium industry in China from 2005 to 2020. Nat. Sci. Data 10 (1), 435. http://dx.doi.org/10.1038/s41597-023-02351-4.