Institut européen
European Institute

LUISS
School of Government

Joint Master in Global Economic Governance and Public Affairs

Achieving Economic Security in Critical Raw Materials through the Circular Economy: An Analysis on European Union's Policies and Legislation

Supervised by William Neale

Mar Pujol Arqué

2024/2025

Thesis Pitch

Access: https://youtu.be/L-gvZ_UX2eE

Statutory Declaration

I hereby declare that I have composed the present thesis autonomously and without use of any other than the cited sources or means. I have indicated parts that were taken out of published or unpublished work correctly and in a verifiable manner through a quotation. I further assure that I have not presented this thesis to any other institute or university for evaluation and that it has not been published before.

25.07.2025

Pujol Arqué, Mar

Acknowledgements

The process of writing this thesis has been both a great challenge and a valuable learning opportunity for me. Combining this master's experience with moving to three different countries in a year and starting a full-time internship at the end of the thesis-writing period has presented me with challenging situations, but it has also been a valuable experience that has taught me a great deal about myself. This achievement would not have been possible without the unwavering support of those closest to me. I am deeply grateful to my family and friends back home, whose encouragement has been essential throughout this journey. I would also like to thank the people who have guided me and have shared their knowledge to help me produce the best thesis possible. First of all, my supervisor, William Neale, who has guided me through each step of the process. I greatly appreciate his availability and understanding throughout these months, as well as his willingness to share his expertise and knowledge. I would also like to acknowledge all the CIFE and Luiss staff, especially Omar and McKenzie, who have always been available to respond to any question and provide advice throughout this process. Lastly, to all the newfound friends I have made this year, with whom I have shared this special experience. I am deeply grateful for all the moments we have had the opportunity to share over the last few months and for all the unconditional support they have provided me with.

Abstract

The twin green and digital transitions have intensified the demand for critical raw materials (CRM), essential for strategic sectors such as renewable energy, digital technologies, aerospace, and defense. However, the European Union's (EU) heavy reliance on CRM imports from a limited number of countries presents significant risks to resource security and supply stability. In this context, the circular economy (CE) has emerged as a tool to decrease dependencies by promoting recycling, substituting, extending product lives, and reintroducing secondary materials to the market. This study presents a qualitative policy analysis focusing on how key EU legislation and policy frameworks support the adoption of circular economy approaches to enhance economic security and sustainability for CRMs. By conducting a comparative analysis between titanium metal and cobalt circularity barriers and drivers, the study identifies different policy gaps affecting both material-specific barriers and broader systemic challenges hindering the integration of circularity into the EU's raw materials strategy. It also explores how the implementation of market instruments and strategies, including public procurement, taxation, or minimum recycled content, could enhance the establishment of a single market for secondary raw materials. This research contributes to the existing literature and policy debate by illustrating the potential of circular economy principles in attaining economic security in strategic areas, while safeguarding environmental sustainability and upholding competitiveness.

Keywords: *Critical Raw Materials, Circular Economy, Economic Security, European Union*

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Background

The global transition towards a "green" and digital economy has dramatically increased the demand for critical raw materials (CRMs), making their secure supply one of the most pressing challenges for policymakers. Listed by the European Union (EU) under the Critical Raw Materials list, these materials have become critical because of their economic importance and supply risks, playing an essential role in strategic sectors such as renewable energy, digital technologies, aerospace, and defense (European Commission, 2023). As a result of these strategic applications, the International Energy Agency predicts that the global demand for these materials will increase significantly in the next two decades, creating a risk of the depletion of the reserves of some of them, such as lithium, cobalt, and nickel, by 2050 (Suikkanen & Turunen, 2024). In the European Union in particular, the demand for key materials like rare earth metals and lithium is expected to increase six-fold by 2030 and twelve-fold by 2030 respectively, facing significant challenges to secure access to them given the current global competition (Carrara et al., 2023).

The EU's limited domestic production capacity for these materials has led to the creation of heavy dependencies on imports from a limited number of countries. This creates significant supply vulnerabilities, including exposure to supply chain disruptions, geopolitical tensions, and market volatility. Recent geopolitical developments like Russia's invasion of Ukraine have posed concerns about the overreliance on third countries and the EU's vulnerabilities to external shocks. In this context, the EU has put an emphasis on the need to achieve economic security for CRMs to foster resilience and competitiveness of European industries, while meeting the climate and digital objectives set at European level (European Commission, 2023).

In order to decrease the dependency on third countries and achieve resource security, the EU needs to find alternative sources to increase autonomy in these necessary materials. This can be mainly achieved through two strategies, increasing mining and production within the EU; or through circular economy (CE) approaches such as extending functional lives of products containing them, substituting, recycling, and reintroducing the materials that already exist. Given the limited known reserves of virgin CRMs available in the EU, the circular economy emerges as an important tool by decoupling economic growth from material use and its environmental impacts (Baldassarre, 2025). The concept is understood under the Circular Economy Action Plan of the European Commission as maintaining the value of products, materials, and resources in the economy for as long as possible, and minimizing the generation of waste (COM(2015) 614 final, p. 2). European policymakers have recognized the opportunities provided by the CE in reducing dependencies and advancing autonomy, adopting it as an essential strategy in the ambition of a green and competitive economy, and including it as a key component in many EU policy initiatives (Calisto Friant et al., 2021).

The recently adopted Critical Raw Materials Act has enhanced the potential of the circular economy by setting the target of meeting 15% of the EU's annual consumption of strategic raw materials through domestic recycling capacity by 2030 (Watkins et al., 2023). Furthermore, in two recent reports commissioned by European Commission President Ursula von der Leyen to Mario Draghi and by the European Council to Enrico Letta, on European Competitiveness and the Single Market, the criticality of secondary CRMs and the circular single market is also discussed. In his report, Draghi (2024) argues that the EU could potentially meet more than half to three-quarters of its metal requirements for clean technologies by 2050 through local recycling. On the other hand, Letta (2024) claims that the EU should embrace the wide establishment of a circular single market by providing a level playing field for circular materials, products, and services. In this regard, there are fundamental pillars that need to be covered to end the fragmentation of European markets (European Commission, 2020), such as the standardized circularity criteria for products, setting requirements for recycled content in products, unifying approaches to end-of-waste criteria, and increasing funding (Letta, 2024).

1.2. Purpose and Structure

This study aims to address these gaps by examining how European legislation and policy support the circular economy for critical raw materials. To do so, a comparative analysis focusing on two materials, titanium metal and cobalt, is conducted in order to identify possible barriers and drivers of CRMs circularity in the EU. These cases offer complementary insights stemming from different strategic sectors, with titanium metal being essential for aerospace and defense industries, and cobalt constituting a key component in lithium-ion batteries needed for electric vehicle and energy storage industries (Carrara et al., 2023). The study highlights how EU policy frameworks interact with material-specific circularity challenges, providing an overview of both broad and material-specific barriers within the EU.

While the main focus of research is the EU's economic security in relation to critical raw materials through the application of circular economy principles, this study is also guided by several sub-questions that help complement the research scope and provide a comprehensive view on critical raw material management and governance. Mainly, it also explores (1) how current EU policy frameworks balance strategic objectives of sustainability, economic security, and competitiveness when addressing CRMs; (2) what are the policy mechanisms that could better align EU economic security goals with circular economy principles for CRMs; (3) what specific strategies are needed to enhance the single market for secondary raw materials; and (4) to what extent does the current EU classification system for critical raw materials and strategic raw materials effectively support circular economy implementation and economic security objectives. By answering these questions this study argues that while the EU has laid a promising foundation for integrating circular economy principles into its CRM strategy, certain barriers and policy gaps still exist.

To effectively respond to all the research questions and provide a compelling argument, this study is structured in six chapters. Following this introduction, the literature review provides an overview of the state of academic knowledge with regard to the conceptualization of CRMs, criticality assessment and methodologies, and the policy responses and circular economy framework, identifying possible research gaps and situating this research within them. Subsequently, chapter three outlines the methodology and underlines the limitations encountered during the research process. Chapter four presents the case studies of titanium metal and cobalt, analyzing both barriers and drivers to the circularity of the two materials within the EU policy context, and concluding with a comparison between the two. Moreover, chapter five builds on this comparison and synthesizes these findings in a broader discussion, evaluating the current policy framework in the EU and reflecting on future possible directions and the implementation of correcting market instruments. Lastly, the final chapter concludes the study by restating the main findings and proposing avenues for future research.

2. Literature review

2.1. Introduction

The growing importance of raw materials for the global economy, particularly in the context of the energy transition, has driven a surge in academic and policy works on the importance of securing their supply. In the European context, the concept of Critical Raw Materials (CRMs) has gained attention in the past decade and has emerged as a pillar of resource policy, reflecting both economic dependencies and strategic vulnerabilities. Nonetheless, the definition and framing of the concept of criticality has not been linear and it has evolved over time, influenced by changing geopolitical contexts, industry needs, and environmental considerations. This evolution shows that "criticality" is not an internationally agreed concept, but rather a dynamic and context-dependent evaluation considering economic, technological, and political differences. For this reason, a growing number of scholars have conducted criticality assessments to evaluate the differences in methodology and indicator selection, illustrating an ongoing debate about the possible areas for international consensus. The European Union has developed its own methodology over time, refining indicators to better reflect the factors conditioning economic importance and supply risk. Moreover, the European Union's CRMs framework has established a Critical Raw Materials Act (CRMA), and introduced the importance of secondary raw materials in achieving economic security over these resources. This new trend has been reflected in the Union's policy initiatives, increasing the focus on the potential of circularity.

This literature review aims to provide an overview of the ongoing debate about the conceptualization of criticality and the existing conversation around the policy initiatives developed in the EU. It starts with the definition and conceptualization of criticality of raw materials, exploring the origins of the term and the evolution of the EU's categorization, including the existing limitations. It then outlines the ongoing debate about key methodologies and criteria used to assess criticality, identifying limitations and possible grounds for consensus. Lastly, it covers the policy responses that the EU has put in place in order to secure the supply of these resources, and it delves into the potential role that the Circular Economy could play in achieving this resource security, introducing some of the EU initiatives being developed around secondary raw materials.

2.2. Definition and Conceptualization of CRMs

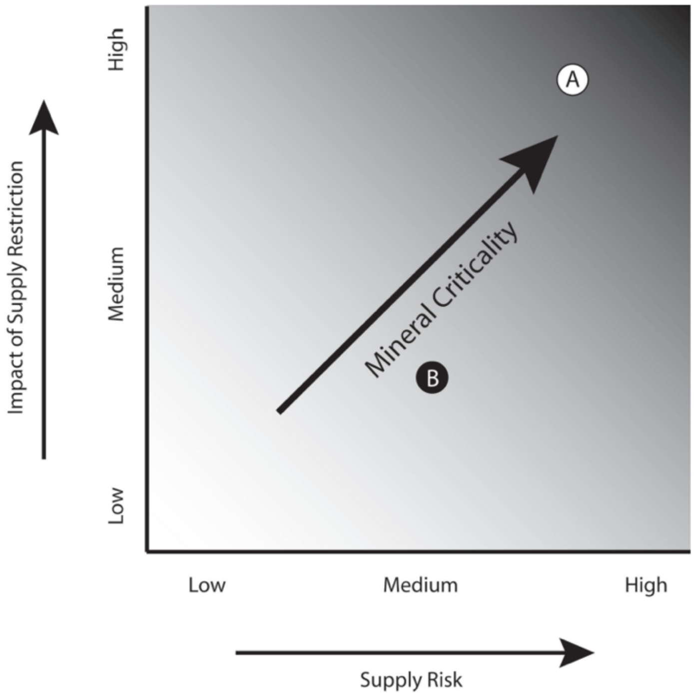
2.2.1. Evolution and Definition of CRMs

Critical raw materials (CRMs) are predicted to be essential in the future, due to their relevant role in the digital and green transitions, and the development of key sectors that are increasingly gaining importance, including the clean energy, defense, and high-technological sectors. Although these trends are foreseen to happen globally, there is currently no internationally agreed-upon single definition of criticality. Therefore, different methodologies are applied to asses and determine the criticality of these elements resulting in a continuously evolving conception.

The concept of criticality has appeared in the literature since the late 1930s, with the approval of the US "Strategic and Critical Materials Stock Piling Act" of 1939 , which recognized the possible supply chain risks due to the reliance on foreign resources and provided for the retention of stocks of certain strategic and critical materials for military, industrial and essential civilian needs of the US defense (IEA, 2022). In 1971, with the oil and cobalt crisis, the Byrd Amendment modified the 1939 Act to include the imports of strategic materials from non-communist countries, even if similar materials could be imported from communist countries. This amendment allowed the US to bypass the embargo on Rhodesia and import key minerals like chromite, further signaling the geopolitical importance of some of these elements (Randolph, 1978, p. 57). In 2008, the US National Research Council highlighted the importance of non-fuel minerals in modern U.S. society with the establishment of a new methodology for determining the criticality of materials based on metal's supply risk (essentiality in use) and impact of supply restriction (subjection to supply restriction) (NRC, 2008). This matrix (***Figure 1***) first directed at US federal agencies, decisions makers and private sector, later became the cornerstone for several frameworks.

Figure 1

Criticality Matrix



Note. From *Minerals, Critical Minerals, and the U.S. Economy*, by NRC, 2008 (https://doi.org/10.17226/12034).

Modern literature has shifted the debate to the criticality of non-energy minerals, aiming at developing methods to evaluate criticality of minerals and reviewing how potential supply bottlenecks could affect national economies, particular industries or technologies (Barteková & Kemp, 2016, p. 4). In their article "Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyse" Erdmann and Graedel (2011), established the first comprehensive review to standardize and compare the methodologies used to assess raw material criticality. The authors argued that "the broad concept of raw material criticality seeks to capture both the supply risks on the one hand and the vulnerability of a system to a potential supply disruption on the other" (Erdmann & Graedel, 2011, p. 7620), building on the two-dimensional matrix between supply risk and vulnerability, while introducing a third dimension based on environmental implications (Jin et al., 2016, p. 82). According to Jin et al. (2016), the frameworks defined by the US's National Research Council (2008) and the one redefined by Erdmann and Graedel (2011) are the most recognized ones and the basis of many of the subsequent analyses and assessments (Jin et al., 2016).

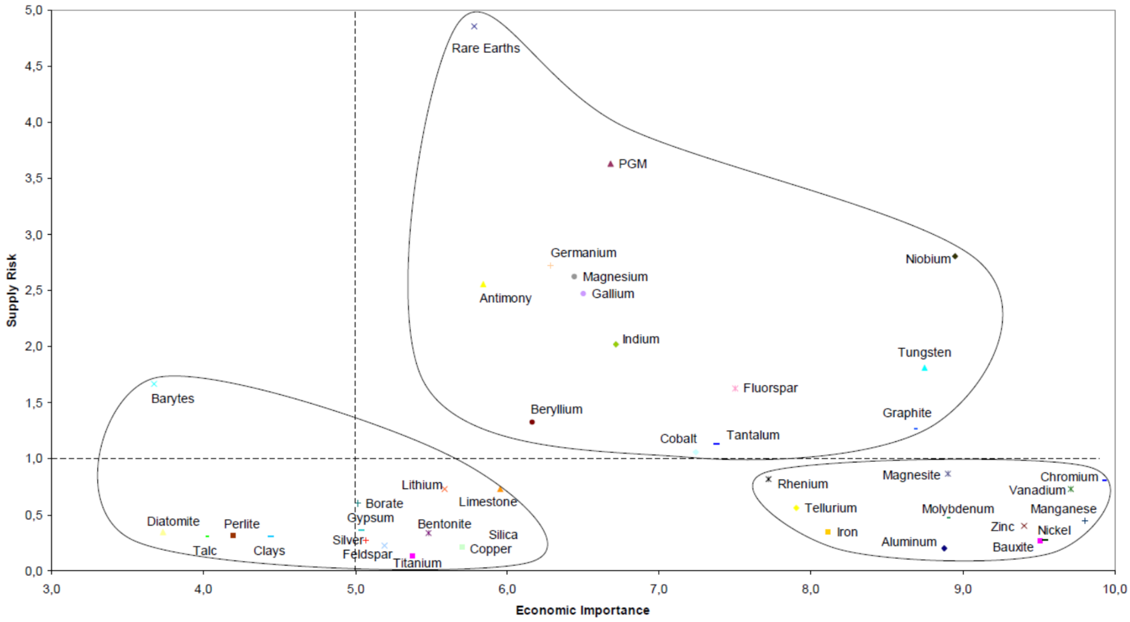
2.2.2. The EU's Categorization of CRMs

The European Union has also recognized the importance of securing the supply of critical raw materials for its economy, launching various initiatives over the years. The first was the 2008 EU Raw Materials Initiative (RMI), a diversification strategy aimed at securing non-energy materials for EU industrial value chains and societal wellbeing, seeking to reduce dependencies by sourcing primary raw materials from the EU and third countries, and increasing secondary raw materials supply through resource efficiency and circularity (European Commission: DG GROW et al., 2023). One of the key priorities within this strategy was the definition of a methodology to establish a list of critical raw materials at EU level. Under the framework of the RMI in 2009 the European Commission established an Ad Hoc Working Group on Defining Critical Raw Materials (AHWG), as an advisory group in identifying the non-energy raw materials considered as critical for the EU (European Commission: DG GROW et al., 2017). This team developed the EU methodology based on the NRC (2008) two-dimension proposal, inverting the axes of the critical matrix (***Figure 2***) (Fernández Gómez et al., 2024, p. 281; Jin et al., 2016, p. 82) and identifying two main criteria defined by the European Commission: DG GROW et al., (2017) as:

> **Economic Importance (EI)** - calculated based on the importance of a given material in the EU end-use applications and performance of its substitutes in these applications (p. 26).
>
> **Supply Risk (SR)** - calculated based on factors that measure the risk of a disruption in supply of a given material (e.g. supply mix and import reliance, governance performance measured by the World Governance Indicators, trade restrictions and agreements, existence and criticality of substitutes) (p. 26).

Figure 2

EU 2011 Criticality Assessment



Note. The 2011 EU criticality assessment included 41 non-energy, non-agricultural raw materials, and listed 14 CRMs. From *Report lists 14 critical mineral raw materials (MEMO/10/263)*, by European Commission, 2010 (file:///Users/martipujolcasals/Desktop/Report_lists_14_critical_mineral_raw_materials.pdf).

The list was established to be updated every three year and was first published in 2011, identifying 14 CRMs out of the 41 candidate raw materials (European Commission, 2011). In 2014 the list increased the number of materials to 20 out of 54 candidates (DG ENTR, 2014). Nonetheless, after the publishing of the list in 2014, DG Joint Research Centre (DG JRC) was commissioned to reevaluate the methodology used and improve the assessment of criticality for 2017. According to G. A. Blengini et al., (2017), while preserving the highest level of comparability with previous EU assessments, specific incremented improvements implemented by DG JRC were necessary to make the methodology more robust and reliable. Following G. A. Blengini et al., (2017):

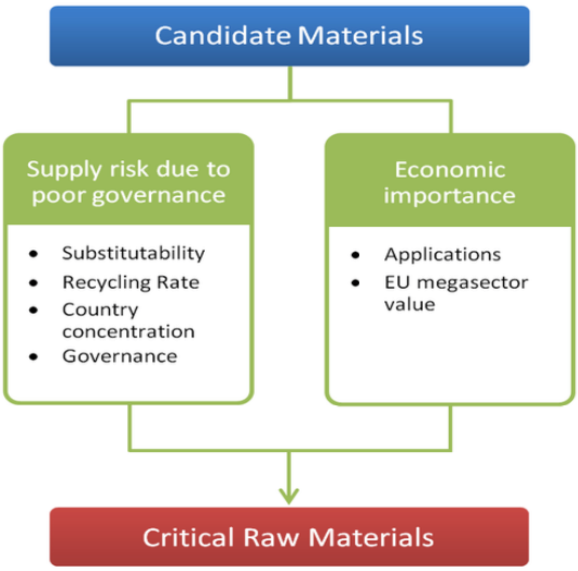
> Improvements in the **SR dimensions** included the incorporation of trade barriers and agreements, adoption of more systemic supply chain approach, consideration import

dependence and better representation of the actual supply to the EU, and reinforcement of the role of recycling along with the improvement of representativeness of data for the EU. On the other hand, considerations for the **EI dimension** accounted for a more detailed and transparent allocation of raw materials uses to their corresponding NACE (Statistical Classification of Economic Activities in the European Community) sectors, and the use of material-specific substitution index (SIEI) to allow for the reduction of potential consequences due to insufficient supply (p. 14).

With the implementation of this new methodology, the EU identified in 2017, 27 CRMs out of 78 candidates, and in 2020 30 out of 83 candidates DG GEOW et al., 2023). The 2020 methodology included some transformations mainly: (1) incorporating a systemic two-stage supply risk assessment, evaluating mining/extracting and processing/refining stages; (2) optimization of data quality and transparency; and (3) better coordination to develop further Material System Analyses, including improvements in End-of-Life Recycling Input Rate (EOL-RIR) results (G. A. Blengini et al., 2020).

Figure 3

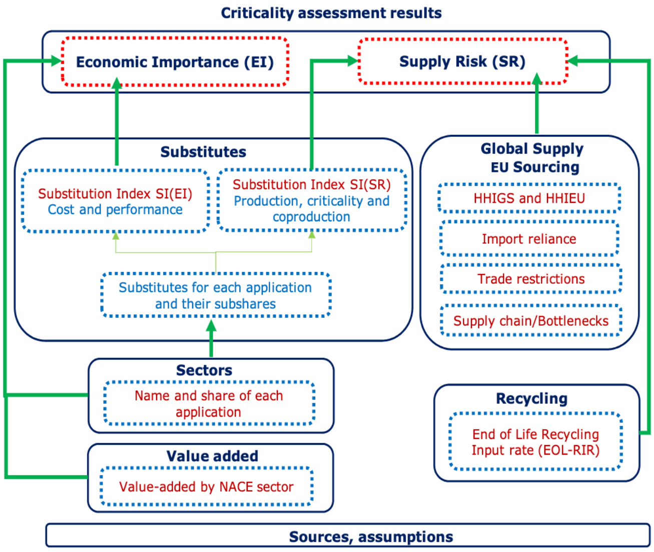
Components of the 2014 EU criticality methodology



Note. From *Report of critical raw materials for the EU*, by DG ENTR, 2014 (https://rmis.jrc.ec.europa.eu/uploads/crm-report-on-critical-raw-materials_en.pdf).

Figure 4

Structure of the 2017 EU criticality methodology



Note. From *Study on the review of the list of critical raw materials – Final report*, by European Commission: British Geological Survey, Bureau de Recherches Géologiques et Minières, Deloitte Sustainability, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs and TNO, 2017 (https://data.europa.eu/doi/10.2873/876644).

2.2.3. Limitations in EU Criticality Methodology

Since 2017 the EU criticality assessment methodology has continuously evolved to incorporate a broader range of factors. In 2023 with the adoption of the Critical Raw Materials Act (CRMA), the methodology was further updated and adapted to the new framework, which will be covered in section 3. However, debate has emerged in the literature about the effectiveness and efficiency of the methodology employed by the EU, highlighting some existing limitations.

According to Espinoza (2023), the lists of CRMs produced by the EU are heavily dependent on the perspective of the people drafting them, making it crucial to preserve transparency in data and calculations as an asset of the EU methodology (p. 15). Moreover, the author argues that methodological difficulties emerge mainly in two aspects, firstly in how to capture the value of raw materials for the EU economy more accurately, and secondly in data limitations such as quantifying net imports of raw materials or estimating recycling rates and its associated risks (Espinoza, 2023, p. 15).

Buijs et al. (2012), focus on the limitations that CRMs lists have as policy tools, arguing that while issues affecting the security of supply are persistent, the criticality of raw materials can vary with the changing market conditions (p. 201). Some of the minerals identified as critical might only present a temporary threat and other underlying long-term problems might not be captured by criticality assessments (p. 207). Moreover, the reliance on historical data and the dynamic nature of raw material markets pose challenges for criticality studies to create long-term policy guidance (p. 207). Thus, the authors state that although shortlists of CRMs are fitted for drawing the attention of policymakers to current issues, the usefulness of these lists as long-term policy instruments depends on the methodology's success in reflecting the underlying risks with supply and the timeframe used in the analysis.

Girtan et al. (2021), further analyze the usefulness of EU'S CRMs reports, stating that due to the evolving nature of the technologies required for the green and digital transition, as well as the country interdependence shown by the Covid-19 pandemic, the reliance on historical geopolitical data make the reports virtually outdated at the time of publication (p. 6). Thus, the authors plead for the incorporation of more defined scenarios taking into account the abundance and scarcity of elements at the global level, and the availability from EU sources, emphasizing that "with the transition of European industry toward climate neutrality, current dependence on fossil fuels could be replaced with a dependence on raw materials" (Girtan et al., 2021, p. 14).

2.3. Criteria and Methodologies for Assessing CRM Criticality

As shown in section 2, the EU assesses criticality based on economic importance (EI) and supply risk (SR). Nonetheless, raw material criticality is a field that has been widely discussed in literature due to the important role that criticality assessments play for the industry and policymakers (Schrijvers et al., 2020, p. 4). Although this study does not seek to focus on the different approaches to criticality assessment, this section will cover an overview of the debate on criticality assessments and will identify possible limitations.

According to Schrijvers et al. (2020), various methodologies have emerged for assessing criticality, each tailored to different contexts and priorities. While some studies evaluate the criticality of raw materials based on their importance to national defense or a country's economy, others focus on specific technologies, industries, or products (p. 14). Thus, although most analyses acknowledge potential supply chain disruptions, the differences in scope and context lead to ambiguities regarding which materials are classified as critical. The two-axis framework between supply risks and the vulnerability to a potential supply disruption described in section 2 has been used by most studies, but its heterogeneous development and implementation has created divergences in results and ultimately hinders unified understanding and effective policymaking (Dewulf et al., 2016; Graedel & Reck, 2015).

In arguing for a common denomination of criticality, literature agrees that heterogeneity and context-dependence of methodologies pose a significant challenge. Graedel and Reck (2015), argue in favor of establishing a uniform methodology to meet the needs of corporations and governments (p. 697). However, the authors acknowledge that creating a harmonized methodology would require extensive consultation among interested parties in order to agree upon a single set of factors where often there is no consensus, including geology, geopolitics, environmental issues, substitutability, and recycling potential (p. 693, 697). Moreover, due to the context-dependency of criticality, it would require periodic reevaluation, considering it as a degree rather than a state (p. 692).

Similarly, Dewulf et al. (2016), focus on the two-axis assessment framework, together with other key aspects such as the scope of the materials, the role of substitution, the delineation of the supply chain and data, and indicator selection. The authors state that the international criticality assessment community should gather on a systemic basis in order to find consensus and convergence on the factors accounted for criticality, including methodological approaches and calculation, required data, and indicators for criticality assessment (p. 173-174). They argue that criticality should be positioned in the broader sustainability debate of raw materials supply, and environmental issues should be considered as an extension to the components accounted for supply risks (p. 170, 174).

One of the principal reasons why consensus is widely unachieved is the focus on demand-side actors and their perspective-dependent evaluation of criticality, centering on the actor's market position and specific context (Schicho & Espinoza, 2024). The study by Schicho and Espinoza (2024) shows that while supply risk considerations are common to all methodologies, the assessment of associated damages differs depending on the system being evaluated, concluding that criticality assessments follow the interests of the actors designing it, with demand-side systems being the main drivers. Following Achzet & Helbig (2013), this is further accentuated by the lack of agreement on the indicators chosen to provide reliable information on the supply risk branch of the assessments, such as substitution, recyclability, or climate change vulnerability. The divergence in indicators used by assessment studies makes their results almost incomparable (p. 436).

Studies also claim that the criticality of materials is a complex issue that should be understood from a multi-parameter approach, considering geological, economic, technological, environmental, and social concerns (Graedel & Reck, 2019). Ioannidou et al. (2019), state that the current framework is largely static, failing to adequately address the socio-economic, technological, or policy dynamics affecting raw material availability and importance. The authors argue that criticality methodologies should develop a more dynamic approach, with dynamic indicators able to adapt to temporal changes and provide more accurate risk evaluation to decision-makers. Similarly, Castro Sejin et al. (2023), agree that the term of criticality assessments must be understood from a multifaceted approach, taking into account various parameters and factors in order to mitigate supply risks, navigate market volatility, and strengthen resource sustainability (p. 14). Through a holistic approach, it is possible to deviate from context-dependent definitions and establish a unified global term for raw materials criticality (Castro Sejin et al., 2023, p. 3)

Overall, the literature covering criticality assessment methodologies calls for a wider consensus on the international level, particularly regarding the selection of indicators. The debate on the future of the methodological framework mainly centers on whether indicators such as climate change vulnerabilities, recyclability, or environmental impacts should be considered in criticality assessments. This debate interconnects with the call to broaden the scope of criticality assessments to successfully cover the different and evolving parameters influencing risk evaluation.

2.4. Policy Responses and the Role of Circular Economy

2.4.1. Key EU Regulations on CRMs

As discussed in section 2.3 the EU updated its CRMs policy in 2023 with a new list identifying 34 out of 70 candidate raw materials as a result of the European Commission's "Study on the Critical Raw Materials for the EU 2023" (European Commission: DG GROW et al., 2023). In 2023 the Commission also launched a Regulation proposal for the establishment of a new framework under a Critical Raw Materials Act (CRMA), "for ensuring a secure and sustainable supply of critical raw materials" (COM(2023) 160 final). Under the CRMA further refinements were introduced to the EU methodology, including a new categorization for Strategic Raw Materials (SRMs). The new classification of SRMs was established to identify the materials "most crucial for strategic technologies used for the green, digital, defense and aerospace applications" (European Commission, 2023). As stated by Espinoza (2023), the recognition of SRMs follows its own methodology and data basis, although the results largely overlap, with 14 out of 16 SRM also classified as CRMs. Nonetheless SRMs are characterized by 3 factors explained by Espinoza (2023) as:

> (1) high expected demand growth, (2) a difficulty to significantly increase production, and (3) comparatively low level of identified economically extractable geological resources (reserves) compared to current production (p. 4).

According to Hool et al. (2024), depite the incorporation of these three criteria, the lack of a transparent and well-determined methodology for the classification of SRMs, could lead to the politization of mineral criticality analysis, making the field more volatile. The introduction of this new category, together with their possible subjection to specific regulations, could create new industry dynamics, with "industries lobbying for specific raw materials to be classified as strategic and putting more resources into SRM projects" (Hool et al., 2024, p. 665).

The CRMA further reshaped the methodology by introducing a set of benchmarks for 2030, such as extracting 10%, processing 40%, and recycling 15% domestically, and ensuring that no more than 65% of the EU's annual consumption from a single-third country

(European Commission, 2023). In addition, it set stricter supply chain monitoring to improve resilience and introduced streamlining permitting procedures for critical raw materials projects in the EU selecting strategic projects (European Commission, 2023). A list of 47 strategic projects was announced in March 2025, aiming at reinforcing the security of supply of CRMs (European Commission, 2025).

The Commission Proposal and later approval of the Act in 2024, fall under the scope of the Green Industrial Plan and the Net-Zero Industry Act, which authors argue are a response to the current geopolitical context and the US Inflation Reduction Act (Gómez et al., 2024, p. 274), as well as part of a global trend towards protectionism on technological development and resources from the clean transition (Hool et al., 2024, p. 662).

2.4.2. Role of Circular Economy in Achieving Economic Security

The CRMA also introduced sustainability and circularity of critical raw materials as key pillars of the EU'S CRMs strategy (European Commission, 2023), recognizing the potential of secondary raw materials in reducing dependencies with external actors.

As discussed in section 3, several studies have evaluated the methods used to determine raw material supply risk, including the inclusion of recycling as an indicator in the calculation of supply risk. However, according to G. A. Blengini et al. (2017), the studies that have added recycling as an indicator have done it in a less prominent role in comparison to the EU methodology, both regarding visibility and impact on the results (p.16). EU methodology has consistently included end-of-life recycling input rate (EOL-RIR)', as a mitigation factor that can lower the risk of supply, considering that the portion of EU supply of CRMs provided by recycling of end-of-life products is more secure than other sources of supply, such as primary supply through mining (G. A. Blengini et al., 2017, p. 17).

As stated by Lundaev et al. (2023), due to the risks associated with mining and abundance limitations, primary materials will not be sufficient to meet the needs of new energy systems. The authors argue that this is further hampered by short-term local criticality evaluations rather than a global criticality concept and long-term sustainability goals that would allow material circularity based on the material flows of the global economy (p. 15). Circularity is perceived as a potential solution to address material criticality and recycling as essential for reducing dependence on primary production. However, low recycling rates and limited scrap availability might decrease the role of recycling in material supply in the short and medium term (until 2050) (p. 14).

Jakimów et al. (2024)**,** also agree with the importance of the recycling pillar of the CRMA, focusing on the potential of circularity in reshoring of the mid-value chain industry to the EU, considering post-fabrication virgin scrap and the untapped potential of recycling materials (p. 1748). Focusing on the case of titanium, the study also discusses the possible trade-offs between EU objectives. While boosting the recycling targets under the CRMA aligns the concern for strategic autonomy with the European Green Deal (p. 1735-1736)**,** the case of titanium value chains highlights the difficulties that the EU might encounter in achieving the combined ambitions of decarbonization and reindustrialization, since doing it so in a way that is economically competitive, and socially and environmentally sustainable, might prove challenging under the current global competition for CRMs (p. 1748).

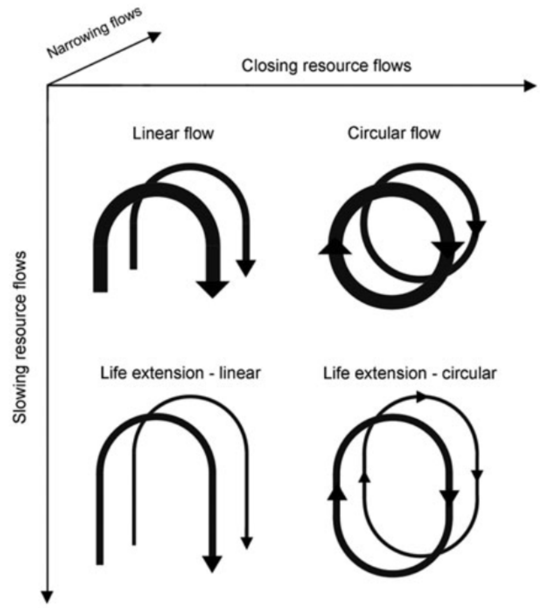
2.4.3. Circular Economy Framework for EU policies

The framework developed by Bocken et al. (2016), as a model for strategies facilitating the transition from a linear to a circular economy has been established as a cornerstone of circularity policies. The study introduces the terminology of slowing, closing, and narrowing resource loops as:

> **Slowing resource loops**: Through the design of long-life goods and product-life extension (i.e. service loops to extend a product's life, for instance through repair, remanufacturing), the utilization period of products is extended and/or intensified, resulting in a slowdown of the flow of resources.
>
> **Closing resource loops**: Through recycling, the loop between post-use and production is closed, resulting in a circular flow of resources. These two approaches are distinct from a third approach toward reducing resource flows:
>
> **Resource efficiency or narrowing resource flows**: aimed at using fewer resources per product (p. 309).

Figure 5

Illustration of linear and circular approaches to reducing resource use



Note. From *Product design and business model strategies for a circular economy*, by Bocken et al., Journal of Industrial and Production Engineering, 2016 (https://doi.org/10.1080/21681015.2016.1172124).

Månberger (2023), applies this terminology to the case of CRMs and the potential of circular economy in contributing to security arguing that circular economy policies can alleviate some pressure on primary metal extraction, which will ultimately be needed due to the finite mineral reserves (p. 76). The study argues that in terms of closing and slowing the loop the impact of reducing primary demand will be minor in the short-term, but will increase exponentially as more renewable energy technologies reach their end-of-life (p. 77-78). Narrowing the loops could be achieved by finding less critical substitutes, though it could result in lower performance and less recyclable material in products (p. 77).

The framework established by Bocken et al. (2016), has emphasized the importance of slowing resource loops through the design of products. According to Van Gaalen and Chris Slootweg (2025), this has created a paradigm shift in product design and material utilization, with the "Design for Circularity" being recognized as the overreaching solution. The authors argue that transitioning towards products already accounted to be recycled and closed-loop systems is crucial for sustainable resource use (p. 4), with "policies encouraging or mandating the use of recycled materials in manufacturing playing a fundamental role in fostering a circular economy, as illustrated by battery recycling in the EU's Battery Directive and Battery Regulation" (p. 5).

2.5. Identification of Research Gaps

This literature review has highlighted existing scholarly debates and research gaps, including the lack of consensus for a standardized criticality assessment methodology and indicator selection, as well as the call for a more holistic approach to criticality evaluations in order to get a broader picture of supply risk factors and avoid short-term biases. Additionally, another research gap that could be further explored is the accuracy and efficiency of CRMs lists and classification. Although the aim of this study is not centered on evaluating criticality assessment methodologies, these debates are important to frame the reason why these resources are considered critical and the evolving nature of the term, as well as the limitations that the current approach presents to policymaking.

Understanding the EU's approach to CRMs policy, particularly the role of the circularity pillar and the broader strategic trends shaping EU policy initiatives, is essential for framing the analysis of the selected case studies. This perspective allows for the identification of possible limitations and barriers that hinder the development of secondary material markets and circularity pathways. Moreover, some of the limitations that could be further researched and that this study wants to tackle include the potential trade-offs between EU policy objectives and the barriers to recycling. Therefore, this study seeks to contribute to the knowledge being produced about the potential of secondary raw materials in reducing dependencies and securing the supply of raw materials. More precisely, it aims to assess how the circular economy of CRMs is treated in the policy narrative of the EU, contributing to the ongoing debate about the new wave of EU policy and its relation to competitiveness and economic security.

3. Research Methodology

3.1. Research Approach and Design

This study examines the intersection between European Union critical raw materials policies and circular economy implementation against the backdrop of evolving economic security concerns. Building on the identified gaps in CRM literature, this research specifically addresses the underexplored integration of circular economy principles within EU criticality policies and frameworks. While existing scholarship has focused extensively on criticality assessment methodologies, limited attention has been given to how circular economy principles are operationalized for CRMs within complex policy environments balancing sustainability, economic security, and competitiveness objectives.

The main research question guiding this study is: How does European legislation and policy support the circular economy for CRMs? To systematically address this overarching question, this study employs a qualitative research approach centered on policy analysis through a comparative case study. Choosing two of the 34 critical raw materials on the EU list as case studies, this research aims to examine how European legislation and policy support circular economy approaches to CRMs, identifying possible drivers and barriers. Following Yin's (2018) methodological framework, the use of a qualitative case study approach enables an in-depth examination of contemporary phenomenon within their real-world contexts, particularly when the boundaries between phenomenon and context are not clearly evident. This is the case of critical raw materials circularity, which cannot be understood without the companion context of the complex policy and market environment in the EU.

The selection of two distinct materials enables the exploration of how the same policy context interacts differently with specific material characteristics. As stated by Yin (2018), multi-case research designs bring substantial analytical benefits, they provide a holistic approach to a complex policy environment while allowing for the selection of purposeful cases rather than representativeness by statistic sampling. The purposeful case selection focuses on choosing the cases that better relate to the research question, in this case, having an understanding of the EU policy and legislative barriers and trade-offs. Moreover, as supported by George and Bennett (2005), small-N studies allow for deeper context analysis and detailed process tracing of policy mechanisms affecting circular economy implementation for different materials.

The approach of comparative case studies has been used in previous circular economy research to interpret regulatory frameworks and industry dynamics, as well as to identify the challenges in the development and functioning of the circular economy (Holzer et al., 2023; Will, 2019). In addition, this research is designed not only to contribute to the literature gaps described in the literature review above (section 2), but as a policy-oriented analysis with practical applications. By creating policy-relevant research, the findings will contribute to both the generation of academic knowledge and the creation of evidence to influence policy decisions (Nutley et al., 2007). The findings will help policymakers understand how the EU policy framework interacts with material and sector specific limitations, as well as identify possible supply bottlenecks, bridging the academic discourse and policy practices in the critical raw materials field.

3.2. Case Study Selection

The two materials selected for the comparative case study portion of this research have been chosen following the "most different" rationale, referring to cases that differ on several specific variables (Zimmerman, 2022). The materials studied, titanium metal and cobalt, are both CRMs and have recently been included in the strategic material list within the CRMA framework, highlighting their key role in strategic areas of the European economy. However, they both diverge in end-use sectors, recycling maturity, and policy focus, enabling the comparison to extend beyond a specific sector or product group. Focusing on these two materials provides a deeper understanding of strategic sectors like the defense and aircraft industries in the case of titanium metal, and the battery sector in the case of cobalt. Thus, this it supports the overall objective of identifying how EU policy frameworks perform across very different material contexts, strengthening the arguments of this study.

3.3. Data Collection

In terms of data collection, the evidence for the research is drawn mainly from primary and secondary type of sources. Additionally, semi-structured interviews with stakeholders, provide complementary qualitative data to the analysis.

3.3.1. Primary Sources

Primary sources consist mainly of EU legislative texts, official reports, and policy documents. These types of sources are essential for responding to the research question since they provide the foundation for the case analysis and are crucial for laying out the legislative context concerning the circular economy and CRMs in the EU. Therefore, EU policy documents, including legislative texts, such as directives and regulations, strategic documents, action plans, and roadmaps have been explored in order to identify key policy trends in the EU and specify possible trade-offs (***Table B 1***). Additionally, official reports and communications from the European Commission have provided a considerable basis for the policy analysis. Finally, technical reports produced by the EU Joint Research Center (JRC), have also provided a solid foundation for the development of the case study analysis. These resources have been retrieved through the Eur-Lex website, the official EU website for legislative texts, as well as public documentation.

In addition to the policy documentation provided by the official EU channels, news and white papers developed by relevant stakeholders have also been used in the research process. The use of these types of sources has been useful in introducing diverse perspectives on the subject of CRMs and the circular economy, as well as on the EU policy landscape. The opinions of different industry sectors, including firms and other type of organizations, contribute to the debate and provide valuable data.

3.3.2. Secondary Sources

Secondary sources, including journal articles, books, policy briefings, news articles and reports, and official websites have been employed throughout the study, particularly in the literature review section. These sources complement the information gathered through the primary sources by providing an academic perspective and theoretical backdrop, context on recent developments and trends, and other supplementary evidence. To identify relevant scholarly literature on the circular economy, EU policies, and critical raw materials, academic search engines like Google Scholar, Scopus, Web of Science, JSTOR / ScienceDirect and SSRN have been used. These tools were also key for identifying suitable theoretical approaches, comparative case studies, and methodological frameworks aligned with this study's research design.

3.3.3. Semi-structured Interviews

This study also employed semi-structured interviews as a complementary qualitative data collection method. Semi-structured interviews were selected because they enable a flexible yet guided conversation through prepared questions, as well as the opportunity to delve deeper into issues raised by participants (Kvale & Brinkmann, 2009). A total of two stakeholder interviews were conducted, adapting the questions to the backgrounds of the interviewees but always tackling frour main topics (see Annex A): general EU policy framework for circularity and CRMs, barriers and drivers of particular CRMs and the possible transferability to CRMs as a whole, potential trade-offs between EU objectives, and the implementation of market instruments to promote the single market for secondary raw materials.

The two interviewees were selected because of their expertise and background tied to both the circular economy and CRMs within the EU policy and institutional context. Their high-level profile and expertise have provided valuable insights and strengthened the analysis by highlighting ongoing policy developments and priorities within the EU context. For this reason, their contribution is especially meaningful in the discussion part of the study as it presents clear examples of future policy developments and it strengthens the arguments around potential policy gaps.

3.4. Limitations and Ethical Considerations

The main limitation encountered while conducting this research has been the fast-evolving nature of the subject in question. Given the changing geopolitical landscape and the acceleration of technological advancements, researching critical raw materials involves the uncertainty that what is classified as critical at the moment of study might not be in the future. Furthermore, while the circularity of critical raw materials is highly important for the economic security of the EU, the legislative texts that have guided this study, such as the Critical Raw Materials Act, have only recently entered into force. As a result, scholarly material and empirical data on the implementation and impact of these policy instruments remain limited. Similarly, the complexities of supply chains and the lack of data sharing among stakeholders for most CRMs hinder the availability of information on key circularity factors, such as the quality and quantity of scrap material, providing incomplete indicators. Thus, as technologies continue to advance and strategic sectors continue to evolve, future research might identify different drivers and barriers than the ones discussed in this study. Lastly, this research has been developed in parallel to the new political cycle of the European Commission in the aftermath of the 2024 elections. While this new legislative term has brought new priorities in the development of EU policies, this study could contribute to the evolving policy landscape and the new Commission's efforts to respond to the challenges outlined in the Letta (2024) and Draghi (2024) recommendations.

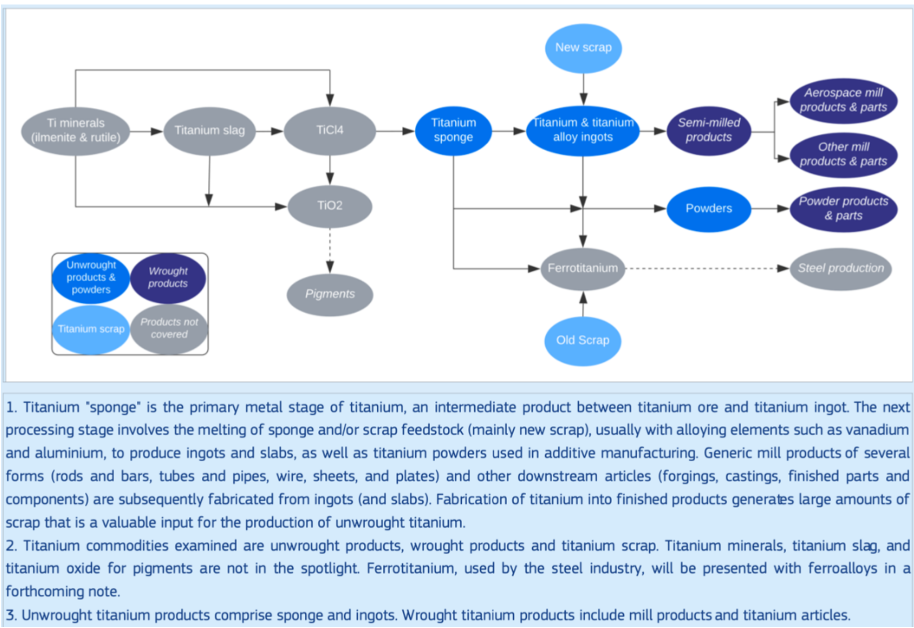
4. Barriers and Drivers to CRMs Circularity

4.1. The Case of Titanium Metal

Titanium metal has emerged as a strategically important material due to its unique combination of strength, low density, and exceptional corrosion resistance. These properties make it indispensable in a range of critical technologies supporting both the green and digital transitions, including smartphones, laptops, additive manufacturing, and robotics (Carrara et al., 2023; Joint Research Centre, 2025). It is mainly used in pigments, and the chemical and medical industries (RMIS, 2024), but most importantly, titanium metal has become crucial for strategic technologies in the aircraft and defense sectors (Blagoeva et al., 2019), which are expected to continue to grow in the future as the European Commission is planning to "ReArm" Europe by 2030. Nonetheless, the EU is facing the challenge of potential supply chain disruption due to its over-reliance on titanium metal imports (Joint Research Centre, 2025).

Figure 6

Titanium's value chain



Note. From *Titanium metal: Impact assessment for supply security*, by Blagoeva et al., European Commission, 2019 (https://publications.jrc.ec.europa.eu/repository/handle/JRC129594).

The EU relies on titanium metal imports for products throughout its entire value chain (***Figure 6***). Because of the difficulty in extracting and processing titanium minerals into primary titanium sponge, the EU depends 100% on the imports from a few countries (Buesa et al., 2025), with China leading global production at 67%, followed by Japan with 18%, the Russian Federation with 6%, Kazakhstan with 4%, and the remaining spread around other regions recounting 5% (RMIS, 2024). While China has become the main player in sponge production, its titanium sponge does not meet quality standards for aerospace applications, leaving Japan, Russia, and Kazakhstan as the leaders in qualified production of aviation-grade sponge. Moreover, China dominates ingot production at around 37%, followed by the US at 28%, accounting for most of the global melting capacity, with the US concentrating a large part of the furnaces capable of recycling titanium metal into ingots (Georgitzikis, et al., 2022, p. 6).

In terms of wrought titanium products and the downstream of the value chain although the EU has been able to develop processing capacity for titanium metal, it still has to import 60% of total EU consumption of wrought titanium (Georgitzikis, et al., 2022, p. 10). In this area, China still maintains a strong position, accounting for 66% of world milled titanium products, followed by the US at 11%, Russia at 10%, Japan at 6%, and the EU and the rest of countries covering 4% and 2.4% respectively (European Commission, Joint Research Centr et al., 2025, p. 21).

As stated in section 2.2.2. the economic importance of the sectors that titanium metal is most needed, as well as the exposure to the supply risks driven by the strong dependency on imports, has classified titanium metal as not only a critical raw material since 2020 (G. Blengini et al., 2020), but also as a strategic raw material as well (European Commission, 2023), further evidencing the importance of achieving autonomy over this material. In addition, Russia's war on Ukraine has increased the supply risk due to the EU's exposure to imports of wrought titanium from Russia, and imports of unwrought titanium and powders from both countries, with Russia being a key exporter of titanium for the aerospace industry (Georgitzikis, et al., 2022, p. 1). Conversely, it has also reinforced the EU's efforts to decrease dependencies on the demand side while calling for more autonomy in armaments, including the aerospace industry. Given the current context, circularity is emerging as a key strategy to secure the supply of this important and necessary metal.

4.1.1. Barriers and Drivers to Titanium Metal Circularity in the EU

As stated in section 3, this case study examines the different barriers and drivers encountered in titanium metal circularity. Through the analysis of qualitative evidence extracted from academic papers and reports this section will identify various bottlenecks stemming from policy, economic factors, geopolitics and supply chains, technology, knowledge transfers, and cultural settings (Rizos & Urban, 2023, p. 1). Understanding these dynamics will provide a basis for analyzing how EU policy initiatives enable or hinder the circularity of titanium metal, bringing this case study to the wider policy and legislative context in the EU.

The first category of barriers and drivers emerging from the literature analysis pertains to **the policy and legislative environment**. The classification of titanium metal as a critical and strategic raw material within the CRMA, has enabled increased focus and research on titanium metal. This could prompt further circularity initiatives in the context of this particular material, also driven by the recycling objective set out under the CRMA. Moreover, following Buesa et al. (2025), this rapidly evolving policy framework could be complemented by the application of end-of-waste criteria and restriction of EU titanium metal scrap exports, which would help surpass the existing barrier driven by the current classification of end-of-life aircraft materials as "waste", and incentivize instead the recovery of materials during aircraft dismantling processes and the subsequent recycling market (p. 75). Another barrier identified by the authors are the safety regulations and recertification requirements that impede the reuse of titanium parts and secondary materials. This is particularly notable in the aircraft industry, where engine and landing gear have a limited life-span defaulting their reuse under the strict regulation set by the European Union Aviation Safety Agency (EASA) (Baldassarre, 2025, p. 6). In the defense sector, similar dynamics occur for to the performance requirements expected for military equipment.

A second set of enablers and barriers tackle different **economic factors**. Firstly, while the circularity of titanium material presents new market opportunities, there are significant doubts about the economic viability of some of the recycling operations. These are further exacerbated by China's dominance over the extraction and processing operations, taking up more than half of the global market and wielding significant pricing power that increases price uncertainty and processing viability in the EU (Denina et al., 2025). In terms of repair and remanufacturing of titanium aviation and defense parts, scholars have found that it has already been established due to the high prices of aircraft materials and components (Baldassarre, 2025, p. 7). Furthermore, the increasing amount of titanium found on aircraft components due to the material characteristics that allow the creation of lighter pieces will create a market opportunity for increased recovery of titanium metal and end-of-life scrap recycling. However, this will also need a regulatory reform regarding end-of-life and waste criteria that will facilitate the economies of scale necessary to make recycling economically viable.

Another economic barrier widely discussed in literature is the existence of buyback schemes for production scrap, limiting the EU's recycling market development by creating competition for feedstock materials. The buyback agreements put in place oblige EU companies to send back the titanium scrap remaining from the manufacturing process to wrought titanium suppliers, mainly located in the US. This represents a huge bottleneck for titanium metal recycling capabilities, which could be even more affected by the current state of trade relations between the EU and the US which could lead to the imposition of high tariffs on exports of titanium scrap to the US. Furthermore, the lack of a domestic titanium remelting industry and the reimbursements EU companies get for the returned scrap make these buyback agreements attractive for EU companies, while creating an asymmetric relationship between the EU and US industries that disincentivizes investments in the European titanium recycling industry (Jakimów et al., 2024, p. 1743). As stated above, other economic barriers can be attributed to the economies of scale needed to make wrought titanium manufacturing and recycling costs viable, which can only be achieved through large capital investments to improve competitiveness, also given the high energy prices and limited access to scrap material (Buesa et al., 2025, p. 75-76).

Technological factors have also been identified as an important set of barriers and drivers. The current recycling infrastructure is both insufficient and inefficient, with technology and capital deployment lagging behind needs. Titanium metal circularity faces a number of technical difficulties that are slowing recycling efforts, including scrap contamination. Scrap that has been contaminated could be more accessible than clean scrap that has been compromised due to buybacks agreements. However, to make this scrap usable, it would require pre-processing technologies (PAM and EBM) that would preserve material quality to meet aerospace-grade standards, as well as the necessary aircraft transport infrastructure to avoid further contamination (Buesa et al., 2025, p. 76-77). In addition to these technical challenges, the implementation of eco-design requirements to facilitate repair and remanufacturing has faced issues emerging from the shift in aircraft design, which has been favoring designs like joint-pieces (blisks) replacing previous separate disks and fan blades while hindering the dismantling process (Baldassarre, 2025; Buesa et al., 2025). Nonetheless, scholars have also identified technology as a clear enabler of circularity. Growing interest from start-ups in collaboration with aircraft and defense industries to scale up additive manufacturing technologies and the installation of new dismantling and forging facilities for material recovery are crucial to reducing dependencies and reliance on primary titanium (Buesa et al., 2025, p. 77). Lastly, the establishment of new dismantling facilities and the growing market for end-of-life scrap recycling also calls for reverse logistics, meaning the capabilities that will allow for this scrap to be reintroduced to the supply chain while seeking an open loop approach where scrap is sourced from multiple sectors (Baldassarre, 2025, p. 8).

The current global political and **geopolitical landscape**, including the pandemic, Russia's invasion of Ukraine, and the change of political cycle in the US, has evidenced the possible supply chain disruptions deriving from geopolitical shifts. While cross-country partnerships could support and accelerate circular economy initiatives through shared resources and expertise, limited international collaboration and coordination for circularity projects currently hinder progress. As stated by Baldassarre (2025), the absence of transfers of know-how, capital, and scrap flows constrains the use of useful technologies such as Electron-Beam Melting (EBM), which enables titanium scrap and sponge to be mixed, and reduces costs (p. 7). The lack of **knowledge transfer** is further accentuated by corporate confidentiality issues that seek to safeguard knowledge on technologies and intellectual property concerns. Dismantling processes that will facilitate the recycling of aircraft components require prior knowledge of the manufacturer to accelerate processes; however, intellectual property protection measures taken by companies limit information sharing and make these tasks more complex. Furthermore, policy measures like product passports and virtual repositories are useful tools that could help overcome these bottlenecks, but they currently lack the support of the industry (Buesa et al., 2025). In this regard, the Incubation Forum for Circular Economy in European Defence (IF CEED), an EU funded project under the LIFE+ Program, has been identifying the most crucial applications of CRMs in defense, paying particular attention to circularity levels and exploring opportunities that tools like Digital Product Passport (DPP) could provide to more circular management of military equipment (EDA, 2025).

As proven by past experiences, cross-country collaboration and the partnership between industry actors will be essential to advance the EU's position in this sector and achieve more autonomy. At the same time, **cultural** progress and growing environmental awareness incentivize the private sector to pursue end-of-life opportunities and transition to service-based solutions. This has also been promoted by EU policy initiatives, with measures like Corporate Social Responsibility (CSR) reports influencing procurement strategies of buyers and growing the demand of recycled goods to meet CSR requirements (Baldassarre, 2025; Buesa et al., 2025).

Table 1

Summary of barriers to titanium metal circularity

Category	Barrier	References
Policy	Stringent safety regulations and recertification requirements restrict reuse of titanium parts	Baldassarre (2025); Buesa et al. (2025)
	Classification of end-of-life aircraft materials as 'waste' hinders recovery and recycling efforts	Buesa et al. (2025)
Economic	High costs of processing, recycling, and capital investments	Baldassarre (2025); Buesa et al. (2025)
	Buyback schemes for production scrap limit EU recycling market development	Baldassarre (2025); Buesa et al. (2025); Buesa et al. (2023)
	Uncertainty regarding economic viability of recycling operations	Buesa et al. (2025)
Geopolitical and Supply Chain	Limited cross-country collaborations and coordination for circular economy initiatives	Baldassarre (2025); Buesa et al. (2025)
	Geopolitical tensions and supply chain disruptions create shortages and price volatility	Buesa et al. (2025)
Technological	Insufficient/inefficient recycling infrastructure and technology deployment	Baldassarre (2025); Buesa et al. (2025); Buesa et al. (2023)
	Technical challenges to including scrap contamination and quality assurance for safety-critical applications	Buesa et al. (2025); Buesa et al. (2023)
	Technical difficulties to implementing eco-design for recycling/reuse/disassembly in titanium components	Buesa et al. (2025); Baldassarre (2025)
Knowledge Transfer	Reluctance to share information and knowledge transfer due to intellectual property concerns	Baldassarre (2025); Buesa et al. (2025)

Table 2

Summary of drivers to titanium metal circularity

Category	Driver	References
Policy	Classification of titanium metal as a critical raw and strategic material promotes circularity initiatives	Baldassarre (2025); Buesa et al. (2025)
	Application of end-of-waste criteria could incentivise EU recycling market development	Buesa et al. (2025)
Economic	Repair and remanufacturing of titanium aviation and defense components present economic opportunities	Baldassarre (2025); Buesa et al. (2025)
	Increased titanium content in new aircraft creates market opportunity for end-of-life scrap recycling	Baldassarre (2025); Buesa et al. (2025)
	Opportunity to recover more titanium from end-of-life aircraft frames	Buesa et al. (2023)
Geopolitical	Cross-country partnerships to produce wrought titanium metal support recycling sustainability	Baldassarre (2025)
Technological	Emerging reverse logistics capabilities for cross-sectoral sourcing and open loop recycling	Baldassarre (2025)
	New aircraft dismantling and forging facilities being established for material recovery	Baldassarre (2025); Buesa et al. (2025)
	Businesses experimenting with new technologies to reduce titanium demand	Baldassarre (2025); Buesa et al. (2025)
Cultural	Carbon footprint differences between primary and secondary titanium influence procurement strategies and CSR reporting requirements	Buesa et al. (2025)
	Environmental awareness incentivizes companies to exploit end-of-life opportunities, repair, and transition to service-based solutions	Buesa et al. (2025); Baldassarre (2025)

4.2. The Case of Cobalt

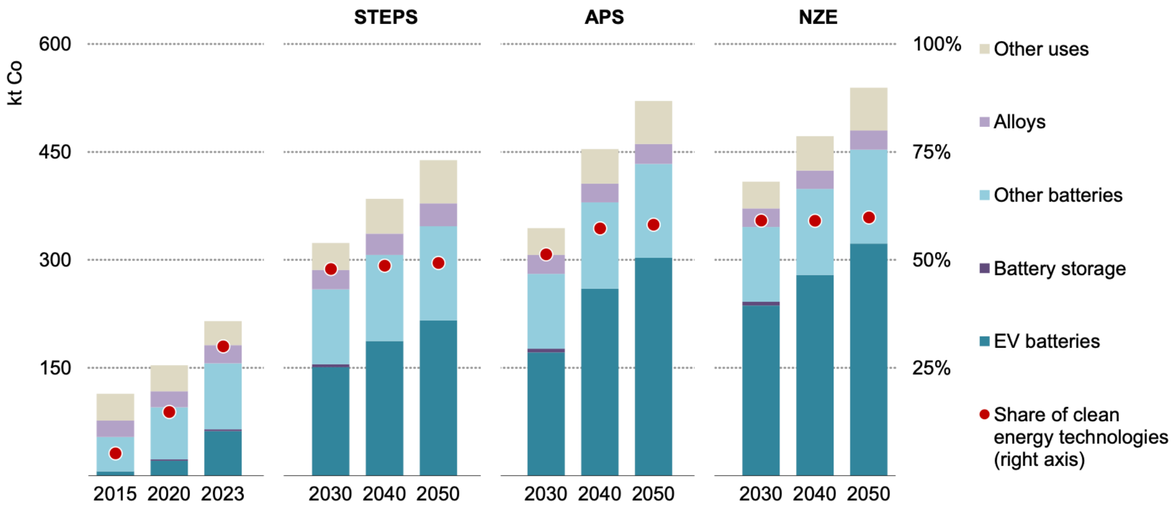
Known for its electrochemical, magnetic, and heat properties, Cobalt has been used to produce valuable heat-resistant alloys that are used in both traditional industries and advanced technologies. These include gas turbine blades, impellers, chemical equipment, and other new energy industry developments, as well as batteries (Huang et al., 2024). Due to these properties, cobalt has become indispensable for several strategic technologies, prompting major economies to designate it as a key mineral in their raw material strategies. In the EU, cobalt has been included in the CRM list since it was first published in 2011 (European Commission, 2011). With the adoption of the CRMA and the 2023 update, cobalt was also classified as a strategic material, further accentuating its criticality and the importance of the technologies where it is used (European Commission, 2023). This strategic consideration is closely tied to the rise of battery technologies, which have been recognized by the EU as a strategic sector because of their crucial role for the energy transition, and for enhancing the competitiveness of the European electric vehicle (EV) industry (Ragonnaud, 2025). The following analysis of the circularity barriers and drivers for cobalt will primarily focus on its role in the EU battery sector, particularly in lithium-ion batteries (LIBs), as this represents one of the most strategically significant and cobalt-intensive applications within the European context.

While battery technologies are rapidly increasing in importance, the extraction and refining of cobalt is still highly geographically concentrated, leaving the EU vulnerable to import dependencies. The main primary producer is the Democratic Republic of Congo (DRC) at 69%, followed by the Russian Federation at 6%, whereas the EU only produces 0.8%, all concentrated in Finland (RMIS, 2024). Cobalt is usually mined as a by-product of other metals, such as nickel and copper, with mining operations often focusing on the concentration of these metals rather than cobalt. Moreover, the primary extraction of cobalt also raises ethical concerns regarding forced and child labor in the DRC, contributing to the growing concerns about cobalt's supply chain vulnerabilities (Alves Dias et al., 2018). On the other hand, China dominates refinery production with 78% of the global share, while the EU holds second place with 9%, primarily driven by Finland (92% of the EU's output) and Belgium (8%) (RMIS, 2024).

According to (IEA, 2024) different forecasts (***Figure 7***), while cobalt's demand will not rise as much as other battery metals, EV batteries will be the main drivers of rising cobalt demand, with a significant difference from other applications (p. 156). Within a battery composition cobalt is mainly found in the battery cell (***Figure 8***) which constitutes the basic unit of the battery and typically contains two electrodes, a cathode and an anode, which carry the positive and the negative charge respectively, and are in contact with an electrolyte (Ragonnaud, 2025, p. 2). The cell is part of the larger battery modules, which are contained in a battery pack. Lithium-ion batteries generate electricity through an electrochemical process where, during discharge, lithium ions accumulate in the anode material and flow toward the cathode, creating electrical current as electrons flow from the anode to the cathode through external terminals (Botelho Junior et al., 2021, p. 2). Cobalt is crucial for the cathode of batteries, this component of the battery is also used to classify the different types of Li-ion battery's chemistry, with lithium nickel manganese cobalt oxide (NMC) being the most commonly used cathode chemistry where cobalt is found (Botelho Junior et al., 2021; Ragonnaud, 2025). While cobalt demand in the EU is expected to grow 5 times by 2030 and 15 by 2050, market preferences toward low-cobalt or cobalt-free cathodes, and debate around the substitutability of cobalt in Li-ion batteries, might slow demand growth (Alves Dias et al., 2018; Botelho Junior et al., 2021; IEA, 2024).

Figure 7

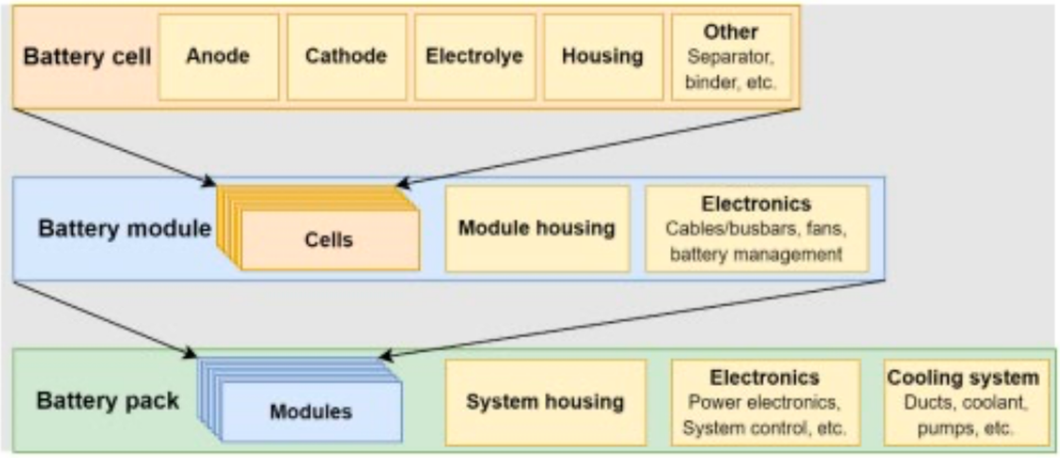
Scenarios of global cobalt demand outlook by sector



Note. The different charts correspond to each possible scenario developed by the IEA. STEPS: Stated Policies Scenario; APS: Announced Pledges Scenario; NZE: Net Zero Emissions. In all scenarios, EV batteries represent the largest sector for growing cobalt demand.

From *Global Critical Minerals Outlook 2024*, by IEA, International Energy Agency (IEA), 2024 (https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf)

Figure 8
Components of a common battery



Note. From *Powering the EU's future: Strengthening the battery industry*, by Ragonnaud, G., European Parliament, 2025 (https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2025)767214)

Given the existing economic importance and supply risks of cobalt, enhancing circularity through the battery value chain could decrease the dependencies currently in place. The EU's RMIS, estimates suggest that recycling could contribute up to 51% of the EU's cobalt demand by 2040.

4.2.1. Barriers and Drivers to Cobalt Circularity in the EU

Following the methodology described in section 3 and followed in section 4.1.1, by analyzing industry reports and perspectives, along with peer-reviewed academic papers, this section will explore a set of cobalt circularity barriers and drivers, focusing on policy, economic factors, supply chain, technology, culture, environmental conditions, and knowledge transfers. This evaluation will enable the identification of the main opportunities in cobalt circularity while highlighting possible bottlenecks and policy gaps slowing the development and implementation of circular initiatives.

In terms of the **policy and regulatory context**, while the introduction of EU-funded projects, strategies and frameworks like the EU Battery Regulation and the Digital Product Passport, show significant potential for attracting new business models into the value chain and improve information sharing across the industry, several concerns still exist about their effective implementation (Rizos & Urban, 2023, p. 7). One of the main issues identified is the lack of standardization requirements for battery design and chemistry, since the difference in battery types and chemistries increases the complexity and slows the process of cobalt recovery, refurbishing and remanufacturing (Earl et al., 2022). Moreover, literature and industry have pointed out that unclear policy regarding post-consumer used EV batteries and a lack of battery longevity at the design and production stages, hinder the enforcement of product responsibility, as well as the collection and recycling of battery components like cobalt (Cobalt Institute, 2023; Earl et al., 2022). This also poses concerns about possible trade-offs emerging from circularity objectives and regulations, given that meeting the EU's recycled content targets of LIBs might interact or constrain other initiatives such as enhancing battery repurposing, life-span extension, and aiming at retaining the material for their maximum utility (Zhou et al., 2024, p. 1289). Thus, despite recycled content targets for metals like cobalt being a good tool for enhancing battery recycling and the recovery of cobalt from EoL batteries, it might encounter difficulties from other circularity strategies.

Economic factors and incentives also play a crucial role in the development of cobalt circularity. The policy incentives promoted by the EU, including long-term deals and subsidies, have led to growing investor interest and new business models, attracted by the revenue opportunities emerging from circularity initiatives like e-waste and EV battery collection and end-of-life treatment (Cobalt Institute, 2023; Earl et al., 2022). Nonetheless, these opportunities also face significant economic uncertainties. Following Rizos & Urban (2023), in the case of batteries, the large initial investment needed for large-scale recycling plants and the price volatility of the materials recovered create doubts around the economic viability of recycling (p. 5). For cobalt, the presence of other metals in cobalt-containing scrap further affects the feasibility of recycling operations (Earl et al., 2022). Finally, despite the potential energy savings and price opportunities compared to primary cobalt, price fluctuations between primary and secondary cobalt, together with new batteries becoming more economically competitive, create a lack of a clear competitive advantage between secondary and primary cobalt to convince the market. Moreover, if recovery and recycling targets for cobalt were to be met in the EU, the absence of battery manufacturing facilities would lead to exports of secondary cobalt to third countries, undermining the possibility of reducing dependencies and decreasing environmental benefits by incrementing transport emissions.

Supply chain factors present both collaborative opportunities and fundamental structural problems. The shift to EV batteries containing cobalt cathodes will present significant recovery opportunities as batteries reach their end-of-life after exhausting their lifespan of between 8 and 15 years (Cobalt Institute, 2023, p. 16). However, existing losses to waste streams and low collection infrastructure are preventing the recovery of spent batteries classified as scrap, which could be a major source of secondary cobalt. Moreover, it also hinders reuse opportunities for batteries with remaining energy storage capacities whose life and value could be extended through energy storage applications (Rizos & Urban, 2023, p.1). According to (Rizos & Urban, 2023), partnerships along the supply chain would allow for extended collaboration and coordination of interests among stakeholders, offering potential for more integrated circularity solutions and more efficient material flows through the decentralization of recycling infrastructure (p. 3).

Technological factors represent another group of barriers and enablers, intricately linked to the previously discussed economic and supply chain dynamics. As has been mentioned, insufficient implementation of infrastructure for LIBs lifecycle management can slow material recovery and battery circularity (Rizos & Urban, 2023, p. 2). This is further accentuated by the difficult extraction of cobalt from spent LIBs. Battery Materials Recycling technologies, most commonly pyrometallurgy and hydrometallurgy, are used to recover cathode materials like cobalt (Yoo et al., 2023), although prior sorting processes need to be in place in order to tailor the recycling process to the specific type of feedstocks (Cobalt Institute, 2023). For cobalt, the difficulty also stems from the different forms in which it appears and the lack of specialized and flexible recycling processes, which could be improved by mindful battery design to create easily dismantlable cells while preserving high-quality standards. Nonetheless, battery design is currently limited by the lack of policy and economic incentives, as well as the need to improve the traceability of secondary cobalt (Cobalt Institute, 2023). In this context, continuous technological advancement and enhanced digital technologies present huge drivers for overcoming some of the barriers described above, including progressing in LIBs battery management, improved material recovery, and better data availability and traceability (Rizos & Urban, 2023). At the same time, it is driving changes in the battery chemistry mix, which could result in shifts in material intensities of LIBs and slow the demand for cobalt (Zhou et al., 2024, p. 1290).

The technological barriers identified, particularly regarding battery design and material traceability, are deeply related to limits within **knowledge transfers**. Scholars and industry experts argue that while EU initiatives like the battery passport are leading to increased transparency and data collection about battery history and service life of a battery cell, there are still concerns about data reliability and confidentiality, as well as the lack of common standards for data sharing linked to challenges in protecting intellectual property and personal data (Cobalt Institute, 2023; Earl et al., 2022). In the case of batteries, this is particularly important due to the large number of batteries being imported from third countries, particularly China, where the government has launched the development of a Chinese digital battery passport to facilitate transparency and trade with the EU (WEF, 2023).

Overall, the **environmental** contributions that circularity of cobalt could bring to energy savings, reducing water consumption, and lowering greenhouse gases (GHG) and sulfur oxides (SOx) emissions, compared to primary extraction, is a crucial enabler for building momentum for cobalt recycling (Rahimpour Golroudbary et al., 2022). Although there are still concerns about the need to enhance consumer awareness about circular solutions, the ongoing change in the **cultural** settings that has brought increased environmental awareness and demand for sustainable products can promote the needed economic incentives and company-driven innovation to expand cobalt recycling efforts and integrate circularity more deeply into supply chains.

Table 3

Summary of barriers to cobalt circularity

Category	**Barrier**	**References**
Policy	Lack of standardization requirements for battery design and chemistry	Earl et al. (2024)
	Unclear or complex policies, particularly regarding post-consumer regulations, producer responsibility and life extension	Rizos & Urban (2024) Cobalt Institute (2023) Earl et al. (2024)
	Trade-offs between circularity objectives and regulations	Rizos & Urban (2024) Zhou et al. (2024)
Economic	Uncertainty regarding economic viability of recycling	Rizos & Urban (2024) Cobalt Institute (2023)
	High price volatility	Cobalt Institute (2023) Earl et al. (2024)
	Lack of clear competitiveness advantage between secondary and primary cobalt	Cobalt Institute (2023) Earl et al. (2024)
Supply Chain	Losses along the supply chain and waste streams	Rahimpour Golroudbary et al. (2022)
	Low collection rates of end-of-life products	Rahimpour Golroudbary et al. (2022) Rizos & Urban (2024) Cobalt Institute (2023)
Technological	Lack of collection infrastructure and inefficient waste separation limit cobalt recovery	Rahimpour Golroudbary et al. (2022) Cobalt Institute (2023)
	Lack of traceability systems for secondary materials	Cobalt Institute (2023)
	Technical challenges to implementing eco-design for recycling/reuse	Rizos & Urban (2024) Cobalt Institute (2023)
Cultural	Lack of consumer awareness and interest in circular solutions	Rizos & Urban (2024)
Knowledge Transfer	Lack of transparency and reluctance to exchange data	Rizos & Urban (2024) Cobalt Institute (2023) Earl et al. (2024)

Table 4

Summary of drivers to cobalt circularity

Category	Driver	References
Policy	EU high-level strategies and EU-funded projects, including the EU Battery Regulation and the Digital Product Passport	Rizos & Urban (2024) Cobalt Institute (2023)
Economic	Long-term deals, subsidies and incentives in the EU	Earl et al. (2024)
	Revenue opportunities from circular business models	Rizos & Urban (2024) Cobalt Institute (2023)
	High energy and raw material prices for primary cobalt	Rizos & Urban (2024)
Supply Chain	Establishing new partnerships across the supply chain	Rizos & Urban (2024)
Technological	Technological advancements in recycling processes, waste separation and battery lifespan extension and repurposing	Rahimpour Golroudbary et al. (2022) Rizos & Urban (2024) Zhou et al. (2024)
	Digital and smart technologies enabling circularity	Rizos & Urban (2024)
Environmental	Contribution of cobalt recycling to energy saving and water consumption as well as to avoiding or reducing GHG and SOx emissions	Rahimpour Golroudbary et al. (2022)
Cultural	Environmental awareness and increased demand for circular/sustainable products promotes company-driven innovation initiatives	Rahimpour Golroudbary et al. (2022)

4.3. Material Comparison and Concluding Remarks on Barriers and Drivers

The analysis conducted in this section has revealed distinct circularity challenges stemming from the characteristic applications and value chains of titanium metal and cobalt. The particular sectoral contexts in which these materials are used have provided a better understanding of the potential factors that could enhance or prevent the implementation of the circular economy for CRMs (Alivojvodic & Kokalj, 2024). Thus, while the material-specific evaluations help understand the barriers to implementing circularity, the comparative case studies also highlight areas of common improvement that can lead to identifying possible policy gaps or prospective areas of intervention.

Focusing on material-specific barriers for titanium metal within the aerospace and defense industries, stringent safety regulations and recertification requirements have emerged as a crucial obstacle to material reuse. The classification of end-of-life aircraft materials as "waste," further compounds the challenges. Another barrier specific to titanium metal is the buyback schemes that systematically drain EU scrap feedstock to US suppliers, creating structural dependencies that undermine domestic recycling capacity. Conversely, cobalt faces a different set of uncertainties, centered on the rapidly evolving battery sector, where a lack of standardization in battery design and chemistry impedes efficient recovery processes. In economic terms, the relative competitiveness of secondary versus primary materials is also affected by the volatility inherent in emerging battery markets. The technological capabilities needed for circularity processes are also particular to each material. In the case of titanium metal, it requires specialized pre-processing technologies to handle contaminated scrap for aerospace-grade applications, while cobalt faces challenges in efficient extraction from diverse battery chemistries through pyrometallurgy and hydrometallurgy processes. Additionally, both materials encounter eco-design implementation barriers that impede end-of-life recovery, with titanium's aircraft joint-pieces designs hindering dismantling processes and cobalt facing a lack of standardization for batteries and trade-offs in eco-design objectives.

Despite these differences, both materials show similar barrier patterns across most categories. Both face insufficient recycling infrastructure, intellectual property concerns limiting knowledge transfer, and economic viability uncertainties regarding large-scale operations. The classification of both materials as critical and strategic under the CRMA serves as a common policy driver, yet implementation gaps persist. Firstly, both materials find end-of-waste criteria as an area that needs extended harmonization, to address titanium's aircraft material classification issues and cobalt's post-consumer battery regulations. Secondly, the analysis also highlights the importance of creating more frameworks for economic incentives to promote the development of recycling infrastructure and help overcome the material-specific challenges, ensuring the economic viability of EU circularity operations. Lastly, following Kirchherr et al. (2018), special attention needs to be paid to the barriers that go beyond the technical aspects, focusing on the obstacles posed by cultural and behavioral factors, including insufficient consumer interest or hesitant company culture (p. 271). In both cases, this also interferes with the barriers posed by fragmented knowledge transfers and intellectual property concerns, hindering data sharing through the value and supply chain, and slowing recycling processes.

These cases demonstrate that while technical solutions are available, policy coordination across regulatory frameworks remains a significant bottleneck. To meet the targets outlined in the CRMA and reduce the supply dependencies and trade-related vulnerabilities associated with these materials, it is essential to implement cohesive policy initiatives that address material-specific challenges while simultaneously leveraging common drivers such as environmental awareness and cross-industry partnerships.

5. Discussion

5.1. Policy Framework in the European Union

As covered in section 2 and section 3 the European Union has developed a comprehensive and complex policy framework that integrates circular economy principles with securing the supply of CRMs. This policy architecture is continuously evolving, as the circular economy is becoming increasingly relevant in topics related to achieving European economic security. Nonetheless, the analysis of titanium metal and cobalt circularity reveals a set of trade-offs and discrepancies within the EU's policy architecture, raising important questions about the circularity of CRMs. Building on the comparison conducted in section 4, this part of the study will discuss some of the main barriers and policy gaps identified, starting with a general view on the EU's CRMs policy framework.

According to Turunen and Suikkanen (2024), the EU has used several different regulatory strategies when it comes to CRMs management and recovery in particular, including indirect and direct measures targeting both single CRMs and the collective as a whole. As a crucial aspect for closing the resource loop, rising material recovery has been a major pillar and objective for CRMs circularity, as numbers remain low for most materials. To this end, various EU instruments are presented as important, mainly those frameworks regulating waste streams such as the Waste Framework Directive (WFD) and the Waste from Electrical and Electronic Equipment (WEEE) Directive. These texts do not prioritize the recovery of CRMs specifically, but they do set out recovery targets for weight-based bulk fractions in the waste streams where products or parts containing CRMs can be recovered. More interesting for this study is the introduction of new legislative texts such as the EU Battery Regulation in 2023, which aims to target a product group specifically and sets out recovery targets for CRMs more directly, bringing a new angle on circularity by specifically addressing battery materials like cobalt. The introduction of new recovery obligations for battery materials, beyond those covering bulk waste streams, has the potential to more directly address the deficiencies in recycling infrastructure and material recovery identified in section 4. Additionally, the adoption of the CRMA establishes a coordinated approach to managing CRMs, setting ambitious targets to ensure their free movement within the single market while applying circularity principles to achieve this objective (Regulation (EU) 2024/1252).

The case studies developed above have enabled a better understanding of the policy and regulatory environments of two strategic materials, exemplifying the diversity in approach within the EU framework. Titanium metal's governance appears to be more fragmented due to its role in the defense and aircraft industries, which are usually regulated nationally. Conversely, cobalt falls within the scope of the Battery Regulation and is mandated by more stringent recovery and minimum recycled content targets, although companies are still in the process of adapting to its requirements. Nonetheless, the circularity of both materials is constrained by material-specific barriers that significantly hinder progress toward achieving the targets set under the CRMA and require targeted interventions. Titanium metal is severely limited by buyback schemes that drive production scrap away from EU recycling processes, while the reproposing of scrap is further constrained by stringent recertification and safety standards (Buesa et al., 2025). Additionally, materials from EoL waste are difficult to recover due to high economic costs and an insufficient classification policy for aircraft components. In the case of cobalt, despite being a material considered for recovery targets and recycled content under the Battery Regulation, it still faces barriers due to the lack of standardization in battery design and chemistries, which heavily complicates efficient recovery. This poses the question of the need to go beyond policy initiatives targeting product groups and focus on implementing instruments on materials specifically in order to accelerate processes. According to Turunen & Suikkanen (2024), though this is an approach that needs to be considered and could prove to be essential for specific materials, rapid technological advancements coupled with volatile geopolitical environment and the lack of a single definition of "criticality" could create technical lock-ins and leave the legal provisions to be constantly outdated due to the rapid changing environment.

Continuing to build on the analysis conducted above, the comparison between the two materials has highlighted a set of tensions within the EU policy architecture that impact the circularity of CRMs more broadly. These tensions include bottlenecks that extend beyond "hard" barriers such as technological and economic constraints, encompassing instead "softer" factors such as cultural environments (De Jesus & Mendonça, 2018, p. 85).

As has been explained in section 4.3., insufficient knowledge transfers and data sharing across supply and value chains create significant limitations for both materials, a challenge also identified by other scholars who have called for greater policy attention (Rizos & Urban, 2023). Despite the implementation of EU policies like the EU Digital Product Passport under the Eco-design for Sustainable Products Regulation and the Battery Passport under the EU Battery Regulation, aiming at coordinated action to close the gap on the lack of transparency and reliable product data, stakeholder participation is still required to increase awareness. Relevant stakeholder engagement is fundamental to building confidence about the benefits of information sharing and increased transparency to bridge knowledge gaps and accelerate circularity solutions. Nonetheless, this has to be coupled with addressing stated cultural barriers to circular economy implementation (Kirchherr et al., 2018). Increased environmental awareness, together with policy and economic incentives, is essential for driving industry involvement and fostering innovative business models that favor cooperation and collaboration among value and supply chain stakeholders. Clear information and data on critical aspects such as waste management practices can significantly enhance investor confidence and boost circular economy implementation (Rizos & Urban, 2023).

On the whole, although the policy framework being developed by the European Commission responds to the growing significance of CRMs and rising supply risk concerns, the deployment of these policies has occurred significantly later than the regulation and infrastructure implemented by other major global economies such as China and the US, which currently control key sections of CRMs supply chains. Thus, while the EU aims at creating a more coherent regulatory framework that will enable the efficient management of CRMs, meaningful results will probably be delayed in the short and medium term, as it requires significant transformations. As discussed in the sections above, it will entail the development of costly recycling and recovery infrastructure, as well as significant cultural shifts towards deeper awareness of circular solutions in order to drive business initiatives and demand. Additionally, some materials, such as cobalt, are locked up in long-life assets and will need to wait years in order to have the necessary EoL scrap to meet growing demand through circularity. Overall, it will require increased policy attention and incentives to speed up processes and gain market space.

5.2. Future Policy Directions and Market Instruments

The new Commission established after the 2024 European elections has given way to a new policy cycle deeply rooted in economic security and competitiveness. The reports commissioned to Mario Draghi and Enrico Letta on EU competitiveness and the single market have guided several other policy instruments, also addressing circularity and CRMs. Focus has been put on boosting European competitiveness and rebuilding a robust European industry for the green transition. Two important texts in this regard are the Communication on a Competitiveness Compass and the approval of the Clean Industrial Deal, which are particularly significant as they outline the vision for the new Commission mandate. With the Compass, the Commission aims at closing the innovation gap, drafting a joint roadmap for decarbonization and competitiveness, and reducing external dependencies while increasing security (Solský, 2025). Similarly, the Clean Industrial Deal (CID) builds on the European Green Deal and outlines a series of legislative initiatives that intend to implement the overarching strategy of the EU for the upcoming years. It mainly centers on combining the industrial transformation needed with competitiveness and economic resilience (Hermwille et al., 2025). Both of these texts acknowledge the key role that CRMs will play in reducing dependencies and strengthening domestic industry, with the CID introducing circularity and easier access to materials in its decarbonization strategy. Additionally, the forthcoming Circular Economy Act will be the main vehicle for integrating circularity into the CRMs strategy, focusing on the economic factors by dealing with supply and demand bottlenecks and creating a level playing field for primary and secondary materials. The already adopted Net-Zero Industry Act also follows this line, enhancing European manufacturing for net-zero technologies and addressing barriers to scaling up production in Europe and increasing competitiveness.

The task of enhancing productive sectors in the EU and achieving the goals described above without creating trade-offs with climate objectives presents multiple challenges. The process of reindustrializing certain sectors of the European economy, or reshoring midstream industry and recycling capacity as in the case of some CRMs, will require more energy-intensive processes, particularly for sectors that depend on high-temperature operations or continuous energy demand. Thus, despite the legislative environment being developed around the promotion of clean industry and decarbonization of sectors, certain trade-offs could appear for climate targets, particularly if this transformation is not accompanied by the necessary economic incentives. As has been argued by interviews conducted for this study (see Annex A), in the case of CRMs, while increasing circularity and recycling decreases GHG emissions compared to primary production, it will inevitably bring trade-offs in the medium and short term, as setting up the necessary infrastructure for recycling, processing and manufacturing domestically will require significant economic and energy input. Moreover, as demand for CRMs is expected to continue growing in the upcoming years, driven by the rise of digital and green technologies, it will further create tensions with environmental concerns.

The proposed Circular Economy Act, expected by 2026, aims to support competitiveness and economic growth through the circular economy, complementing the Competitiveness Compass and the Clean Industrial Deal, while acknowledging the importance of the circular economy in reducing trade-offs and externalities, and striving to become a global leader in the circular economy by 2030. In doing so, the new Act will extend the scope of already existing policy where CRMs are already relevant, such as the WEEE, to establish a single market for secondary raw materials and waste, focusing also on CRMs (Interviewee 2, see Annex A). Wanting to close the gap on issues like low collection rates and make circularity more economically viable, it will also include new initiatives such as the implementation of trans-regional "circularity hubs" across member states, where waste streams can be aggregated to extract CRMs more cost-effectively. To this end, other tools and market instruments might prove essential in creating the necessary economies of scale and business environments. As stated by Letta (2024) in his report, a Circular Single Market is needed to simultaneously support environmental sustainability and drive economic growth through new business models and increased consumer awareness. Together with Letta, in his report Draghi (2024), also proposes public procurement and private buyer initiatives endorsed by the EU as drivers for empowering consumers and demand for circular products, while ensuring that public spending aligns with the EU’s broader objectives.

Public procurement has increased in significance over the last decades within the EU due to its role as a policy instrument for demand-side innovation (Milios, 2018, p. 870), showing the most potential for securing demand for secondary CRMs and integrating the secondary single market. The EU has already incorporated it in the Clean Industrial Deal and the Net-Zero Industry Act, and the Commission plans to review the public procurement framework in 2026 to introduce sustainability, resilience, and European preference criteria in public procurement for strategic sectors (European Commission, 2025). Another tool that has grown in importance is minimum recycled content targets for products. As discussed above, these are already covered through the Eco-design Regulation and the Battery Regulation for specific materials like cobalt. Nonetheless, as outlined in section 4, although this measure constitutes an essential element for achieving a closed resource loop and aligns with prevailing trends in circularity development, it simultaneously introduces potential trade-offs between strategies that prioritize slowing resource flows versus those focused on closing material loops. Lastly, as the interviews conducted for this research have shown (see Annex A), these and other microeconomic adjustment instruments, such as hedonic pricing or reduced taxation of recycled content will be needed to correct externalities and enhance the secondary raw materials market. Hedonic pricing could put the emphasis on the attributes of products containing CRMs, providing premium prices to products with high recycled content, while secondary materials could benefit from tax breaks to encourage consumption of recycled products. However, as the demand for CRMs continues to grow and the need to reduce dependencies and advance economic security will become more urgent, increased research on these tools and the best approach will be needed in order to make a timely implementation.

6. Conclusions

This study has examined how European legislation and policy support the circular economy for critical raw materials, focusing on the cases of titanium metal and cobalt to explore how material-specific challenges interact with the broader European policy framework. Through qualitative content analysis of EU legislation and policy initiatives, this research has shown that while the EU has made substantial progress in integrating circular economy principles into its resource strategies, important gaps remain, preventing the full implementation of these ambitions.

The findings have revealed that the EU has created a comprehensive regulatory framework with ambitious targets and provisions, particularly through the recycling benchmarks set out in the CRMA. Nonetheless, as the titanium metal and cobalt case studies demonstrate, these targets often struggle against sector and material-specific barriers that create supply bottlenecks and hinder the recovery and recycling processes of materials. These particularities pose the question of whether material-specific instruments and policy interventions should be undertaken in cases where a particular barrier severely restricts the circularity of a certain material, as is the case with titanium metal and buyback agreements. In addition, the case studies have highlighted the different policy approaches to CRMs, with specific materials like cobalt being governed by multiple frameworks, including product-specific legislation like the Battery Regulation. This exemplifies the diverse avenues of the EU policy architecture and mechanisms, tackling both CRMs directly and indirectly. However, recurrent barriers have been identified across both materials, signaling areas where increased policy coordination is needed.

The main gaps that have been identified include insufficient recycling infrastructure, limited harmonization of end-of-waste criteria, economic uncertainties around large-scale recycling operations, and fragmented knowledge transfers. While most EU frameworks that address these gaps more directly, such as the CRMA and the Battery Regulation, have only been adopted recently, with companies still in the process of adapting to their implementation, these overarching barriers highlight the need for increased policy attention and the establishment of stronger obligations under EU regulation to ensure the effective enforcement of provisions aimed at driving circularity, including recovery and recycled content requirements. As stated in the discussion, overcoming these barriers will largely require the allocation of additional economic resources and the provision of targeted incentives, as well as profound cultural transformations aimed at fostering new business models and consumer behaviors conducive to circularity.

As technological advancements continue to progress and demand for renewable technologies like EV batteries continues to grow, the importance of reducing dependencies on CRMs imports and achieving supply security will become increasingly urgent. This is further accentuated by the current geopolitical environment and the need to create reliable yet diversified partnerships at EU level. As there is currently no universally accepted definition of "criticality," and materials are evaluated primarily based on economic importance and security risks within the EU, the prevailing volatility and associated uncertainties may underscore the criticality of a new set of materials in the future. For this reason, a holistic EU policy approach is needed, encompassing all aspects of CRM's security, including circularity and other fundamental pillars like trade partnerships and domestic processing. A diversified and adaptive policy mix will be required to respond to a rapidly changing environment and to secure the supply of CRMs more effectively.

This study aims to illustrate that, despite existing barriers, circular economy measures can become core components of Europe's economic security strategy. Amid the new Commission's focus on competitiveness and decarbonization of industrial sectors, a functioning circular economy for CRMs has the potential to enhance the EU's global competitiveness, create new industrial opportunities, and mitigate supply chain vulnerabilities exacerbated by geopolitical tensions and market volatility. To do so, and in response to the Letta and Draghi recommendations on establishing a single market for secondary materials, additional research is required to examine the implementation of market instruments aimed at securing demand and fostering a level playing field for secondary materials. Moreover, future studies should also analyze the impact of forthcoming legislation, such as the proposed Circular Economy Act, on harmonizing rules for secondary raw materials and enabling a truly integrated single market.

7. Bibliography

ACEA. (n.d.). *EU BATTERY SUPPLY CHAIN & IMPORT RELIANCE* (p. 2). European Automobile Manufacturers' Association (ACEA). https://www.acea.auto/files/ACEA_Fact_sheet-EU_battery_supply_chain_and_import_reliance.pdf

Achzet, B., & Helbig, C. (2013). How to evaluate raw material supply risks—An overview. *Resources Policy*, *38*(4), 435–447. https://doi.org/10.1016/j.resourpol.2013.06.003

Agovino, M., Cerciello, M., Musella, G., & Garofalo, A. (2024). European waste management regulations and the transition towards circular economy. A shift-and-share analysis. *Journal of Environmental Management*, *354*, 120423. https://doi.org/10.1016/j.jenvman.2024.120423

Alivojvodic, V., & Kokalj, F. (2024). Drivers and Barriers for the Adoption of Circular Economy Principles towards Efficient Resource Utilisation. *Sustainability*, *16*(3), 1317. https://doi.org/10.3390/su16031317

Alves Dias, P., Blagoeva, D., Pavel, C., & Arvanitidis, N. (2018). *Cobalt: Demand supply balances in the transition to electric mobility.* (No. JRC112285). Publications Office of the European Union. https://data.europa.eu/doi/10.2760/97710

Amending Directive 2008/98/EC on Waste, No. Directive (EU) 2018/851. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L0851

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

Barteková, E., & Kemp, R. (2016). *Critical raw material strategies in different world regions* [Working paper]. The United Nations University–Maastricht Economic and Social Research Institute on Innovation and Technology (UNU-MERIT).

Blagoeva, D., Pavel, C., Wittmer, D., Huisman, J., & Pasimeni, F. (2019). *Materials dependencies for dual-use technologies relevant to Europe's defence sector* (No. EUR 29850 EN). Publications Office of the European Union. https://data.europa.eu/doi/10.2760/570491

Blengini, G. A., Nuss, P., Dewulf, J., Viorel Nita, Peirò, L. T., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., & Ciupagea, C. (2017). EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements. *Resources Policy*, *53*, 12–19. https://doi.org/10.1016/j.resourpol.2017.05.008

Blengini, G., Latunussa, C., Eynard, U., Matos, C., Georgitzikis, K., Pavel, C., Carrara, S., Mancini, L., Unguru, M., Blagoeva, D., Mathieux, F., & Pennington, D. (2020). *Study on the EU's list of Critical Raw Materials (2020) Final Report*. European Commission. https://doi.org/10.2873/11619

Bocken, N. M. P., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering*, *33*(5), 308–320. https://doi.org/10.1080/21681015.2016.1172124

Botelho Junior, A. B., Stopic, S., Friedrich, B., Tenório, J. A. S., & Espinosa, D. C. R. (2021). Cobalt Recovery from Li-Ion Battery Recycling: A Critical Review. *Metals*, *11*(12), 1999. https://doi.org/10.3390/met11121999

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*. 5th

Product Lifetimes and The Environment Conference (PLATE) 2023 Conference, Aalto-yliopisto, Finland. https://doi.org/10.13140/RG.2.2.11104.66566

Buesa, A., Jakimów, M., Piñero, P., Maury, T., Latunussa, C., Pedauga, L., Samokhalov, V., Baldassarre, B., Mathieux, F., Rueda-Cantuche, J. M., Stijepic, D., Reys, A., Bilous, A., Notom, P., & Tercero, L. (2025). *Titanium metal in the EU: Strategic relevance and circularity potential*. Publications Office of the European Union. 10.2760/5871804

Buijs, B., Sievers, H., & Tercero, L. (2012). Limits to the critical raw materials approach. *Proceedings of the ICE - Waste and Resource Management*, *165*, 201-208(7). https://doi.org/10.1680/warm.12.00010

Calisto Friant, M., Vermeulen, W. J. V., & Salomone, R. (2021). Analysing European Union circular economy policies: Words versus actions. *Sustainable Production and Consumption*, *27*, 337–353. https://doi.org/10.1016/j.spc.2020.11.001

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, Á., Somers, J., Telsnig, T., Veeh, C., Wittmer, D., Black, C., … 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. 10.2760/386650

Castro Sejin, A., Mammadli, A., & Barakos, G. (2023). *Criticality of raw materials -a clarification and redefinition of the term worldwide*.

Cobalt Institute. (2023). *Towards a Circular Value Chain of Cobalt*. Cobalt Institute. https://www.cobaltinstitute.org/sustainability/circular-value-chain-of-cobalt/

Commission Decision: Recognising Certain Critical Raw Material Projects as Strategic Projects under Regulation (EU) 2024/1252 of the European Parliament and of the Council, No.

C(2025) 1904 final, European Commission (2025). https://webgate.ec.europa.eu/circabc-ewpp/d/d/workspace/SpacesStore/1958718b-21e9-40f4-9c9f-42a58dc4c5a3/file.bin

Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Securing Europe's Resource Supply for a Sustainable Future, No. COM(2025) 85 final, European Commission (2025). https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52025DC0085

Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC, No. Regulation (EU) 2023/1542. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542

De Jesus, A., & Mendonça, S. (2018a). Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. *Ecological Economics*, *145*, 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001

De Jesus, A., & Mendonça, S. (2018b). Lost in Transition? Drivers and Barriers in the Eco-innovation Road to the Circular Economy. *Ecological Economics*, *145*, 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001

De Oliveira, R. P., Benvenuti, J., & Espinosa, D. C. R. (2021). A review of the current progress in recycling technologies for gallium and rare earth elements from light-emitting diodes. *Renewable and Sustainable Energy Reviews*, *145*, 111090. https://doi.org/10.1016/j.rser.2021.111090

Denina, C., Scheyder, E., Burton, M., & Scheyder, E. (2025, July 24). Exclusive: Rio Tinto weighs sale of titanium business, sources say. *Reuters*. https://www.reuters.com/world/americas/rio-tinto-weighs-sale-titanium-business-sources-say-2025-07-24/

Dewulf, J., Blengini, G. A., Pennington, D., Nuss, P., & Nassar, N. T. (2016). Criticality on the international scene: Quo vadis? *Resources Policy*, *50*, 169–176. https://doi.org/10.1016/j.resourpol.2016.09.008

DG GROW, Deloitte Sustainability., British Geological Survey, Bureau de Recherches Géologiques et Minières, & Toegepast natuurwetenschappelijk onderzoek. (2017). *Study on the review of the list of critical raw materials: Final report.* Publications Office. https://data.europa.eu/doi/10.2873/876644

Draghi, M. (2024). *The future of European competitiveness*. European Commission. https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en

Earl, C., Shah, I. H., Cook, S., & Cheeseman, C. R. (2022). Environmental Sustainability and Supply Resilience of Cobalt. *Sustainability*, *14*(7), 1–10. https://doi.org/10.3390/su14074124

EDA. (2025). *IF CEED Critical Raw Materials*. European Defence Agency (EDA). https://eda.europa.eu/what-we-do/eu-policies/if-ceed-old/project-circles/critical-raw-materials

Erdmann, L., & Graedel, T. E. (2011). Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses. *Environmental Science & Technology*, *45*(18), 7620–7630. https://doi.org/10.1021/es200563g

Espinoza, L. A. T. (2023). *UNDERSTANDING THE METHODOLOGY BEHIND THE EU LIST OF CRITICAL RAW MATERIALS*. https://doi.org/10.24406/publica-2455

Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020, No. Regulation (EU) 2024/1252. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401252

Establishing a Framework for the Setting of Ecodesign Requirements for Sustainable Products, Amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and Repealing Directive 2009/125/EC, No. Regulation (EU) 2024/1781. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401781

European Commission. (2010). Critical raw materials for the EU [MEMO/10/263]. *European Commission*. https://ec.europa.eu/commission/presscorner/detail/es/memo_10_263

European Commission. (2020). *Circular economy action plan*. DG ENVI European Commission. https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en

European Commission. (2023). *Critical Raw Materials Act—European Commission*. https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials/critical-raw-materials-act_en

Feichtinger, G., & Posch, W. (2025). Evaluation of European Critical Raw Material Assessments under Energy Transition Considerations: Applications and Prospects. *Circular Economy and Sustainability*. https://doi.org/10.1007/s43615-024-00493-0

George, A. L., & Bennett, A. (2005). *Case studies and theory development in the social sciences*. MIT Press.

Georgitzikis, K., D`elia, E., & Eynard, U. (2022). *Titanium metal: Impact assessment for supply security* (Policy Brief No. JRC129594). European Commission. https://publications.jrc.ec.europa.eu/repository/handle/JRC129594

Girtan, M., Wittenberg, A., Grilli, M. L., De Oliveira, D. P. S., Giosuè, C., & Ruello, M. L. (2021). The Critical Raw Materials Issue between Scarcity, Supply Risk, and Unique Properties. *Materials*, *14*(8), 1826. https://doi.org/10.3390/ma14081826

Glöser, S., Tercero Espinoza, L., Gandenberger, C., & Faulstich, M. (2015). Raw material criticality in the context of classical risk assessment. *Resources Policy*, *44*, 35–46. https://doi.org/10.1016/j.resourpol.2014.12.003

Gómez, J. F., Basterra, M. L., Sánchez, J. M., & Mosquera-López, S. (2024). Critical Raw Materials and Strategic Relations between the EU and China: The Role of the EU Critical Raw Materials Act. In Y. Li, F. J. B. S. Leandro, J. Tavares Da Silva, & C. Rodrigues (Eds.), *The Palgrave Handbook on China-Europe-Africa Relations* (pp. 271–300). Springer Nature Singapore. https://doi.org/10.1007/978-981-97-5640-7_13

Graedel, T. E., & Reck, B. K. (2015). Six Years of Criticality Assessments: What Have We Learned So Far? *Journal of Industrial Ecology*, *20*(4), 692–699. https://doi.org/10.1111/jiec.12305

Graedel, T. E., & Reck, B. K. (2019). Defining the Criticality of Materials. In S. E. Offerman (Ed.), *Critical Materials: Underlying Causes and Sustainable Mitigation Strategies* (Vol. 05). WORLD SCIENTIFIC. https://doi.org/10.1142/11007

Hermwille, L., Leipprand, A., Kiyar, D., Ruß, M., Hullmann, C., Elsner, C., Xia-Bauer, C., Venjakob, J., Obergassel, W., Berg, H., Wilts, H., Thomas, S., Samadi, S., & Fischedick, M. (2025). *Rapid assessment of the Clean Industrial Deal: An initial assessment of the EU Commission's industrial policy work programme for 2025-2029*. Wuppertal Institute for Climate, Environment and Energy. https://doi.org/10.48506/opus-8789

Holzer, D., Mair-Bauernfeind, C., Kriechbaum, M., Rauter, R., & Stern, T. (2023). Different but the Same? Comparing Drivers and Barriers for Circular Economy Innovation Systems in Wood- and Plastic-Based Industries. *Circular Economy and Sustainability*, *3*(2), 983–1011. https://doi.org/10.1007/s43615-022-00210-9

Holzer, D., Popowicz, M., Rauter, R., Silberschneider, K., & Stern, T. (2023). Parallel universes, one circular goal: An empirical study comparing Austrian wood- and plastic-based industries. *Sustainable Production and Consumption*, *43*, 46–61. https://doi.org/10.1016/j.spc.2023.10.014

Hool, A., Helbig, C., & Wierink, G. (2024). Challenges and opportunities of the European Critical Raw Materials Act. *Mineral Economics*, *37*(3), 661–668. https://doi.org/10.1007/s13563-023-00394-y

Huang, Y., Chen, P., Shu, X., Fu, B., Peng, W., Liu, J., Cao, Y., & Zhu, X. (2024). Extraction and recycling technologies of cobalt from primary and secondary resources: A comprehensive review. *International Journal of Minerals, Metallurgy and Materials*, *31*(4), 628–649. https://doi.org/10.1007/s12613-023-2734-2

IEA. (2022). *Strategic and Critical Materials Stock Piling Act – Policies*. IEA. https://www.iea.org/policies/15534-strategic-and-critical-materials-stock-piling-act

IEA. (2024). *Global Critical Minerals Outlook 2024*. International Energy Agency (IEA). https://iea.blob.core.windows.net/assets/ee01701d-1d5c-4ba8-9df6-abeeac9de99a/GlobalCriticalMineralsOutlook2024.pdf

Ioannidou, D., Heeren, N., Sonnemann, G., & Habert, G. (2019). The future in and of criticality assessments. *Journal of Industrial Ecology*, *23*(4), 751–766. https://doi.org/10.1111/jiec.12834

Jacobson, D. M., Turner, R. K., & Challis, A. A. L. (1988). A reassessment of the strategic materials question. *Resources Policy*, *14*(2), 74–84. https://doi.org/10.1016/0301-4207(88)90049-9

Jakimów, M., Samokhalov, V., & Baldassarre, B. (2024). Achieving European Union strategic autonomy: Circularity in critical raw materials value chains. *International Affairs*, *100*(4), 1735–1748. https://doi.org/10.1093/ia/iiae127

Jin, Y., Kim, J., & Guillaume, B. (2016). Review of critical material studies. *Resources, Conservation and Recycling*, *113*, 77–87. https://doi.org/10.1016/j.resconrec.2016.06.003

Joint Research Centre. (2025). *Closing the loop on the EU's titanium supply chain—European Commission*. European Commission. https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/closing-loop-eus-titanium-supply-chain-2025-01-23_en

Kirchherr, J., Piscicelli, L., Bour, R., Kostense-Smit, E., Muller, J., Huibrechtse-Truijens, A., & Hekkert, M. (2018). Barriers to the Circular Economy: Evidence From the European Union (EU). *Ecological Economics*, *150*, 264–272. https://doi.org/10.1016/j.ecolecon.2018.04.028

Kvale, S., & Brinkmann, S. (2009). *InterViews: Learning the craft of qualitative research interviewing* (2nd ed.). Sage Publications, Inc.

Lehmann, H. (Ed.). (2018). *Factor X: Challenges, Implementation Strategies and Examples for a Sustainable Use of Natural Resources* (Vol. 32). Springer International Publishing. https://doi.org/10.1007/978-3-319-50079-9

Letta, E. (2024). *Much more than a market*. Consilium Europa. https://www.consilium.europa.eu/media/ny3j24sm/much-more-than-a-market-report-by-enrico-letta.pdf

Lundaev, V., Solomon, A. A., Le, T., Lohrmann, A., & Breyer, C. (2023). Review of critical materials for the energy transition, an analysis of global resources and production databases and the state of material circularity. *Minerals Engineering*, *203*, 108282. https://doi.org/10.1016/j.mineng.2023.108282

Månberger, A. (2023). Critical Raw Material Supply Matters and the Potential of the Circular Economy to Contribute to Security. *Intereconomics*, *58*(2), 74–78. https://doi.org/10.2478/ie-2023-0016

Mayfield, D., & Lewis, A. (2013). *Environmental Review of Coal Ash as a Resource for Rare Earth and Strategic Elements*.

Milios, L. (2018). Advancing to a Circular Economy: Three essential ingredients for a comprehensive policy mix. *Sustainability Science*, *13*(3), 861–878. https://doi.org/10.1007/s11625-017-0502-9

National Research Council (NRC). (2008). *Minerals, Critical Minerals, and the U.S. Economy* (p. 12034). National Academies Press. https://doi.org/10.17226/12034

Nutley, S. M., Walter, I., & Davis, H. T. O. (2007). *Using Evidence: How Research Can Inform Public Services*. Policy Press.

Offerman, S. E. (2019). *Critical Materials: Underlying Causes and Sustainable Mitigation Strategies* (Vol. 05). WORLD SCIENTIFIC. https://doi.org/10.1142/11007

On Waste and Repealing Certain Directives, No. Directive 2008/98/EC. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098

On Waste Electrical and Electronic Equipment (WEEE), No. Directive 2012/19/EU. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02012L0019-20180704

Panchal, R., Singh, A., & Diwan, H. (2021). Does circular economy performance lead to sustainable development? – A systematic literature review. *Journal of Environmental Management*, *293*, 112811. https://doi.org/10.1016/j.jenvman.2021.112811

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 (2023). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160

Ragonnaud, G. (2025). *Powering the EU's future: Strengthening the battery industry* (Policy Brief No. PE 767.214). European Parliament. https://www.europarl.europa.eu/thinktank/en/document/EPRS_BRI(2025)767214

Rahimpour Golroudbary, S., Farfan, J., Lohrmann, A., & Kraslawski, A. (2022). Environmental benefits of circular economy approach to use of cobalt. *Global Environmental Change*, *76*, 1–11. https://doi.org/10.1016/j.gloenvcha.2022.102568

Randolph, R. S. (1978). The Byrd Amendment: A Postmortem. *World Affairs*, *141*(1), 57–70. http://www.jstor.org/stable/20671758

Righett, E., & Rizos, V. (2023). The EU's Quest for Strategic Raw Materials: What Role for Mining and Recycling? - Intereconomics. *Intereconomics*, *58*(2). https://www.intereconomics.eu/pdf-download/year/2023/number/2/article/the-eu-s-quest-for-strategic-raw-materials-what-role-for-mining-and-recycling.html

Rizos, V., & Urban, P. (2023). Exploring Barriers to the Implementation of Circularity Processes for Batteries. *RawMat 2023*, *15*, 59. https://doi.org/10.3390/materproc2023015059

Rizos, V., & Urban, P. (2024). Barriers and policy challenges in developing circularity approaches in the EU battery sector: An assessment. *Resources, Conservation and Recycling*, *209*, 1–11. https://doi.org/10.1016/j.resconrec.2024.107800

RMIS. (n.d.-a). *Lithium-based batteries supply chain challenges*. RMIS - Raw Materials Information System. Retrieved July 15, 2025, from https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749

RMIS. (n.d.-b). *RMIS - Critical and strategic materials*. RMIS - Raw Materials Information System. Retrieved March 23, 2025, from https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials

RMIS. (2024). *RMIS - Raw materials' profiles*. RMIS - Raw Materials Information System. https://rmis.jrc.ec.europa.eu/rmp/Titanium%20metal

Schicho, M., & Tercero Espinoza, L. (2024). Criticality assessment for raw materials: Perspectives and focuses. *Mineral Economics*. https://doi.org/10.1007/s13563-024-00474-7

Schrijvers, D., Hool, A., Blengini, G. A., Chen, W.-Q., Dewulf, J., Eggert, R., Van Ellen, L., Gauss, R., Goddin, J., Habib, K., Hagelüken, C., Hirohata, A., Hofmann-Amtenbrink, M., Kosmol, J., Le Gleuher, M., Grohol, M., Ku, A., Lee, M.-H., Liu, G., … Wäger, P. A. (2020). A review of methods and data to determine raw material criticality. *Resources, Conservation and Recycling*, *155*, 104617. https://doi.org/10.1016/j.resconrec.2019.104617

Strategic and Critical Materials Stock Piling Act, No. 53 Stat. 811 (1939). https://www.govinfo.gov/content/pkg/COMPS-674/pdf/COMPS-674.pdf

Theodosopoulos, V. (2020). *The Geopolitics of Supply: Towards a new EU approach to the security of supply of critical raw materials?* (No. 2020/05; p. 10). Institute for European Studies, Vrije Universiteit Brussel. https://www.brussels-school.be/sites/default/files/IES-PB-The-Geopolitics-of-Supply_0.pdf

Turunen, T., & Suikkanen, J. (2024). EU and Recycling of Critical Raw Materials: Stuck in Legal Limbo? *European Energy and Environmental Law Review*, *33*(Issue 3), 139–149. https://doi.org/10.54648/EELR2024009

U.S. Department of Energy. (2011). *Critical Materials Strategy* (No. DOE/PI-0009; p. 196). https://www.energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf

Van Gaalen, J. M., & Chris Slootweg, J. (2025). From Critical Raw Materials to Circular Raw Materials. *ChemSusChem*, *18*(2), e202401170. https://doi.org/10.1002/cssc.202401170

Watkins, E., Bergeling, E., & Blot, E. (2023). *Circularity and the European Critical Raw Materials Act*.

WEF. (2023). *Digital Battery Passports: An Enabler for Sustainable and Circular Battery Management* (p. 5). World Economic Forum. https://www3.weforum.org/docs/WEF_Digital_Battery_Passport_2023.pdf

Will, M. (2019). Towards a Sustainable Circular Economy – Remarks on plastics and wood-waste sector. *The Central European Review of Economics and Management*, *3*(4), 149–183. https://doi.org/10.29015/cerem.862

Yin, R. K. (2018). *Case Study Research and Applications: Design and Methods* (6th ed.). SAGE Publications.

Yoo, E., Lee, U., Kelly, J. C., & Wang, M. (2023). Life-cycle analysis of battery metal recycling with lithium recovery from a spent lithium-ion battery. *Resources, Conservation and Recycling*, *196*, 107040. https://doi.org/10.1016/j.resconrec.2023.107040

Zhou, H., Yang, Y., Li, W., McKechnie, J., Thiede, S., & Wang, P. (2024). EU's recycled content targets of lithium-ion batteries are likely to compromise critical metal circularity. *One Earth*, *7*, 1288–1300. https://doi.org/10.1016/j.oneear.2024.06.017

Zimmerman, J. (2022). Small N. In *They differ significantly in end-use sectors, recycling maturity, and policy focus—Which enriches the comparison. This supports your aim to identify how EU policy frameworks perform across very different material contexts, which* *makes your policy recommendations more robust.* Northwestern University Libraries. https://nulib-oer.github.io/empirical-methods-polisci/small-n.html

Disclaimer: Generative AI technology was utilized for brainstorming, structuring, and proofreading assistance; however, all content within this document remains original.

8. Annex

8.1. Annex A

8.1.1. Interview 1

Interviewee: Alejandro Buesa Olavarrieta

Institution: Joint Research Center

Interviewer: Mar Pujol Arqué

Date of interview: 12.06.2025

Location of interview: Online

[1] Supporting the circular economy approach to critical raw materials? Do you see any lagging parts, or are we going in the right direction?

On one hand, the circular economy has been a key part of the agenda for European policymakers for a long time now. Perhaps the most important piece of legislation is going to be the Circular Economy Act, which has already been announced and is foreseen to be ready soon. On the other hand, the importance of critical raw materials, or even strategic raw materials, has also been present. There have been several lists of critical raw materials with a uniform methodology dating back to 2017, if I'm not mistaken, for the first version. So, I would say that work on both dimensions exists and has existed for a while.

What is changing now is that circularity, besides being a catalyst for the twin transition and sustainable development, has now turned into a matter of economic security in parallel with the development of expectations in the defense sector and the changing geopolitical landscape. As much as both things are not new, the combination of both, or the narrative, has shifted quite quickly in the last one or two years.

From what I see as part of the policymaking process, there are no loopholes or grey zones for the time being. The main dimensions of policymaking for circularity and critical raw materials, and the intersection of both, are there. Maybe the time has come now to evaluate whether policy actions can be taken for specific materials. This is a problem the EU policymaking process often encounters: we can have a list of critical raw materials and a methodology to determine which ones are critical, but at the end of the day, we need material-specific or technology-specific policy. What we are starting to do now is tackle the individual needs of sectors or materials. So, I would say the policy landscape is quite consistent, but it is still too early to expect that all areas are covered.

[2] How do you assess the methodology for the criticality assessment? For example, titanium is also strategic, but there isn't a set methodology for strategic materials. Should the methodology become more structured or sector-specific? How do you capture technological change?

For the critical raw material list, there is a quantitative assessment based on supply risk and economic importance, which incorporates some dynamic components, such as macroeconomic flows and historical averages for exports or import concentration. But I think that at some point, we will need to render this assessment slightly more dynamic. There are projections for demand for critical raw materials, and these are used, but we could integrate them much more consistently into the criticality assessment.

This is an evolving methodology. Given that the pieces are already there, such as demand forecasts at the material and technology level, I wouldn't rule out an update to the methodology for critical raw materials in the near future. It works well because it captures the relevant dimensions, but it can always work better.

Regarding titanium, most critical raw materials in the list are usually evaluated at different stages of the supply chain, from extraction to semi-manufactured products and final products. Titanium is a special case because the ores (ilmenite and rutile) are abundant, but semi-finished titanium, from the point it becomes titanium sponge, is not abundant. For the first time in the latest CRM list, titanium had to be classified specifically as titanium metal, which shows that the current framework has some flexibility to accommodate these cases.

As for the distinction between strategic and critical, I believe there is solid ground for not having a systematic methodology for "strategic" materials, because strategic status is very much related to the sectors of the EU considered essential or economically vital. The landscape evolves fast, and EU policymaking, while careful, benefits from having some degree of flexibility. For example, the war in Ukraine prompted us to realize how important the defense industry is as a catalyst for innovation and as a driver for economic security.

This allowed us to assign more importance to strategic materials linked to this sector. Similarly, for sectors like data centers or ICT infrastructure, where technologies evolve rapidly, a fixed five-year methodology might lag behind reality. The strategic designation allows policymakers to legislate more quickly when necessary.

[3] How do you see the interplay between achieving economic security for critical raw materials and meeting decarbonization objectives? Could these goals clash? Which EU bodies will play a role here?

This is a very good point. Starting from the end, yes, the European Investment Bank (EIB) has already expressed willingness to adapt its funding tools and strategy to support decarbonization in the EU. This covers any emissions abatement achievable through the circular economy. For example, if you can melt one ton less of virgin titanium and use scrap instead, that's already a huge energy saving for the producer. This is particularly relevant for energy-intensive sectors, which are common in critical raw material value chains.

The European Commission has also expressed its willingness to reduce red tape and simplify procedures for projects involving secondary processing or extraction of critical raw materials. Recently, there has been a list of projects related to critical raw materials receiving EU support. I think the whole ecosystem of European institutions and funding schemes will support such initiatives.

As for trade-offs, yes, there will inevitably be trade-offs, especially in the medium and short run. Setting up infrastructure for recycling, processing, or manufacturing domestically in the EU is not only expensive and energy-intensive but also time-consuming, often taking up to a decade to become fully operational. What do we do in the meantime?

There are also trade-offs in terms of trade policy. For example, with titanium, we could cut every buy-back agreement with the United States, but this has serious consequences for trade relationships. The Commission is aware of these sensitivities.

On the energy mix and the green transition, trade-offs exist too. Even with growing reliance on renewable energy, we are still far from 100% renewable sources. But mathematically, fostering circularity will have a net positive impact on emissions and the environment.

In the meantime, mechanisms like the Carbon Border Adjustment Mechanism (CBAM) help ensure that if we cannot produce something cleanly in the EU, we at least import it from cleaner sources. There's no "free lunch." We've long known that we would need to make sacrifices, especially regarding extraction and mining. Mining can be environmentally harmful, but if done with minimized impacts and proper compensation, it can make sense from an economic and social perspective.

[4] Which market tools could foster an integrated secondary raw material market? Are tools like public procurement, minimum recycled content targets, taxation, or public funding plausible?

Yes, I think they are plausible. In fact, my work program for the next three years will focus heavily on the secondary raw material market. Any typical microeconomic adjustment tool to correct externalities—like hedonic pricing or public support—is plausible.

That said, we lack sufficient quantitative analysis in this area. So far, we've over-relied on qualitative studies because of limited data availability and disclosure difficulties. I'm glad the JRC is starting to address this because we need a flexible modeling framework to test different tools, such as recycled content targets, taxes on non-recycled content, or public procurement. We also need to evaluate their welfare, economic, and environmental impacts.

Currently, impact assessments for regulations like the Sustainable Product Regulation tend to be sector- or material-specific, but a more integrated and quantitative approach is needed.

[5] Focusing on titanium, what are the main barriers you've identified? Could these be transferred to other materials, or are they unique?

I see two distinct sets of drivers and barriers: one is material- or sector-specific, and the other is common across materials. Regulatory barriers, like recertification requirements, tend to be common. For instance, recertifying a component for aerospace use is equally cumbersome whether it's titanium or another material.

On the other hand, titanium faces very specific barriers, like buy-back agreements with third countries, which are contingent on its global abundance and processing infrastructure. From a qualitative perspective, it's important to distinguish between these general and material-specific barriers.

This distinction is reflected in legislation. For example, the Critical Raw Materials Act applies to all CRMs, while the WEEE Directive adds another layer for materials used in electronic equipment. Ideally, we would also quantify these barriers to understand their welfare impacts and prioritize them accordingly.

[6] What other materials would you recommend studying for a comparative analysis with titanium?

As a researcher, I would rule out mainstream materials like bauxite or rare earths. They're too widely used, and the scope would be overwhelming. It makes more sense to focus on something limited in scope, similar to titanium.
Cobalt could be a good candidate because it has a similar profile and a lot of research is available, especially on extraction and processing. You might also look into materials like bismuth or beryllium, which are used in fewer technologies but are still high on the supply risk scale.

I recommend reviewing the Carrara et al. report on supply chain analysis and material demand forecasts for strategic technologies. It maps critical and strategic materials across technologies and sectors and includes useful data on supply risks and bottlenecks. It could help you identify a good candidate material to study.

8.1.2. Interview 2

Interviewee: Florian Flachenecker
Institution: European Commission, DG ENVI
Interviewer: Mar Pujol Arqué
Date of interview: 14.07.2025
Location of interview: Online

[1] Could you start by explaining your background, what you work on at the Commission, and how you assess the current EU policies on circular economy and critical raw materials?

I work in DG Environment on circularity, in particular on the Circular Economy Act. I lead a task force in DG Environment that specifically works on this, which includes a critical raw materials (CRM) component. My background is in economics; I wrote my PhD on circularity, focusing on how circular innovations affect business competitiveness and greenhouse gas emissions, using mainly quantitative econometric analysis.

Regarding CRMs, of course the key piece of legislation is the Critical Raw Materials Act, which you are familiar with. It contains a circularity element, which, while not its main focus, is still an important one. What I want to emphasize more is how this links to the Circular Economy Act. In the mission letter to our Commissioner and in the political guidelines of our President, there is an announcement of the Circular Economy Act to establish a single market for secondary raw materials and waste, particularly related to critical raw materials.

This is the angle we are working on, with a focus on waste of electrical and electronic equipment (WEEE), as these contain a lot of CRMs. We recently published the evaluation of this directive, which could be useful for you, as it gives insight into the direction we are thinking of for revising this legislation as part of the Circular Economy Act. One of the key findings is that collection rates are very low, only about 50% of mobile phones, for example, are collected, despite containing many CRMs. Increasing collection is one element we want to focus on.

We also want to extend the scope of what the directive covers, for example to include heat pumps, wind turbines, and undersea cables, which contain CRMs but are insufficiently covered by legislation at present.

But legislation can only go so far. We can incentivize or require that a certain amount of secondary CRMs are used in products, but the challenge is also economic. Extracting tiny amounts of valuable CRMs is labor-, energy-, and capital-intensive, so economies of scale are needed. One idea we are exploring under the Circular Economy Act is "circularity hubs", cross-member-state hubs where waste streams can be aggregated to extract CRMs more economically.

Another area we want to explore is mining waste. There is likely a significant amount of CRMs in mining tailings, but we lack sufficient information. We want to ensure member states gather data on the CRM content of mining waste so we can assess whether recovery makes economic sense.

[2] In my thesis, I'm comparing titanium and cobalt as case studies, which have very different barriers to circularity. How do you see legislation progressing in terms of tackling material-specific issues? Should we group CRMs by similar challenges or address them individually?

That's a very good question, and not an easy one to answer. I don't think we have a fully developed approach in the Commission on this yet.

I fully agree that each CRM is different and faces different constraints. This is typical for circularity, each material or waste stream has its own challenges. The CRM Act sets overall targets across all CRMs, but colleagues working on the WEEE revision, for instance, try to identify key CRMs relevant for particular waste streams and prioritize based on criteria such as the absence of a functioning market or high relevance to WEEE.
Batteries are a bit different, as they are governed by their own regulation. For materials like titanium, the policy and legal responses need to be tailored. If they are too general, they risk failing to address actual barriers or addressing irrelevant ones.

I don't think we have a perfect solution yet. However, there are large EU-funded projects like Futurama, which aim to map CRMs across waste streams, including WEEE and construction and demolition waste, to better understand their distribution. This could help inform more tailored policymaking in the future.

[3] In your work, have you identified knowledge transfer or intellectual property barriers? For example, with initiatives like the battery passport, how do you handle the challenge of requiring companies to share sensitive information?

This is indeed a tricky part of policymaking. To mandate that companies provide information on CRMs as part of product passports, you need a solid basis. That requires having enough information to justify the requirement, but not having so much that no further information is needed, so it's a chicken-and-egg problem.

In the Circular Economy Act, we are trying to close this gap particularly for mining waste, by requiring more information from member states. On the product side, other pieces of legislation already provide mechanisms for this, so we don't duplicate them in the Act.
There is huge potential in product passports. Once producers must disclose material contents, including CRMs, recyclers can use this information for better recovery. But there is a trade-off: sharing too much detail could risk exposing proprietary information. So, we need to balance transparency with protecting intellectual property.

[4] On the economic side, how do you see market tools, like public procurement, taxation, or minimum recycled content requirements helping develop a secondary raw material market?

That's exactly what the Circular Economy Act aims to do: work on both supply and demand sides.

On the supply side, we want much better collection, especially separate collection, to ensure a sufficient and high-quality supply of materials for recycling. We also want to make landfill and incineration more expensive, using economic instruments such as a cap-and-trade system for landfill permits. This would reduce landfilling in an economically efficient way.

Extended producer responsibility is another key tool, potentially linked to eco-modulation, so recyclable products with higher recycled content are cheaper than those without.
On the demand side, we want to ensure that secondary materials are used rather than exported or landfilled. Tools like recycled content requirements in products, green public procurement, and possibly VAT exemptions for secondary materials are all being considered.

What trade-offs do you see between EU climate targets and the increased demand for CRMs to support technological and industrial growth? What funding tools could help bridge the gap?

The key trade-off is that while increasing circularity and recycling decreases greenhouse gas emissions compared to primary production, demand for CRMs keeps growing. We want more digital devices, more batteries, and more green technologies, so consumption rises. Addressing this demand is politically and socially challenging.

There are also additional externalities beyond environmental ones, economic security, for example. Supply disruptions for CRMs don't just impact luxury goods like smartphones but also critical sectors like healthcare or agriculture.

On funding, we estimate a €27 billion annual investment gap for the circular economy. Public funding will play a role, through the EU budget, state aid frameworks, and institutions like the EIB and national promotional banks. But private funding is crucial. Tools like the sustainable finance taxonomy can help direct private investment toward circular solutions. Ultimately, for circularity to scale, the economics need to work—once they do, financing will follow.

8.2. Annex B

Table B 1

EU Policy Framework Supporting the Circular Economy for CRMs

Policy/Initiative	Legal Status	Main Scope	Relevance to CRMs	Support to CE
Critical Raw Materials Act (CRMA)[1]	Regulation (adopted in 2024)	Defines strategic and critical raw materials; sets benchmarks for extraction, processing, recycling, and diversification; creates Strategic Projects and monitoring mechanisms	Central initiative for CRM security and resilience	Sets a 15% recycling benchmark by 2030; encourages secondary raw materials, investment in recycling infrastructure
Batteries Regulation[2]	Regulation (adopted 2023)	Requirements for batteries' carbon footprint, recycled content, durability, and removability	Addresses key CRMs in batteries: lithium, cobalt, nickel	Mandates recycled content targets; material recovery and collection schemes; product passport for traceability
Ecodesign for Sustainable Products Regulation (ESPR)[3]	Regulation (adopted in 2024)	Framework for product-specific sustainability requirements (e.g. durability,	Targets CRM use in energy-related and high-impact products	Enables design for circularity, CRM traceability, and mandatory

[1] Regulation (EU) 2024/1252. *Establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020*. European Parliament and Council. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401252

[2] Regulation (EU) 2023/1542. *Concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC*. European Parliament and Council. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542

[3] Regulation (EU) 2024/1781. *Establishing a framework for the setting of ecodesign requirements for sustainable products, amending Directive (EU) 2020/1828 and Regulation (EU) 2023/1542 and repealing Directive 2009/125/EC*. European Parliament and Council. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401781

		repairability, recyclability, % of recycled content)		recycled content for certain components
Waste Electrical and Electronic Equipment (WEEE) Directive[4]	Directive (recast 2012/19/EU)	Collection, recycling, and recovery targets for e-waste; extended producer responsibility schemes for producers	E-waste contains CRMs like rare earths, cobalt, and precious metals	Sets collection and recycling targets; encourages urban mining of CRMs
Waste Framework Directive (WFD)[5]	Directive (2008/98/EC, amended in 2018 and proposed revision in 2023)	Establishes waste hierarchy, extended producer responsibility, recycling targets; new proposals emphasize textiles and circularity	Lays legal foundation for waste recovery and prevention of waste of CRMs across sectors	Promotes prevention, reuse, recycling, and material recovery of products containing CRMs
Circular Economy Action Plan (CEAP)[6]	Non-binding Communication	Strategic roadmap for CE across sectors; focus on electronics, batteries, construction, and critical materials	Identifies CRMs as a priority for CE efforts	Promotes eco-design, reuse, recycling, and substitution of CRMs

[4] Directive 2012/19/EU. *On waste electrical and electronic equipment (WEEE)*. European Parliament and Council. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:02012L0019-20180704

[5] Directive 2008/98/EC. *On waste and repealing certain Directives*. European Parliament and Council. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098

[6] European Commission (2020, March 11). Communication from the Commission to the European parliament, the Council, the European economic and social committee and the Committee of the regions: A new Circular Economy Action Plan for a cleaner and more competitive Europe (COM(2020) 98 final). https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF