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CIRCULAR ECONOMY AND RARE MATERIALS: A CHALLENGE FOR THE EUROPEAN COUNTRIES*

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Abstract. The paper provides a knowledge increase of the circular economy model in the context of rare materials in Europe. Rare materials play a crucial role in various industries but are often associated with limited availability and environmental concerns. The paper highlights the importance of circular economy strategies in Europe to enhance the sustainable management and utilization of rare materials. It emphasizes the need for comprehensive policies, collaborative initiatives, and technological innovations to foster the transition towards a circular economy for rare materials in Europe. With the circular economy approach, Europe could minimize the environmental impact, reduce dependence on imports, and promote the sustainable use of rare materials, ultimately contributing to a more resilient and sustainable future.

Keywords: circular economy; European countries; rare materials; sustainability

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1. Introduction

The concept of a circular economy has gained significant attention in recent years as a means to foster sustainable economic growth and address the challenges of resource depletion and environmental degradation. At the heart of the circular economy is keeping products, materials, and resources in use for as long as possible, maximizing their value, and minimizing waste and environmental impacts. Within the circular economy context, rare materials hold a unique position. Rare materials, such as rare earth elements, lithium, and platinum group metals, are critical components in various industries, including electronics, renewable energy, and advanced technologies. They possess unique properties essential for producing high-performance and innovative products. However, the limited availability and the challenges associated with their extraction, processing, and disposal raise concerns about their sustainability and the need for more responsible management practices. The circular economy offers a framework to address these challenges and promote a more sustainable approach to rare materials. By implementing principles of the circular economy, such as designing for longevity and recyclability, promoting resource efficiency, and fostering product reuse and recycling, it becomes possible to reduce the demand for virgin rare materials and minimize the associated environmental impacts. The circular economy provides a holistic and systematic approach to maximize the value of rare materials throughout their lifecycle, from extraction to end-of-life recovery.

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Furthermore, the circular economy encourages the development of innovative technologies and processes that facilitate the recovery and recycling of rare materials from discarded products. By establishing efficient recycling systems, advanced separation techniques, and robust supply chains, it becomes possible to extract valuable rare materials from waste streams and reintroduce them into the production cycle, reducing the need for primary extraction. However, implementing the circular economy principles for rare materials takes time and effort. Technological limitations, economic feasibility, and geopolitical considerations can hinder achieving a fully circular and sustainable system. Collaboration between industries, governments, and research institutions becomes crucial to developing and deploying innovative solutions, promoting responsible sourcing practices, and addressing the complexities of rare materials within a circular economy framework. The paper aims to investigate if the circular economy provides a strategic pathway to address the sustainability challenges posed by rare materials. By integrating circular economy principles, such as resource efficiency, product reuse, and recycling, it becomes possible to maximize the value of rare materials, reduce environmental impacts, and foster a more sustainable and resilient economy. The circular economy offers a promising approach to ensure the long-term availability and responsible management of rare materials supporting sustainable development. The literature review section provides an overview and critical analysis of existing research and scholarly works relevant to the topic of the study. The methodology section describes the approach and procedures used to conduct the research study. The results section presents the findings obtained from the data analysis and interpretation. The discussion section provides an opportunity to interpret and explain the results obtained from the study. The conclusion section serves as a summary and final statement of the study's key findings and their broader implications.

2. Literature Review

The circular economy is an economic model (Murray et al., 2017) that aims to minimize waste (Song et al., 2015), keep products and materials in use for as long as possible (Motz et al., 2001; Zecca et al., 2023) and regenerate natural systems (Morseletto, 2020; Piccinetti et al., 2023). It is possible to realize the concept of "closing the loop" (Hobson, 2016) by designing out waste and pollution (Hill, (2020), maximizing the value of products (Romero-Hernández et al., 2018), and ensuring that materials are reused, repaired, or recycled (Cole et al., 2019; Caratas et al., 2021). On the other hand, rare materials (Torreggiani et al., 2021) have limited availability in nature or are difficult to extract and process (Ang et al., 2020). They are often essential components in various industries, including electronics, renewable energy, and advanced technologies. Rare materials include rare earth elements, such as neodymium and lithium, used in producing magnets and batteries, respectively (Omodara et al., 2019). The circular economy can be crucial in managing rare materials more sustainably. By implementing circular economy principles, such as product design for longevity and recyclability, efficient resource management, and the use of renewable or recycled materials, we can reduce the demand for virgin rare materials. This can help alleviate the environmental impact of their extraction, processing, and disposal. Additionally, the circular economy promotes product reuse, remanufacturing, and recycling, which can help recover and retain rare materials from discarded products. By implementing efficient recycling systems and developing innovative technologies, we can extract rare materials from end-of-life products and reintroduce them into the production cycle. This reduces the need for primary extraction and decreases reliance on limited natural resources. However, it is important to note that the circular economy alone may not fully address the challenges associated with rare materials. Technological limitations, economic feasibility, and geopolitical considerations can still challenge achieving a fully circular and sustainable system for rare materials. Nonetheless, integrating circular economy principles can contribute to more responsible and efficient management of these valuable resources. Technological limitations can impact the management and utilization of rare materials in several ways: extraction and processing: rare materials often require specialized extraction and processing techniques due to their unique properties or occurrence in complex geological formations. Technological limitations in these areas can affect the efficiency and feasibility of extracting rare materials from ore bodies or other sources. Developing and improving extraction technologies is crucial to ensure a sustainable supply of rare materials (Balaram, 2019). Rare materials are often present in small quantities within complex products, making their recovery and recycling challenging. Technological limitations in separation, sorting, and recycling processes can hinder the efficient extraction of rare materials from end-of-life products. Developing advanced recycling technologies that can economically and effectively recover rare

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materials from diverse waste streams is essential (Graedel, et al., 2016). This approach may restrict the availability of viable substitutes or alternative materials for rare materials. If no suitable alternatives exist, the demand for rare materials may grow despite their limited availability. Investing in research and development to discover or create alternative materials or technologies can help mitigate reliance on rare materials (Stratiotou Efstratiadis et al., 2022). Material efficiency and design actions can impact the rare materials required for specific applications. Advancements in materials science and engineering can enable the development of new materials or the optimization of existing materials, reducing the overall demand for rare materials in various industries. Addressing these actions means to realize economic feasibility. Economic feasibility (Jaroni et al., 2019) plays a significant role in managing rare materials. Several factors influence the economic feasibility of rare materials, including their availability, extraction costs, market demand, and geopolitical considerations. Rare materials are concentrated in small areas worldwide, and availability and scarcity may be strategic factors. The limited availability of rare materials can make their extraction and production more expensive. Some rare materials are found in small concentrations or are geographically concentrated in specific regions, which can increase the costs associated with exploration, mining, and processing. As the scarcity of a rare material increases, its price may also rise, affecting its economic feasibility (Hofmann et al., 2018). The economic feasibility is strictly linked to extraction cost; in fact, rare materials often require specialized extraction techniques, which can be costly. The complexity of extraction processes, the need for advanced equipment, and the environmental impact of extraction can all contribute to higher costs. Technological advancements and economies of scale can potentially reduce extraction costs over time. (Asadollahzadeh, et al., 2021). The literature review highlights the relationship between circular economy and rare materials and, at the same time, underlines a few critical processes that are necessary to be investigated.
Concentration of reserves. Rare materials are often geologically concentrated in a few countries or regions, leading to potential geopolitical implications. For example, China has historically been a dominant producer and supplier of rare earth elements, accounting for a significant portion of global production. The concentration of reserves in specific regions can create supply vulnerabilities and geopolitical dependencies for countries reliant on these materials.
Supply chain vulnerabilities. The global supply chains for rare materials can be complex and susceptible to geopolitical risks. Disruptions in supply due to political conflicts, trade disputes, or export restrictions can impact industries heavily reliant on these materials. This vulnerability has prompted countries and industries to diversify their supply sources and explore alternative material options to mitigate geopolitical risks.
Trade restrictions and tariffs. Geopolitical tensions can lead to the imposition of trade restrictions, tariffs, or export quotas on rare materials. These measures can disrupt supply chains and increase costs for industries dependent on these materials. Trade disputes and protectionist policies can further escalate geopolitical tensions and impact the availability and affordability of rare materials.

Geopolitical trajectories are emerging as strategic variables to create a relation between rare material and circular economy model implementation. Rare materials are critical for several strategic industries, such as defence, electronics, and renewable energy. Countries with significant rare material reserves or production capabilities can leverage their position to gain geopolitical advantages. The strategic importance of rare materials can influence international relations, alliances, and trade dynamics. Furthermore, geopolitical considerations have spurred efforts by countries and industries to explore alternative sources of rare materials. This includes investing in domestic exploration and production, engaging in international partnerships, and supporting research and development to discover new sources or develop alternative materials. Efforts to diversify supply sources aim to reduce geopolitical dependencies and enhance resource security. These trajectories are closely linked to the environmental and social impacts of extracting and producing rare materials. In some cases, geopolitical tensions may result in less stringent environmental regulations or inadequate labour standards in rare material-producing regions. Ensuring responsible sourcing practices and sustainable extraction methods becomes crucial to address these concerns. Managing geopolitical trajectories related to rare materials and circular economy implementation requires international cooperation, dialogue, and strategic planning. In the literature review, critical points emerged: geopolitical trajectories are strategic variables to create a relationship between rare material and circular economy model implementation. The methodology in the next paragraph intends to answer the following research question: In which industrial sectors does Europe execute collaborative actions that realize the circular economy and reduce the use of rare materials?

3. Methodology

A qualitative and quantitative methodology for studying the circular economy and rare materials involves using numerical data, statistical analysis, and mathematical models to quantify and measure various aspects of the topic. Here is an outline of a quantitative methodology for researching if Europe is implementing collaborative actions that realize the circular economy and reduce the use of rare materials. Understanding the current state of rare material management within the circular economy is necessary, assessing the industrial sectors implementing collaborative actions in Europe to reduce rare materials use. The relevant and available data sources for circular economy and rare material production, consumption, and recycling rates have been identified. These sources include Statistical databases Eurostat Circular Economy 2017 - 2023; Industry reports (World Bank 2017 - 2022; International Energy Agency 2017 - 2023); European government publications (EU 2017 - 2023); with particular attention to the regions/countries implementing actions linked to the circular economy model to reduce rare material use in the industrial sectors: Agro Food, Training, Education, ICT, Building, Energy, Mobility, Public and Military Aerospace, and Health. The data for the selected variables are linked to a specific period (2017 – 2022) and across 27 different European regions/countries. The data are comparable to developing descriptive analysis (qualitative) to understand the trends, patterns, and distribution of rare material flows. The data make it possible to build a matrix (quantitative) that highlights the industrial sectors with the greatest criticalities for the 27 European countries as regards reuse (Re) and remanufacturing (Rem) rates. The matrix displays the criticality levels for reuse (Re) and remanufacturing (Rem) rates in different industrial sectors across the 27 European countries. The criticality levels are determined based on relevant metrics, such as the percentage of products or materials reused or remanufactured within a sector and country. The matrix helps identify industries and countries where reuse and remanufacturing activities are thriving or lagging, highlighting areas where there might be room for improvement or critical challenges. A normalization (Singh & Singh, 2020) was performed for each data using the equation min-max method (formula 1):

$$\mathbf{1.}\ \boldsymbol{I_{qc}^{t}} = \frac{\boldsymbol{x_{qc}^{t}} - \min\limits_{c}\left(\boldsymbol{x_{qc}^{t_0}}\right)}{\max\limits_{c}\left(\boldsymbol{x_{qc}^{t_0}}\right) - \min\limits_{c}\left(\boldsymbol{x_{qc}^{t_0}}\right)}$$

Starting from this assumption, differentiations can be calculated in the following

y(w,s) = α(s) + β(s)(g(w) + ε(w,s))
w Country, w = 1,2....W
s Sub Dimension of differentiation, s=1,2...S
y (w,s) observed score on indicator s for country w
g(w) Unobserved performance. g(w) is assumed to be a normally distributed random variable with mean 0 and standard deviation 1.
ε(w,s) The phrase disruption is also known as the term mistake. It reports the perception and measurement error, as well as sample variance. Furthermore, it demonstrates the erroneous link between the specific notion indicated by indicators and the related broader component of efficacy.α(s) β(s) Coefficients are helpful in mapping, together with the disturbance term ε(w,s), unobserved governance into the observed data.
σ ε2(s) Variance of the disturbance terms of indicators common to all countries

Unobserved components also shape differentiation. The efficiency of these unseen components is judged by algebraically summing the scores acquired on each dimension y. (w;s). Following this hypothesis, it is possible to evaluate the unknown performance g(w); however, putting the error term and g(w) into brackets together is preferable. The model includes the following assumption: the random terms (disturbance terms) ε(w,s) are not correlated with each other, i.e. perception errors are not correlated across dimensions and countries. To identify the model parameters, it is essential to consider that the mean of ε(w,s) is zero for all w,s. The disturbance term has the same variance, σε2(w), among countries within a set indicator but may have a different variance among dimensions. Unobserved governance and observed indicators are linearly related, ε(w,s) are statistically independent of g(w) for all w and s. Both g(w) and ε(w,s) have a joint normal distribution. Starting with Min Max method, estimates of α(s), β(s) and σε(s) are achieved, and this model is founded on the next Likelihood function (formula 2):

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$$2. L\ [\ w; \alpha, \beta, {\sigma_\varepsilon}^2(1), \dots, {\sigma_\varepsilon}^2\ (S)\ ] = \prod_{w=1}^{W} (2 \cdot \pi)^{-\frac{W}{2}}\ |\Omega|^{-\frac{1}{2}} \exp[y(w) - \alpha] \exp[y(w) - \alpha]'\ \Omega^{-1}\ [y(w) - \alpha]$$

S = score of dimension
W = number of countries
y(w) = the Sx1 vector of the y(w,s)'s for country w
y = the WSx1 vector of the y(w,s)'s for all countries α = Sx1 vector of the α(s)'s
β = Sx1 vector of the β(s)'s
Ω = ß ß' + diag {σε2(s)•β(s)2}

The formula 3 (weights p) expresses a relationship in which each indicator in the aggregation technique is inversely proportional to its error variance, i.e. the smaller the weight, the greater the variance of the error term.

$$3. \mathrm{p(s)} = \frac{\sigma_\varepsilon(s)^{-2}}{1 + \sum_{s=1}^{s(w)} \sigma_\varepsilon\ (s)^{-2}}$$

Equation 3 assesses performance by taking a weighted average of the rescaled observed scores. These rescaled scores are derived by subtracting α (s) from each observed score y(w,s) and then dividing the result by β (s). It is feasible to rewrite equation 1 in this manner while assuming a mathematical expectation. Because this is a calculation of expected values, we can assume that the expected value of the disturbance term, ε (w,s), is 0. Equation 4 (mean) and 5 (standard deviation) assumptions indicate that the conditional distribution of unobserved governance g(w) is normal.

$$4. E[g(w)|y(w), \alpha, \beta] = \sum_{s=1}^{S(w)} p(s) \cdot \frac{y(w,s) - \alpha(s)}{\beta(s)}$$

$$5. sd\lfloor g(w)|y(w), \sigma_\varepsilon^2(1), \dots, \sigma_\varepsilon^2(S)\rfloor = [\ \sum_{s=1}^{S(w)} \sigma_\varepsilon^2(S)^{-2}\ ]^{-1/2}$$

The variation of the (w,s) (equation 5) on each indicator increases as the number of specific indicators in which a single country appears decreases. Each indicator is rescaled so that more significant results are equivalent to better outcomes. A further rescaling is achieved by deleting the lowest possible score and dividing by the gap between the lowest and highest possible scores. The estimates of the α(s), β(s) and σ_ε^2(s), are achieved using Equation 2. The low level of σ_ε^2(s) means that indicators will show similar results to the other indicators. The error variances will be more considerable if the indicators are uncorrelated. This score association underpins the concept of efficacy and is not directly related to perception errors. Because the results of equation 3 are inversely proportional to their imputed error variance, the indicators that reveal a high correlation will have a higher weight in the weight calculation than other indicators. Equation 4 can now be approximated for each country, yielding an estimate of the degree of performance g(w). Finally, equation 5 calculates the standard error of these estimations. Each country's efficacy assessments are rescaled by subtracting the mean across countries and dividing by the standard deviation across nations. The results are in the -2.5 to 2.5 range. The standard error (Equation 5) is calculated once more. The four indices, i.e., European Countries, Industrial Sector, availability risk, reuse and remanufacturing rare materials used, create a general performance highlighted with a matrix method. This method allows you to respond to the RQ, highlighted at the end of the paragraph relating to the literature review.

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4. Results

Shared policies across all 27 European countries linked to the circular economy and rare materials for each industry sector, qualitative methodology, are reported in Table 1. The detailed projects are reported in Table 1. Table 1 does not show the sectors with no shared projects among the 27 European countries: Agro Food, Training, and Education.

Table 1. Shared projects policies across all 27 European countries linked to the circular economy and rare materials (*)

ICT	BUILDING	ENERGY SECTOR	MOBILITY	PUBLIC/MILITARY AEROSPACE	HEALTH
WEEE	EPBD	RET	EV	ESP	SP
RoHS	GBCS	EFM	CID	SAF	EPR
ErP	CDwM	CEWE	SPT	WRR	WRR
GPP	CPP	BESR	UMS	LCAEd	GHI
EUCEAP	BREEAM	GM&SG	FES		
	LEED		LCATI		

(*) *Source*: our elaboration on Eurostat Circular Economy, Industry Reports and European Government Publications (2017 – 2023). Our elaboration

Shared policies across all 27 European countries linked to the circular economy and rare materials in the ICT sector highlight the following projects:
Waste Electrical and Electronic Equipment (WEEE) Directive: The WEEE Directive establishes requirements for collecting, recycling, and recovering electronic waste. European countries are implementing this directive, setting up systems to ensure the proper disposal and recycling of ICT equipment at the end of its life cycle. This directive promotes the circular economy by encouraging the recovery of valuable materials from electronic waste. European countries involved: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Restriction of Hazardous Substances (RoHS) Directive: The RoHS Directive restricts the use of hazardous substances in electrical and electronic equipment. It aims to reduce the environmental and health risks associated with these substances. By limiting the presence of harmful materials in ICT products, the directive promotes the use of safer and more recyclable materials. European countries involved: Austria, Denmark, Estonia, Finland, France, Germany and Italy.

Eco-design Requirements for Energy-Related Products (ErP): The Eco-design requirements for energy-related products aim to improve the environmental performance of energy-consuming products, including ICT devices. These requirements set energy efficiency standards and encourage using recyclable and repairable materials in the design and production of ICT equipment. European countries involved: Belgium, Denmark, Estonia, Finland, France, Germany and Italy.

Green Public Procurement (GPP): European countries have implemented GPP policies that include criteria for ICT equipment. These policies promote the purchase of environmentally friendly products, including ICT devices that meet specific sustainability requirements, such as energy efficiency, recyclability, and recycled materials. European countries involved: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Italy, Netherlands, Portugal, Slovakia, Slovenia, Spain and Sweden.

European Union Circular Economy Action Plan (EUCEAP): The Circular Economy Action Plan of the European Union includes initiatives to promote sustainable and resource-efficient products, including ICT equipment. This plan encourages the extension of product lifetimes, the use of recycled materials, and the adoption of circular business models in the ICT sector. European countries involved: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, all 27 Countries.

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Shared policies across all 27 European countries linked to the circular economy and rare materials in the Building sector highlight the following projects:

Energy Performance of Buildings Directive (EPBD): The EPBD sets requirements for the energy performance of buildings and aims to promote energy efficiency in the building sector. Many European countries have implemented this directive, including provisions for using sustainable and recycled materials in building construction and renovation. European countries involved: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Slovakia, Slovenia, Spain, Sweden,

Green Building Certification Systems (GBCS): Several European countries have adopted or developed green building certification systems that encourage sustainable and resource-efficient building practices. These systems often promote the use of environmentally friendly materials, including those with recycled content, and encourage circular principles in the construction and operation of buildings. European countries involved: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Spain, and Sweden.

Construction and Demolition Waste Management (CDwM): European countries have regulations and initiatives to manage construction and demolition waste. These policies promote recycling and resource recovery from construction and demolition sites, reducing the demand for new materials and encouraging using recycled materials in building projects. European countries involved: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Portugal, Slovakia, Slovenia, Spain and Sweden.

Circular Public Procurement (CPP): Many European countries have introduced circular procurement policies requiring sustainable and resource-efficient construction practices. These policies promote using recycled materials, adopting circular business models, and considering the life cycle impacts of building materials in public procurement processes. European countries involved: Austria, Belgium, Croatia, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Netherlands, Portugal, Slovakia, Slovenia, Spain and Sweden.

Sustainability Standards and Labels: European countries often adopt or recognize sustainability standards and labels for buildings, such as BREEAM (Building Research Establishment Environmental Assessment Method) and LEED (Leadership in Energy and Environmental Design). These standards consider the use of sustainable materials and promote resource efficiency in the construction and operation of buildings. European countries involved: Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Shared policies across all 27 European countries linked to the circular economy and rare materials in the energy sector highlight the following projects:
Renewable Energy Targets (RET): Many European countries have set renewable energy targets to increase the share of renewable energy sources in their energy mix. These targets promote developing and deploying sustainable energy technologies, often prioritizing using materials with a lower environmental impact and reducing reliance on rare materials. European countries involved: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Netherlands, Poland, Portugal, Spain, Sweden,

Energy Efficiency Measures (EFM): European countries have implemented various energy efficiency measures and regulations to reduce energy consumption in the energy sector. These measures include energy efficiency standards for appliances, buildings, and industrial processes. By improving energy efficiency, countries can reduce the overall demand for energy and the need for resource-intensive energy generation. European countries involved: Austria, Belgium, Denmark, Finland, France, Germany, Netherlands, Portugal, Spain and Sweden.

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Circular Economy in Waste-to-Energy (CEWE): Some European countries have implemented circular economy principles in the waste-to-energy sector. This involves promoting energy and valuable materials recovery from waste streams through technologies such as anaerobic digestion and incineration with energy recovery. These practices help reduce waste volumes, recover resources, and minimize environmental impacts. European countries involved: Austria, Belgium, Denmark, Finland, France, Germany, Netherlands, Portugal, Slovakia, Slovenia, Spain and Sweden.

Battery and Energy Storage Regulations (BESR): European countries have established regulations and standards for the safe and environmentally sound management of batteries and energy storage systems. These regulations often aim to promote sustainable and recyclable materials in batteries, encourage responsible disposal, and support the development of circular business models for energy storage. European countries involved: Denmark, Estonia, Finland, France, Germany, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Grid Modernization and Smart Grids (GM&SG): European countries are investing in grid modernization and developing smart grids to enable a more efficient and flexible energy system. These initiatives often involve the integration of renewable energy sources, energy storage, and demand response mechanisms, which contribute to a more sustainable and resource-efficient energy sector. European countries involved: Austria, Netherlands, Portugal, Spain and Sweden,

Shared policies across all 27 European countries linked to the circular economy and rare materials in the mobility sector highlight the following projects:

Electric Vehicle (EV) Incentives: Many European countries have introduced incentives to promote the adoption of electric vehicles. These incentives include financial incentives, tax benefits, and subsidies for purchasing electric vehicles. By encouraging the transition to electric mobility, these policies aim to reduce the environmental impact of transportation and promote the use of materials with a lower ecological footprint. European countries involved: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Charging Infrastructure Development (CID): European countries invest in developing charging infrastructure for electric vehicles. This includes the installation of public charging stations and incentives for private charging infrastructure. By expanding the charging network, countries aim to support the widespread adoption of electric vehicles and facilitate the circularity of energy used in the mobility sector. France, Germany, Netherlands, Spain, Sweden.

Sustainable Public Transportation (SPT): Many European countries have implemented policies to promote sustainable public transportation systems. This includes using low-emission buses, trams, and trains and integrating renewable energy sources into public transportation networks. These policies reduce the reliance on fossil fuels and promote more sustainable and resource-efficient mobility. European countries involved: Austria, Belgium, Bulgaria, Croatia, Denmark, Estonia, Finland, France, Germany, Ireland, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Slovakia, Slovenia, Spain and Sweden.

Urban Mobility Strategies (UMS): European countries are developing urban mobility strategies that prioritize sustainable and active modes of transportation, such as walking, cycling, and public transit. These strategies aim to reduce congestion, improve air quality, and promote shared mobility services, which can help optimize resource utilization. European countries involved: Austria, Denmark, Finland, France, Germany, Netherlands, Spain and Sweden.

Fuel Efficiency Standards (FES): European countries have adopted fuel efficiency standards for vehicles to reduce fuel consumption and greenhouse gas emissions. These standards encourage the development and adoption of fuel-efficient technologies, often requiring the use of materials with a lower environmental impact. European countries involved: Austria, France, Germany, Netherlands, Portugal, Slovakia, Slovenia, Spain and Sweden.

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Life Cycle Assessment in Transport Infrastructure (LCATI): Some European countries are integrating life cycle assessment (LCA) approaches into the planning and designing of transport infrastructure. LCA evaluates the environmental impacts of infrastructure projects throughout their life cycle, including material extraction, construction, use, and end-of-life. Countries can promote more sustainable and circular mobility solutions by considering the environmental impact of materials and infrastructure choices. European countries involved: Austria, Denmark, Finland, France, Germany, Italy, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Shared policies across all 27 European countries linked to the circular economy and rare materials in the public and private aerospace sector highlight the following projects:
European Space Policy (ESP): The European Space Policy provides a framework for cooperation among European countries in space activities, including the aerospace sector. The policy promotes sustainable and responsible space exploration, efficiently encouraging resource use and minimizing waste generation. European countries involved: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Italy, Netherlands, Poland, Portugal, Spain and Sweden.

Sustainable Aviation Fuels: Several European countries have established policies and initiatives to promote the use of sustainable aviation fuels (SAF). SAFs are derived from renewable feedstocks and help reduce greenhouse gas emissions from the aerospace sector. By supporting the development and adoption of SAFs, countries aim to promote circularity and reduce the sector's environmental impact. European countries involved: Austria, Belgium, Denmark, France, Germany, Netherlands, Portugal, Spain and Sweden,

Waste Reduction and Recycling (WRR): European countries have implemented waste reduction and recycling measures in the aerospace sector. These measures include collecting and properly disposing of aerospace waste, such as metal scraps, plastic components, and other materials. Recycling initiatives aim to recover valuable materials and minimize the environmental impact of aerospace activities. European countries involved: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Life Cycle Assessment and Eco-design (LCAEd): European countries promote the integration of life cycle assessment (LCA) and eco-design principles in the aerospace sector. LCA evaluates the environmental impacts of aerospace products and processes throughout their life cycle, from raw material extraction to end-of-life. Eco-design encourages using recyclable and sustainable materials and efficient manufacturing and maintenance processes. European countries involved: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden.

Shared policies across all 27 European countries linked to the circular economy and rare materials in the health sector highlight the following projects:
Sustainable Procurement (SP): European countries promote sustainable procurement practices in the health sector, which consider the environmental and social impacts of products and services. This includes procuring medical devices, equipment, and pharmaceuticals produced with sustainable materials that follow circular economy principles. European countries involved: Austria, Denmark, Estonia, Finland, France, Germany, Italy, Luxembourg, Malta, Netherlands, Spain and Sweden.

Extended Producer Responsibility (EPR): Several European countries have implemented EPR schemes for medical waste, including pharmaceuticals and medical devices. These schemes hold producers responsible for properly managing and disposing of their products at the end of their life cycle, encouraging them to design products focusing on circularity and resource efficiency. European countries involved: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain and Sweden.

Waste Management and Recycling (WRR): European countries have regulations and initiatives for adequately managing and recycling healthcare waste. These policies aim to reduce the environmental impact of healthcare

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activities, including the appropriate handling and disposal of rare materials found in medical devices and equipment. European countries involved: Austria, Belgium, Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Slovakia, Slovenia, Spain and Sweden.

Green Hospital Initiatives (GHI): Some European countries have established green hospital initiatives that promote sustainability and circularity in healthcare facilities. These initiatives focus on energy efficiency, waste reduction, and using environmentally friendly materials in constructing, renovating, and procuring medical equipment. European countries involved: Austria, Belgium, Croatia, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain and Sweden.

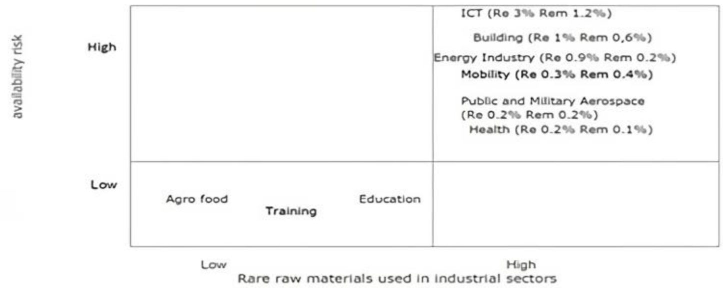

Figure 1. Elaboration on Eurostat Circular Economy, Industry Reports and European Government Publications (2017 – 2023)
Source: the authors

Applying the quantitative approach developed in the methodology paragraph, elaborating the matrix shown in Figure 1 is possible.

5. Discussion

The necessity for a systemic cultural transformation is highlighted by the essential transition from the linear economic-productive model to the circular economic-productive model (Meadows et al., 1972) has a big impact. The well-highlighted limits of the development of the linear model and the relative possible solutions date back to the 1970s, but it seemed useless to reflect and act at the time on the combination of development and sustainability today, 2023, that uselessness is the center of the economic and social life of every country in every part of the world. The shift, which has multiple paths, emphasizes two strategic pillars: geopolitical trajectories related to rare materials and circular economy implementation, developed in the paper. These two pillars entail shifting from a fossil-fuel-based and mechanical-technology-based socioeconomic structure to one based on mineral resources and digital technologies. The mineral-digital binomial, for example, is based on microchips and scarce raw materials such as silicon and palladium; microchips are in every product and, thus, in all productions. Magnets, particularly permanent magnets, enable wind power with their blades, but their applications include transportation and electronics. Cobalt and lithium are also crucial in creating batteries for the urban mobility industry and in mass-produced devices such as personal computers and smartphones. Rare materials in continuous extraction and use growth, as the IEA (2023) reported.

A shift that follows the existing cultural, systemic model of extracting, creating, using, and discarding is short-term, and it still needs to ensure the dual need for development and sustainability. Mineral-digital resources, which captivate a rising portion of the world's customers, present an economic and geographical problem: the quantity of these resources is limited and unequally distributed on the earth. Depletion of reserves in the medium term, geographical problem, physical availability and price of raw materials in the near term, economic difficulty. The impact of the Russian-Ukrainian war on the supply of energy resources, geopolitical and economic, is a recent example; the example of the past, in 2010 and not yet resolved is China, a global monopolist together with Africa, a geographical area in which China's economic control is solid, for the supply of rare raw materials. In this context, Europe's position is quite limited: it is a consumer but not a producer, resulting in a high reliance. The European Union specifies a list of rare critical materials and strategic production components for all economic sectors with high supply risk. In the Union's economic history, the list is followed by rules that must reduce supply risks and build strategic collaborations. The goal is to diminish European reliance because the shift can only occur with access to scarce raw resources. It is important to remember that in our world's history, extracting has meant deforestation, polluting soil and water, reducing and/or losing biodiversity, or development without sustainability, negatively modifying the life of the environment and local communities. A reading of the initiatives carried out by local communities to defend their living spaces is exciting. A new cultural, systemic approach to recovering and reusing rare materials at the end of their life cycle can address the possible relationship between rare but commonly utilized raw elements in consumer items and dependence on them. The European Union calls on Member States to implement the circular economy (Marino et al., 2022; 2021), but the problem is also present in other geographical areas, such as Latin America and Africa (Marino et al., 2022a), emphasizing the importance of accelerating the transition through the recovery, reuse, and reuse of rare raw materials. The study reveals shared projects and not shared policies on the part of the Member States of Europe. The production of the products is not shared. In this logic, the absence of relevant projects, productions and developments in the food and training sector is also of interest. The European brand does not exist. It has not yet been created, and the implementation of the circular economy by reducing the waste of rare materials is essential to strengthening the geopolitical trajectories of Europe, which should be united not only in intentions but in economic decisions and technological productions regarding the implementation of the circular economy concerning rare raw materials. While shared policies in the circular economy and rare materials in 27 European countries demonstrate a collective commitment to sustainable practices, there are some limits and challenges to consider:

Diverse regulatory frameworks: European countries have their regulatory frameworks and national priorities, which can lead to variations in the implementation of shared policies. This can result in differences in interpretation, enforcement, and timing of policy adoption, making it challenging to achieve consistent and harmonized approaches across all countries.

Varied resource availability: European countries have different access levels to rare materials and resources. Some countries may have more significant reserves or access to certain rare materials, while others may face scarcity. This variability can affect the implementation and effectiveness of shared policies related to rare materials, as countries may have different levels of reliance on these materials in their respective industries;

Economic considerations: Transitioning to a circular economy and addressing rare materials can involve significant costs and investments. European countries differ in economic resources, technological capabilities, and industrial structures. Implementing shared policies in the circular economy may require financial support, technical expertise, and infrastructure development, which could pose challenges for some countries with limited resources;

Stakeholder engagement and coordination: Achieving a circular economy and addressing rare materials requires collaboration and engagement among various stakeholders, including governments, industries, research institutions, and civil society. Coordinating efforts and ensuring effective participation from all relevant stakeholders across 27 European countries can be complex and time-consuming;

Monitoring and reporting: Monitoring and evaluating the progress of shared policies in the circular economy and rare materials across 27 European countries can be challenging. Harmonizing data collection methods, setting common indicators, and ensuring accurate reporting from all countries can be difficult, which may affect the ability to assess the impact and effectiveness of these policies;

Transboundary challenges: Some circular economy and rare materials issues may have transboundary implications, such as waste movement or sourcing materials from outside the European Union. Addressing these challenges requires cooperation and coordination among countries, as well as aligning policies with global frameworks and initiatives:

Despite these limitations, the shared policies in the circular economy and rare materials among European countries provide a foundation for collaboration, knowledge-sharing, and coordinated action. They help foster a common understanding of the importance of sustainability and resource efficiency and provide opportunities for countries to learn from each other's experiences and progress in addressing these challenges. Collaborative efforts can focus on diversifying supply sources, promoting responsible sourcing and production practices, fostering recycling and circular economy approaches, and encouraging research and development for alternative materials. Countries can work towards a more stable and sustainable rare material supply chain by addressing geopolitical challenges.

Conclusion

The circular economy approach offers a promising solution to the challenges associated with rare European materials. By Improving resource efficiency, recycling, and waste reduction, the circular economy can contribute to the sustainable management and utilization of these critical resources. Europe's focus on implementing comprehensive policies, fostering collaboration, and driving technological innovation is crucial for successfully transitioning to a circular economy for rare materials. In particular, intervening in this regard to diverse regulatory frameworks, the varied resource availability, stakeholder engagement and coordination, monitoring and reporting of shared policies, and transboundary challenges are actions that improve the shared geopolitical trajectory. Europe can mitigate environmental impacts, reduce dependence on imports, and ensure the long-term availability of rare materials. Embracing the principles of the circular economy for rare materials aligns with sustainability goals. It presents economic opportunities and a pathway towards Europe's more resilient and resource-efficient future.

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