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# Circularity Reinforcement of Critical Raw Materials in Europe: A Case of Niobium

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## Abstract

Critical Raw Materials attract increasing attention due to their depleting reserves and low recyclability. Niobium, one of the most rare and vital elements, is primarily found in Brazil. This research explores the potential impact of Circular Economy (CE) strategies on mitigating niobium's criticality within Europe. First, a niobium supply chain is designed and analysed by Enterprise Input–Output modelling. Second, the supply risk is calculated based on the criticality matrix proposed by the European Commission under three scenarios associated with resources, technologies, and policies. The results show that urban mining is a potential solution to reduce niobium's criticality and mitigate its environmental impacts. A higher recycling input rate and/or a mix of recycling and substitution strategies is necessary to offset niobium's criticality. Aligned with the CE action plan, the research offers a scientific foundation to strategically prevent the risk of niobium supply shortages.

**Keywords** Critical raw materials · Circular economy · Niobium supply chain · Enterprise input–output · Scenario analysis

## Introduction

Raw materials are essential to the economy and society because they are required by all manufacturing industries. The consumption of finite materials such as metals, fossil fuels, and minerals is still on the rise and could double within the next 60 years [23]. The availability of Critical Raw Materials (CRM) is endangered [12]. These materials are characterized by their high economic importance and by a high risk regarding their supply.

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Therefore, their criticality attracts urgent attention from the European Commission (EC) [12]. One of the 30 CRM identified by the EC is *Niobium (Nb)*. It has been classified as a CRM in the European Union (EU)'s initial list since 2011 with its criticality[1] score increased from 2.8 to 3.9 [12]. Niobium spreads worldwide, however, over 90% of its total reserves are located in Brazil [10]. The supply risk of niobium is due to its high concentration of production in one country, its production being mainly performed by one company, an uncertain recycling rate, and a moderate substitutability [10].

Niobium is widely used as a strengthening component for high-strength low alloy (HSLA) stainless steels in the form of ferro-niobium (FeNb). Ferro-niobium only contains 65% of pure niobium and accounts for 89% of the worldwide niobium demand [2]. Beyond being a crucial material to the economy, the use of niobium holds further issues. Niobium is one of the CRM with the highest forecasted demand growth, second only to lithium [12]. According to the EC its demand will keep rising at an annual growth rate of 8% [10, 12]. However, the recycling rate remains relatively low at 20 to 30% [10, 29]. Additionally, no valid substitute for niobium exists as possible substitute materials imply increased costs and/or a decreased performance [10]. Various studies show that along the whole supply chain of the production of niobium greenhouse gases (GHG) are emitted, resulting in low environmental sustainability [19].

The aforementioned challenges call for practical solutions to reduce the criticality of niobium. One of the potential solutions could be a shift to Circular Economy (CE), an economic system where "the economic and environmental value of materials is preserved for as long as possible by keeping them in the economic system, either by lengthening the life of the products formed from them or by looping them back in the system to be reused" [13]. Opposed to a linear economy model of take-use-dispose, a CE model promotes practices of reducing, reusing, and recycling [39]. CE not only helps to avoid the generation of waste but also to reduce the emission of GHG, and economic growth is decoupled from the use of new resources [13]. In the case of CRM, implementing CE principles holds a high potential of reducing the dependency on present suppliers and the exploitation of new resources, which has already been highlighted in various recent articles [3, 14, 24]. Particularly, urban mining could be helpful to recover the value of critical materials via reusing and recycling following the concept of CE. In this study, we take urban mining as a meaningful branch of CE and investigate the niobium's criticality at an urban scale under future scenarios.

The potential effects of different CE strategies on niobium criticality remain unexplored. There is little predictive decision-making basis that can support policymakers to mitigate niobium criticality. Whereas the literature provides certain knowledge on raw material supply chain analysis [4, 7, 28, 32, 36, 37], a research gap exists in numerical evaluations of CE solutions in a CRM supply chain combining EU's criticality assessment matrix under future scenarios. There is a great demand for a tailored method that facilitates supply chain design and evaluation by integrating the elements of both criticality and circularity. Therefore, this research aims to develop an integrated evaluation method for CRM supply chains by taking niobium as an example. The main research question is: "To what extent does the implementation of a CE strategy impact niobium's criticality and the environmental performance of its supply chain under future scenarios?".

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[1] An indicator identified by the European Commission that measures the economic importance and the supply risk of a critical material.

To answer this question, this research applies an integrated method linking an Enterprise Input–Output (EIO) modelling and a criticality assessment in CE scenario analysis. Input–Output models have already been used in numerous ways to investigate approaches related to circular economy, e.g., for industrial symbiosis [41] or life cycle impact assessments of recycled materials [31], and are a common method to analyse supply chains [38]. The EIO model is a particular type of I-O models serving as an accounting and planning tool that outlines the flows of material, energy, and water as well as monetary flows of production on a company level, a supply chain level, and for various supply chains [41]. Besides, the criticality assessment method is adopted from a criticality matrix established by prior studies and the EC [9, 18]. By means of the matrix, both supply risk and economic importance are quantified, and CRM can be positioned in the two-dimensional matrix. Furthermore, three future scenarios are proposed by considering variables which impact a niobium supply chain, namely, (1) a supply shortage of niobium, (2) the introduction of a new recycling technology, and (3) potential changes in governmental policies. These scenarios are meaningful to explore the research question since they include external disruptions in supply quantity, technology and policy effects on recycling ratio changes.

This research investigates how to mitigate the criticality of a niobium supply chain. The results serve as a decision support basis for substantiated forecasts of material, waste, and emission flows along the niobium supply chain. Theoretically, this research adds to the currently existing literature by providing a method to assess the current challenges related to niobium production under potential scenarios. Overall, this study contributes to the implementation of a circular niobium supply chain. The results can be regarded as a predictive knowledge basis for policy recommendations on CRM reservations.

## Theoretical Background

In this section, the theoretical background is provided by introducing (1) the concept of urban mining as a CE strategy, and (2) the current evaluation method for CRM.

### Urban mining as a Circular Economy strategy

Urban mining is a CE strategy according to which raw materials are sourced from already existing objects and infrastructure [24]. Especially durable goods such as cars, technical devices, buildings, and landfill sites are used as “urban mines” to serve the demands of the economy [17]. Key studies dealing with urban mining have already emphasized the potential benefits of urban mining, especially to master the rising amount of e-waste [35, 44] and in this context also to recover CRMs from this waste stream [24]. Another advantage of urban mining is the ability to create forecasts of future material flows considering the life span of the goods materials can be sourced from. Through a preceding analysis, products can be efficiently salvaged at the end-of-life stage instead of entering waste management [17]. Due to urban mining, a circular product flow can be achieved not by recycling the whole product, but by recovering raw materials from the product at its end-of-life and reintroducing these materials to the market [24, 35].

The demand for niobium is on the rise [10], while its criticality has increased and the environmental impact of a niobium supply chain needs to be mitigated [12]. To meet this rising demand for niobium and reduce the dependency on suppliers and the environmental impact, urban mining can potentially be a feasible strategy as high-strength steel containing

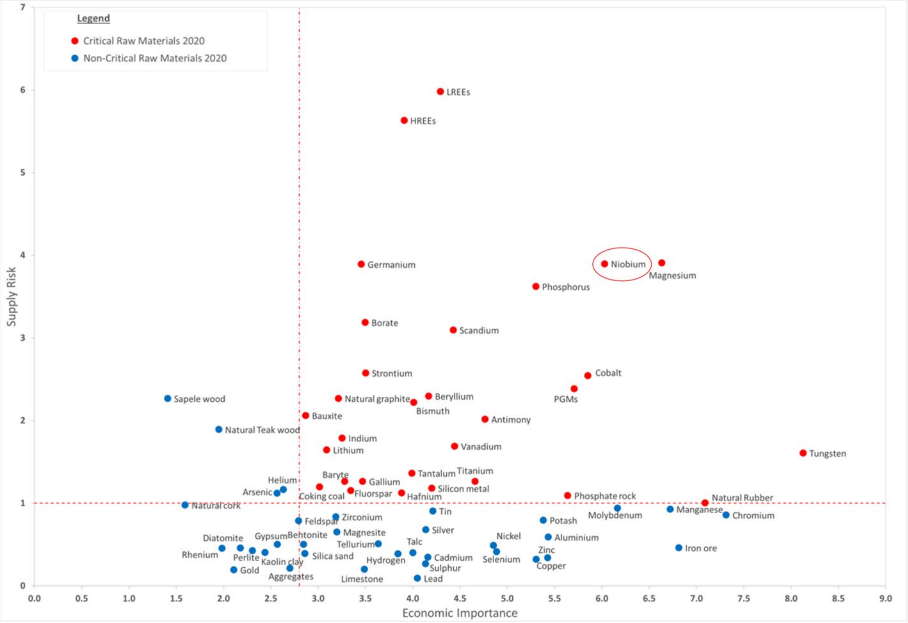

**Fig. 1** Criticality Matrix 2020 [12]

niobium is used in goods which are commonly used for urban mining, e.g., infrastructure such as buildings and pipelines or cars [17]. Furthermore, most of the niobium-bearing goods show a relatively stable lifespan, e.g., cars with an estimated lifespan of 10 years or pipelines with an estimated lifespan of 60 years [6]. This ensures a more reliable and accurate forecasting of future material streams in the niobium supply chain.

## Critical raw material classification

The EU’s definition of CRM includes two dimensions by which CRM can be classified, namely, supply risk and economic importance. According to the [9], supply risk (SR) is the risk of a disruption of the supply of a material and is influenced by various factors such as the global supply concentration, substitutability, import reliance, recycling rate, governance of the country of origin and possible trade restrictions. The economic importance (EI) of a material reflects the extent to which a material is essential for an economy, measured by the value-added of sectors using the material [12]. At a corporate level, the economic importance can be measured by the revenue that is impacted by the material [20].

Based on these two criteria, a criticality matrix is established serving as an assessment tool for raw material criticality. Using the matrix, both supply risk and economic importance are quantified, and CRM can be positioned in the two-dimensional matrix [18]. The threshold for criticality lies at a value of 2.8 for economic importance and 1 for supply risk. When a material receives a score that is higher than these threshold values in both dimensions, it is classified as critical. Niobium scores high in both dimensions (EI = 6.0; SR = 3.9) in comparison to other raw materials and is therefore classified as one of the

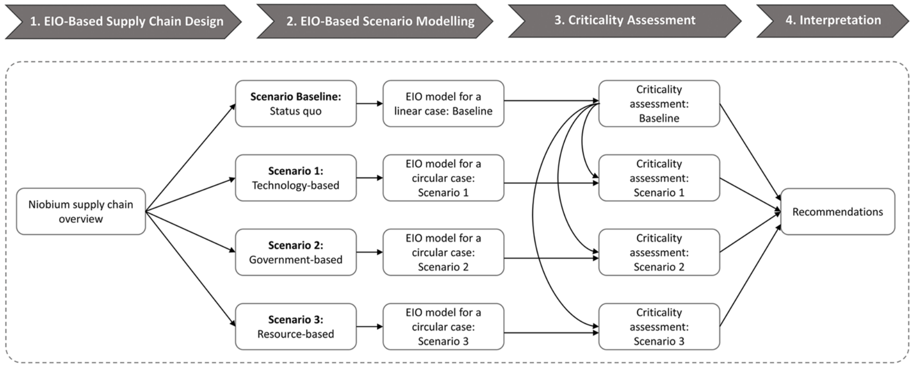

**Fig. 2** Research design overview

most CRM for the European Union (Fig. 1). For criticality assessment, each dimension is quantified by various factors, for instance, the supply risk depends on geological and economic factors, such as the remaining time until depletion of a material, social and regulatory factors, for instance the Human Development Index (HDI) and geopolitical factors, such as the World Governance Indicator (WGI) which indicates the political stability of a country.

Furthermore, a third dimension of environmental implications has gained importance. Graedel et al. [20] have elaborated a criticality assessment framework for metals which considers environmental impacts as a third dimension. The result is a three-dimensional criticality space with the three axes of supply risk, economic importance or as Graedel et al. [20] phrased it, vulnerability to supply restriction, and environmental implications in which CRM can be positioned [21]. This framework addresses not only economic and geopolitical issues but also the environmental implications of using a certain material. The environmental implications are calculated by adding up two damage categories, human health and ecosystems, from the mining stage of a metal to the manufacturing of a first intermediate product which is then used in most end products.

## Research Design and Methodology

In this section, an overview of research design and structure is provided. The computational theories are explained for an EIO model and criticality assessment. Then, the future scenarios are defined based on resource shortage, technology development, and policy interventions.

### Research Overview

To lay the foundations for subsequent analysis, the theoretical principles on CRM, CE, urban mining, and current issues concerning the niobium supply chain were described in the previous sections. As a preliminary basis for the EIO analysis, a flow diagram of the niobium supply chain is developed to provide an overview of the material and waste streams related to the niobium supply chain in the status quo. Second, the three future scenarios are defined considering imminent trends towards CE and the looming crisis of a niobium shortage. Next, the EIO analysis and criticality assessment for each scenario are conducted. Finally, the results are analysed and discussed to lead to a conclusion. An overview of research design is depicted in Fig. 2.

As pointed out by the literature, data on the supply chain and life cycle of niobium and ferro-niobium is scarce [2, 8]. Therefore, data on energy consumption, GHG emissions, material use and waste occurring along the niobium supply chain are retrieved from various sources including the data provided by CBMM [5], the biggest producer of niobium technology. The import numbers of ferro-niobium into the European Union are taken from PROMETIA's factsheet on niobium and tantalum [26]. A detailed overview of all sources for each variable can be found in Supporting Information A.

## Enterprise Input–Output Modelling

To explore the possibility of establishing urban mining as a strategy to improve the current environmental issues related to the niobium supply chain, the Input–Output (I-O) model method is applied. This research adapts the approach of an Enterprise Input–Output (EIO) model. EIO models facilitate the analysis of environmental impacts occurring along the supply chain by modelling not only the inputs and primary outputs but also the waste streams and emissions produced in different stages [1, 41].

Particularly, three types of flows are modelled: (i) main inputs/outputs produced by niobium supply chain processes, i.e., intermediate deliveries, (ii) primary inputs purchased out of the niobium supply chain, and (iii) wastes and by-products produced as secondary outputs by the processes of a niobium supply chain.

Let $Z_0$ be the matrix of intermediate deliveries, $f_0$ is the vector of final demands, and $x_0$ the vector of gross outputs. If $n$ processes are considered, the matrix $Z_0$ is of size $n$ x $n$, and the vectors $f_0$ and $x_0$ are $n \times 1$. Each process has a single product as its main output.

There are $s$ primary inputs, not produced by one of the $n$ production processes but purchased from out of the niobium supply chain. Next to the main outputs, the processes also produce $m$ by-products and wastes. $r_0$ is the primary input vector of size $s \times 1$ and $w_0$ is the by-product/waste vector of size $m \times 1$, respectively.

Then, we shortly describe the equations adopted from Yazan et al. [42]. Define the intermediate coefficient matrix $A$ as follows:

$$A = Z_0 \hat{x}_0^{-1} \tag{1}$$

where a 'hat' is used to denote a diagonal matrix. Accordingly;

$$x_0 = Ax_0 + f_0 = (I - A)^{-1} f_0 \tag{2}$$

It is possible to estimate $R$, the $s$ x $n$ matrix of primary input coefficients with the element $r_{kj}$ denoting the use of primary input $k$ (1,…, s) per unit of output of process $j$, and $W$, the $m$ x $n$ matrix of its output coefficients with element $w_{lj}$ denoting the output of by-product or waste type $l$ (1,…, m) per unit of output of process $j$. It results:

$$r_0 = Rx_0 \tag{3}$$

$$w_0 = Wx_0 \tag{4}$$

## Criticality Assessment

To assess the criticality, EC's assessment matrix is adopted, considering the dimensions of economic importance and supply risk and focusing on the European Union's market. The evaluation of the supply risk and of the economic importance will be executed as follows:

**Economic Importance (EI)** To calculate the Economic Importance, raw material end-use applications are assigned to the EU's manufacturing sectors, which are grouped at the two-digit level of NACE (Nomenclature of Economic Activities) Rev.2. The Gross Value-Added (GVA) of each application sector is then weighted by the application share of the respective sector and added up. At first, the unscaled Economic Importance is calculated by multiplying the sum of the weighted GVAs ($\text{Total\_GVA}_{\text{w}}$) with the substitute index for EI ($\text{SI}_{\text{EI}}$).

$$EI_{unscaled} = Total\_GVA_{w} \times SI_{EI} \tag{5}$$

In order to obtain the scaled EI, the unscaled EI score is divided by the highest value of the manufacturing sector NACE Rev.2 at the two-digit level. The result is then multiplied by 10 to obtain the value for EI on a scale from 1 to 10.

$$EI_{scaled} = EI_{unscaled}/GVA_{max} \times 10 \tag{6}$$

**Supply Risk (SR)** The supply risk can be calculated for two life-cycle stages, the extraction stage and the processing stage. As the EC assesses the processing stage as the more critical stage for niobium, only this stage will be taken into account for SR calculation. The first step to obtain the value for SR, is to multiply the squared share of production (SOP) of each producing country with the scaled WGI of each producing country ($\text{WGI}_{\text{scaled}}$) which can be obtained from the World Bank. The result of this multiplication is the "contribution to the Herfindahl-Hirschmann-Index WGI ($\text{HHI}_{\text{WGI}}$). This calculation is conducted with SOP both on global (GS) and EU (EU) supply level for each production country.

$$(HHI_{WGI})_{GS} = (SOP_{GS})^2 \times WGI_{scaled} \tag{7}$$

$$(HHI_{WGI})_{EU} = (SOP_{EU})^2 \times WGI_{scaled} \tag{8}$$

The $\text{HHI}_{\text{WGI}}$ is then multiplied with the trade variable *(t)* which reflects the component of trade restrictions such as export taxes, export quotas and export prohibitions, for each production country. The variable *t* is based on OECD database of export restrictions and EC's database on trade agreements.

$$(HHI_{WGI-t})_{GS} = (HHI_{WGI})_{GS} \times t \tag{9}$$

$$(HHI_{WGI-t})_{EU} = (HHI_{WGI})_{EU} \times t \tag{10}$$

The sum of the $\text{HHI}_{\text{WGI-t}}$ of the individual production countries equals the total $\text{HHI}_{\text{WGI-t}}$.

The supply risk is then calculated as follows:

$$SR = [(HHI_{WGI-t})_{GS} \times IR/2 + (HHI_{WGI-t})_{EU} \times (1 - IR/2)] \times (1 - EOL_{RIR}) \times SI_{SR} \tag{11}$$

IR is the import reliance reflecting the extent to which the EU relies on the import of a certain material. $SI_{SR}$ refers to the substitute index for supply risk and EOL-RIR stands for end-of-life recycling input rate which is used as the recycling indicator in this framework. In contrast to the recycling rate which measures the amount of waste recycled in relation to waste generated, the EOL-RIR or recycling input rate measures how much of a material's input into the production system comes from secondary raw materials sourced through the recycling of end-of-life products [12].

## Scenario Definition

Scenario analysis is a widely used tool to forecast the economy's development in a defined period of time [34]. Different scenarios manifest varying images of the future described by a set of possible outcomes [25]. In this study, three scenarios are proposed to investigate different processes which stress the need for CE. Each scenario builds on incipient or imminent developments which may occur in the near future and have an impact on the niobium supply chain.

### Linear Case

The linear case reflects the status quo, in which 100% of HSLA steel is produced with ferro-niobium sourced in Brazil. In the CRM reports provided by EC, the recycling indicator is known as an End-Of-Life Recycling Input Rate (EOL-RIR), which measures the input of secondary material from old scrap in relation to the total input of materials (primary and secondary) in the EU [12]. The EOL-RIR for niobium lies at 0 and therefore, for the status quo a recycling input rate of 0 will be assumed.

### Resource-Based Scenario

The resource-based scenario manifests how a sudden shortage of niobium due to an interruption of the niobium supply chain impacts the criticality of niobium. The causes for such a scenario are related to the factors which contribute to niobium's supply risk. Firstly, the EU has an import dependency of 100% for niobium as no niobium is sourced in Europe. Niobium has a high supply concentration as 92% of niobium is imported into the EU from Brazil, the main producing country of niobium and as already discussed, no viable substitute for niobium exists [10]. Second, Brazil's country governance has an impact on the supply risk of niobium. In the EC's criticality assessment, the scaled World Governance Index (WGI) is used to rate the governance of the countries which produce potential CRMs. A high-scaled WGI reflects a weak governance and increases a material's supply risk and thus, its criticality. For Brazil, a scaled WGI of 5.08 was determined which is relatively high and therefore increases the supply risk [12].

In 2012, 19,000 tons of ferro-niobium were imported into the European Union while in 2015 imports increased to more than 22,000 tons [10]. According to the 8% projected rise in demand, the ferro-niobium demand in the European Union is estimated as 43,200 tons in 2022 [26]. Brazil covers 85% of the European niobium demand [12] and would therefore have to supply 36.720 tons in 2022 to meet the demand. The resource-based scenario will show how a bottleneck triggered through the restriction of ferro-niobium exports to the EU (with a quota of a maximum of 32.000 tons imposed by the Brazilian government) can be mitigated through CE strategies. As only 87.15% of the demand can be covered by primary resources in this scenario, the EOL-RIR accounts for 12.85% as this proportion of the total input needs to be sourced from secondary sources.

### Technology-Based Scenario

The technology-based scenario analyses how the introduction of innovative technology can lead to higher recyclability, which impacts the criticality of niobium. At present, niobium has a high recycling rate of more than 50% [21]. However, most of these recycling processes are non-functional and the niobium cannot be up-cycled to its original application areas. The main recycling issue of niobium is the lack of identification of niobium-containing steel before melting. Consequently, niobium-containing steel is diluted with other steel types. Niobium can currently be mostly recycled from HSLA steel scrap from end-of-life products, especially end-of-life vehicles (ELVs), which are recycled at a rate of 80% in the European Union [19].

In the technology-based scenario, a type of technology is introduced to detect niobium-containing HSLA steel in recycling facilities. It determines the niobium concentration and separates it from other steel scraps will increase the sorting efficiency. As a result, less HSLA steel will be diluted with other types of steel. Therefore, the devaluation of HSLA steel during the recycling process can be avoided. In Europe, the research project "Innovative Circular Economy: Raw materials from own province" has developed recycling techniques to recover CRMs such as platinum group metals and rare earth elements from waste streams such as power plant fly ash and wastewater [27]. In this scenario, a similar technology which detects and measures niobium-containing HSLA steel will be introduced and established in recycling facilities by the year 2024. The projected calculation of secondary HSLA steel in 2025 is demonstrated in Table 1.

As a recycling rate of 100% of all available HSLA steel is not possible, a sensitivity analysis is conducted to understand how a successively increasing recycling rate may impact the outcome of the EIO analysis. It explores how the niobium supply chain will be

**Table 1** Calculation of secondary HSLA steel in 2025

| Year | FeNb Demand Total (t) | Percentage used in the automotive sector | FeNb demand automotive sector (t) | HSLA steel demand automotive sector (t) | Niobium concentration | Steel scrap recycling rate from ELVs |
|---|---|---|---|---|---|---|
| 2014 | **43,016**[a] | **28%**[b] | **12,044**[a] | **12,044,480**[a] | **0.10%**[a] | **100%**[c] |
| | FeNb Demand Total (t) | Recycling rate automotive sector | Secondary FeNb (t) | HSLA steel demand total (t) | Secondary HSLA steel (t) | Percentage of secondary HSLA steel in relation to total HSLA steel demand (EOL-RIR) |
| 2024 | **50,000**[a] | **87%**[d] | **10,478** | **50,000,000** | **10,478,697** | **20.96%** |

Source: [a][26]; [b][10]; [c][40]; [d][15]

transformed towards more circularity due to the implementation of the new niobium detection and sorting technology and to what extent, consequently, the criticality of niobium will be impacted.

### Government-Based Scenario

In the government-based scenario, the effects of governmental policies are analysed in the form of incentives. This scenario builds on the European Green Deal [11]. Considering CRMs, the Green Deal emphasizes the importance of CE and defines the sourcing of materials from secondary sources as a central strategy. According to the EC, the market for secondary raw materials and by-products shall be promoted supporting the development of closed-loop supply chains [11]. Although various policy documents have been introduced over the last decade (i.e. European flagship initiative, 2011; CE package, 2015; Europe 2020 strategy), the definitions of most of the policy goals are rather vague, non-mandatory and qualitative, lacking concrete timeframes or quantitative goals all member states have to comply with [22, 43]. In February 2021, the European Parliament stressed the need for recycled content quotas in response to the Circular Economy Action Plan and the Green Deal with the objective of promoting the market for sustainable products [16].

The government-based scenario manifests how the introduction of a specific and binding policy for a recycling input rate for CRM in new products catalyses CE in the niobium supply chain and how the criticality of niobium is impacted. For this scenario, a recycling input rate (EOL-RIR) of 30% will be assumed as of 2030 which provides an adequate timeframe for the recycling industry to adapt.

## Results

This section provides key research results, including a niobium supply chain design overview, EIO analysis results and criticality assessment results.

### Niobium Supply Chain

In this research, we design an EIO-based niobium supply chain with the steps of (1) ore extraction and transportation, (2) ore concentration, (3) ferro-niobium production, (4) HSLA production, and (5) recycling. An overview of a typical niobium supply chain is depicted in Fig. 3.

The raw pyrochlore ore with a concentration of approximately 2.5% $Nb_2O_5$ is extracted from the mine by hydraulic excavators and transported by trucks and a conveyor belt to the concentration unit [2, 8]. To prepare the ore for ferro-niobium production, it undergoes three main steps: concentration through grinding, magnetic separation, flotation, and desliming; sintering with filtering, pelletizing, and grinding; and dephosphorization in an electric furnace. Various waste materials are generated during concentration and ferro-niobium production.

During concentration, the magnetic separation leads to approximately 6.7 tons of waste, desliming and flotation cause another 3.3 tons of waste. After the aluminothermic

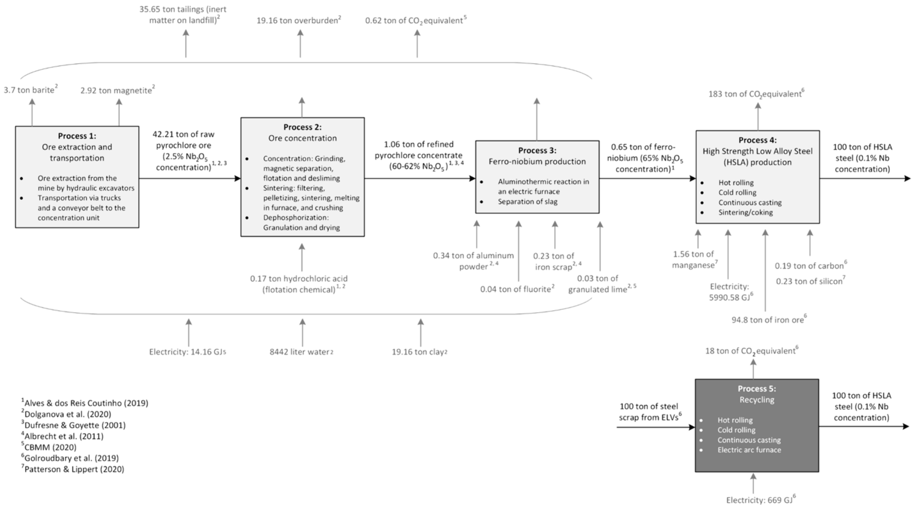

**Fig. 3** Niobium supply chain flow diagram (with recycling processes)

reaction, the ferro-niobium is separated from 1.8 tons of metallurgical slag which goes to landfilling. For the production of one ton of ferro-niobium, 0.96 tons of $CO_2$ are emitted [5] and in total 55t of tailings are produced which proceed to be disposed of on a landfill site [8]. The finished ferro-niobium is then imported into the EU to be further processed (EC, 2015,[26]).

The next step is the production of HSLA steel. In the case of niobium, a concentration of less than 0.1% is needed to enhance the mechanical strength of the steel [26, 30]. The production of HSLA steel consists of four processes, hot rolling, cold rolling, continuous casting, and sintering [19]. Also, the production of HSLA steel causes $CO_2$ emissions, for the output of one ton of HSLA steel 1.83 tons of CO2 are emitted [19].

To recycle niobium, it is not necessary to recover the pure element. After the collection of steel scrap from end-of-life products the scrap is melted in basic oxygen steelmaking furnaces (BOFs) or electric arc furnaces (EAFs). The scrap undergoes four processes: cold rolling, hot rolling, continuous casting, and electric arc furnace. During these processes, a total of 6.69 GJ of energy is consumed and 0.18 tons of $CO_2$ equivalent are emitted per ton of HSLA steel recycled. To visualize the transformed niobium supply chain, the fifth process step of recycling has been introduced to the flow diagram, comparing the inputs and outputs generated for 100 tons of primary HSLA steel and the recycling of 100 tons of HSLA steel.

## EIO Analysis Results

### Linear Case

In the status quo, a recycling input rate of 0% [12] and a niobium concentration of 0.1% in HSLA steel [26] are assumed. The EIO model computes the raw materials needed as well as the emissions, waste and by-products generated in the entire process of the production of HSLA steel (Table 2). All EIO tables can be found in Supporting Information B.

**Table 2** Inputs and outputs in the linear case

| Input | Unit | Linear |
|---|---|---|
| R2: Water | l | 8442 |
| R3: Clay | t | 19.17 |
| R4: Electricity | GJ | 6004.74 |
| R5: Hydrochloric acid | t | 0.17 |
| R6: Aluminium powder | t | 0.34 |
| R7: Fluorite | t | 0.04 |
| R8: Iron scrap | t | 0.23 |
| R9: Granulated lime | t | 0.03 |
| R10: Manganese | t | 1.56 |
| R11: Iron ore | t | 94.8 |
| R12: Carbon | t | 0.19 |
| R13: Silicone | t | 0.23 |
| Waste & emissions | | |
| W1: Barite | t | 3.7 |
| W2: Magnetite | t | 2.92 |
| W3: Tailings | t | 35.64 |
| W4: Overburden | t | 19.17 |
| W5: Water | l | 8442 |
| W6: CO2 equivalent | t | 183.63 |

### Resource-Based Scenario

In the resource-based scenario, due to a supply shortage of 12.85% of the niobium demand in the EU, the shortage will need to be compensated by sourcing secondary HSLA steel from ELVs as urban mines. As a result, the EOL-RIR increases from 0 to 12.85% and the fifth process of "Recycling of ELVs, secondary HSLA steel production" is introduced to the EIO model. As a result, the amount of input materials needed to produce 100 tonnes of HSLA steel can be significantly lowered as recycling requires fewer input materials. The results are displayed in Table 3 which summarizes the input and output materials for the production of 100 tonnes of HSLA steel, of which 12.85 tonnes are produced by recycling.

### Technology-Based Scenario

For the technology-based scenario a maximum EOL-RIR of 20.96% was calculated and integrated into the EIO model. In comparison to the linear model, input material use, emissions as well as waste and by-products produced per 100 tonnes of HSLA steel decreased. With a recycling rate of 100% of all HSLA steel from ELVs in 2025 an EOL-RIR of 20.96% and the following results could be achieved for the production of 100 tonnes of HSLA steel, of which 20.96 tonnes were produced by recycling HSLA steel scrap (Table 4).

**Table 3** Results EIO model, resource-based scenario

| Input | Unit | Linear | Circular | Total reduction | Reduction in % |
|---|---|---|---|---|---|
| R2: Water | l | 8442 | 7364.18 | 1077.83 | 12.77% |
| R3: Clay | t | 19.17 | 16.70 | 2.47 | 12.89% |
| R4: Electricity | GJ | 6004.74 | 5319.46 | 685.28 | 11.41% |
| R5: Hydrochloric acid | t | 0.17 | 0.15 | 0.02 | 13.36% |
| R6: Aluminium powder | t | 0.34 | 0.29 | 0.05 | 13.36% |
| R7: Fluorite | t | 0.04 | 0.03 | 0.01 | 15.03% |
| R8: Iron scrap | t | 0.23 | 0.20 | 0.03 | 13.80% |
| R9: Granulated lime | t | 0.03 | 0.02 | 0.01 | 43.35% |
| R10: Manganese | t | 1.56 | 1.36 | 0.20 | 12.85% |
| R11: Iron ore | t | 94.8 | 82.62 | 12.18 | 12.85% |
| R12: Carbon | t | 0.19 | 0.17 | 0.02 | 12.85% |
| R13: Silicone | t | 0.23 | 0.20 | 0.03 | 12.85% |
| Waste & emissions | | | | | |
| W1: Barite | t | 3.7 | 3.23 | 0.47 | 12.73% |
| W2: Magnetite | t | 2.92 | 2.55 | 0.37 | 12.70% |
| W3: Tailings | t | 35.64 | 31.10 | 4.54 | 12.74% |
| W4: Overburden | t | 19.17 | 16.71 | 2.46 | 12.83% |
| W5: Water | l | 8442 | 7364.18 | 1077.83 | 12.77% |
| W6: CO2 equivalent | t | 183.63 | 162.34 | 21.29 | 11.59% |

As initially a recycling rate of 100% is not possible, a sensitivity analysis was conducted to show how the supply chain is transformed with a recycling rate of respectively 85% and 70%. The EOL-RIR was respectively reduced to 17.82% and 14.67% (Tables 5 and 6).

## Government-Based Scenario

The government-based scenario shows how the implementation of a minimum recycling input rate of 30% for HSLA steel imposed by the European Union triggers more urban mining. Therefore, an EOL-RIR of 30% was assumed and incorporated in the EIO model, leading to the following results for the production of 100 tonnes of HSLA steel, of which 30 tonnes were produced from secondary sources (Table 7).

## Criticality Assessment Results

In the following, the economic importance and the supply risk are calculated. As Environmental Importance (EI) is not impacted by circular economy it will only be calculated once, for the linear case. The Supply Risk (SR) is calculated for each scenario, assessing how the change in recycling impacts SR and niobium's overall criticality. The calculated results are summarised in Table 8 and Fig. 4.

**Table 4** Results EIO model, technology-based scenario, recycling rate = 100%

| Input | Unit | Linear | Circular | Total reduction | Reduction in % |
|---|---|---|---|---|---|
| R2: Water | l | 8442 | 6678.88 | 1763.12 | 20.89% |
| R3: Clay | t | 19.17 | 15.15 | 4.02 | 20.99% |
| R4: Electricity | GJ | 6004.74 | 4886.70 | 1118.04 | 18.62% |
| R5: Hydrochloric acid | t | 0.17 | 0.13 | 0.04 | 21.42% |
| R6: Aluminium powder | t | 0.34 | 0.27 | 0.07 | 21.42% |
| R7: Fluorite | t | 0.04 | 0.03 | 0.01 | 22.94% |
| R8: Iron scrap | t | 0.23 | 0.18 | 0.05 | 21.82% |
| R9: Granulated lime | t | 0.03 | 0.02 | 0.01 | 48.62% |
| R10: Manganese | t | 1.56 | 1.23 | 0.33 | 20.96% |
| R11: Iron ore | t | 94.8 | 74.93 | 19.87 | 20.96% |
| R12: Carbon | t | 0.19 | 0.15 | 0.04 | 20.96% |
| R13: Silicone | t | 0.23 | 0.18 | 0.05 | 20.96% |
| Waste & emissions | | | | | |
| W1: Barite | t | 3.7 | 2.93 | 0.77 | 20.85% |
| W2: Magnetite | t | 2.92 | 2.31 | 0.61 | 20.82% |
| W3: Tailings | t | 35.64 | 28.21 | 7.43 | 20.86% |
| W4: Overburden | t | 19.17 | 15.16 | 4.01 | 20.94% |
| W5: Water | l | 8442 | 6678.88 | 1763.12 | 20.89% |
| W6: CO2 equivalent | t | 183.63 | 148.91 | 34.72 | 18.91% |

**Table 5** Results EIO model, technology-based scenario, recycling rate = 85%

| Input | Unit | Linear | Circular | Total reduction | Reduction in % |
|---|---|---|---|---|---|
| R2: Water | l | 8442 | 6944.55 | 1497.45 | 17.74% |
| R3: Clay | t | 19.17 | 15.75 | 3.42 | 17.85% |
| R4: Electricity | GJ | 6004.74 | 5054.47 | 950.27 | 15.83% |
| R5: Hydrochloric acid | t | 0.17 | 0.14 | 0.03 | 18.30% |
| R6: Aluminium powder | t | 0.34 | 0.28 | 0.06 | 18.30% |
| R7: Fluorite | t | 0.04 | 0.03 | 0.01 | 19.87% |
| R8: Iron scrap | t | 0.23 | 0.19 | 0.04 | 18.71% |
| R9: Granulated lime | t | 0.03 | 0.02 | 0.01 | 46.58% |
| R10: Manganese | t | 1.56 | 1.28 | 0.28 | 17.82% |
| R11: Iron ore | t | 94.8 | 77.91 | 16.89 | 17.82% |
| R12: Carbon | t | 0.19 | 0.16 | 0.03 | 17.82% |
| R13: Silicone | t | 0.23 | 0.19 | 0.04 | 17.82% |
| Waste & emissions | | | | | |
| W1: Barite | t | 3.7 | 3.04 | 0.66 | 17.70% |
| W2: Magnetite | t | 2.92 | 2.40 | 0.52 | 17.68% |
| W3: Tailings | t | 35.64 | 29.33 | 6.31 | 17.71% |
| W4: Overburden | t | 19.17 | 15.76 | 3.41 | 17.79% |
| W5: Water | l | 8442 | 6944.55 | 1497.45 | 17.74% |
| W6: CO2 equivalent | t | 183.63 | 154.12 | 29.51 | 16.07% |

**Table 6** Results EIO model, technology-based scenario, recycling rate = 70%

| Input | Unit | Linear | Circular | Total reduction | Reduction in % |
|---|---|---|---|---|---|
| R2: Water | l | 8442 | 7210.22 | 1231.78 | 14.59% |
| R3: Clay | t | 19.17 | 16.35 | 2.82 | 14.71% |
| R4: Electricity | GJ | 6004.74 | 5222.24 | 782.50 | 13.03% |
| R5: Hydrochloric acid | t | 0.17 | 0.14 | 0.03 | 15.17% |
| R6: Aluminium powder | t | 0.34 | 0.29 | 0.05 | 15.17% |
| R7: Fluorite | t | 0.04 | 0.03 | 0.01 | 16.81% |
| R8: Iron scrap | t | 0.23 | 0.19 | 0.04 | 15.60% |
| R9: Granulated lime | t | 0.03 | 0.02 | 0.01 | 44.54% |
| R10: Manganese | t | 1.56 | 1.33 | 0.23 | 14.67% |
| R11: Iron ore | t | 94.8 | 80.89 | 13.91 | 14.67% |
| R12: Carbon | t | 0.19 | 0.16 | 0.03 | 14.67% |
| R13: Silicone | t | 0.23 | 0.20 | 0.03 | 14.67% |
| Waste & emissions | | | | | |
| W1: Barite | t | 3.7 | 3.16 | 0.54 | 14.56% |
| W2: Magnetite | t | 2.92 | 2.50 | 0.42 | 14.53% |
| W3: Tailings | t | 35.64 | 30.45 | 5.19 | 14.56% |
| W4: Overburden | t | 19.17 | 16.36 | 2.81 | 14.65% |
| W5: Water | l | 8442 | 7210.22 | 1231.78 | 14.59% |
| W6: CO2 equivalent | t | 183.63 | 159.32 | 24.31 | 13.24% |

## Linear Scenario Result

According to the calculation method adopted by the European Commission, the scaled economic importance of niobium equals 6. It is calculated by first determining the total GVA weighted, then calculating the unscaled EI using the substitute index (SI) and finally determining the scaled EI (Tables 9 and 10).

The calculation of SR of niobium yields a value of 3.9 in the linear model and is calculated in the following three steps. As the contribution to the $(HHI_{WGI})_{EU}$ and $(HHI_{WGI})_{EU\text{-}t}$ as well as the contribution to the $(HHI_{WGI})_{GS}$ and $(HHI_{WGI})_{GS\text{-}t}$ for niobium are not affected by a changed EOL-RIR, these figures will not be calculated again for each scenario.

## Future Scenario Results

Table 8 lists the calculation results under four scenarios. In the resource-based scenario an EOL-RIR of 12.85% is assumed which impacts the supply risk as is depicted in the table below. The result is a supply risk of 3.43 in this scenario. The criticality of niobium could be reduced; however, niobium is still located in the critical space in the criticality matrix clearly exceeding the threshold of 1 [12]. For the technology-based scenario, a sensitivity analysis was conducted. The table shows how the supply risk changes when the recycling

**Table 7** Results EIO model, government-based scenario

| Input | Unit | Linear | Circular | Total reduction | Reduction in % |
|---|---|---|---|---|---|
| R2: Water | l | 8442 | 5915.00 | 2527.00 | 29.93% |
| R3: Clay | t | 19.17 | 13.41 | 5.76 | 30.03% |
| R4: Electricity | GJ | 6004.74 | 4404.31 | 1600.43 | 26.65% |
| R5: Hydrochloric acid | t | 0.17 | 0.12 | 0.05 | 30.41% |
| R6: Aluminium powder | t | 0.34 | 0.24 | 0.10 | 30.41% |
| R7: Fluorite | t | 0.04 | 0.03 | 0.01 | 31.75% |
| R8: Iron scrap | t | 0.23 | 0.16 | 0.07 | 30.76% |
| R9: Granulated lime | t | 0.03 | 0.01 | 0.02 | 54.50% |
| R10: Manganese | t | 1.56 | 1.09 | 0.47 | 30.00% |
| R11: Iron ore | t | 94.8 | 66.36 | 28.44 | 30.00% |
| R12: Carbon | t | 0.19 | 0.13 | 0.06 | 30.00% |
| R13: Silicone | t | 0.23 | 0.16 | 0.07 | 30.00% |
| Waste & emissions | | | | | |
| W1: Barite | t | 3.7 | 2.59 | 1.11 | 29.91% |
| W2: Magnetite | t | 2.92 | 2.05 | 0.87 | 29.88% |
| W3: Tailings | t | 35.64 | 24.98 | 10.66 | 29.91% |
| W4: Overburden | t | 19.17 | 13.42 | 5.75 | 29.98% |
| W5: Water | l | 8442 | 5915.00 | 2527.00 | 29.93% |
| W6: CO2 equivalent | t | 183.63 | 133.94 | 49.69 | 27.06% |

rate is respectively 100%, 85% or 70%. The government-based scenario is the scenario that lies furthest in the future and with the highest EOL-RIR (30%).

## Discussion

The results presented in this study offer valuable insights into the niobium supply chain and its environmental and criticality implications. In this section, the scenario analysis results are summarised. Then, research implications are discussed from both theoretical and policy perspectives. Finally, the research limitations are pointed out and future research directions are proposed.

### Summary of Results

The niobium supply chain design presented in this study offers a comprehensive overview of the various stages involved in obtaining niobium for HSLA steel production. It is important to note that niobium's extraction and production processes generate considerable waste and emissions. The production of one ton of ferro-niobium emits 0.96 tons of carbon dioxide and results in 55 tons of tailings sent to landfills.

In all scenarios, the supply risk and environmental impacts of niobium along the supply chain can be improved compared to the linear case. In the resource-based

**Table 8** Calculation of the Total $GVA_{weighted}$ for niobium using sectors in the EU

| Application | NACE sector GVA (M€) | 2-digit NACE sector | Share | Contribution to EI (Share × sector GVA) |
|---|---|---|---|---|
| Construction (Steel) | 148,351 | C25 - Manufacture of fabricated metal products, except machinery and equipment | 45% | 66757.95 |
| Automotive (Steel) | 160,603 | C29 - Manufacture of motor vehicles, trailers and semi-trailers | 23% | 36938.69 |
| Oil & Gas | 55,426 | C24 - Manufacture of basic metals | 17% | 9422.42 |
| Stainless steel | 55,426 | C24 - Manufacture of basic metals | 10% | 5542.6 |
| Special Steel | 44,304 | C30 - Manufacture of other transport equipment | 3% | 1329.12 |
| Total GVA weighted | **119990.78** | | | |
| Sources: | [12, 15] | | | |

scenario, although niobium's criticality remains relatively high, supply risk is reduced from 3.9 to 3.4. By introducing increased recycling in the resource-based scenario, emissions and by-products decrease by at least 11.59%, improving environmental sustainability. In the technology-based scenario, the introduction of ICP-MS technology for ELV steel scrap sorting and recycling leads to supply risk reductions (3.1 at 100% recycling, 3.2 at 85%, and 3.4 at 70%). It also cuts GHG emissions (up to 18.91%) and reduces landfilled tailings to 7.4 tonnes (100% recycling), 6.3 tonnes (85% recycling), and 5.2 tonnes (70% recycling) per 100 tonnes of HSLA steel. The government-based scenario has the most substantial impact, with an EOL-RIR of 30%, reducing GHG emissions by 27.06%. This corresponds to a significant drop in supply risk to 2.75. Despite this improvement, niobium remains a CRM, surpassing the criticality threshold of 1 [12].

## Implications

This research has several implications from both theoretical and policy perspectives. Although prior studies provided a preliminary knowledge basis to analyse different types of CRM supply chains, a global supply chain of niobium received limited attention. This research fills this gap and provides a numerical analytical method to quantify its criticality under future scenarios. The EIO modelling serves as a powerful tool that clarifies and structures the entire niobium supply chain quantitatively.

From a theoretical perspective, adding to the prior research [4, 28, 36], this study adapts the criticality assessment matrix provided by the EU and integrates it with EIO modelling. This novelty creates an extra evaluation perspective and helps to deliver more robust results by considering environmental impacts next to supply risks and economic importance (van den [32, 36, 37]). Therefore, the scientific contribution

**Table 9** Calculation of the $EI_{scaled}$ for niobium, contributions to $(HHI_{WGI})_{EU}$ and $(HHI_{WGI})_{EU\text{-}t}$ as well as $(HHI_{WGI})_{GS}$ and $(HHI_{WGI})_{GS\text{-}t}$

*Calculation of $EI_{scaled}$ for niobium*

| Step | Value | Calculation |
|---|---|---|
| SI(EI)= | 0.97 | |
| EI(unscaled)= | 116391.057 | Total GVA weighted × SI(EI) |
| Highest value of the manufacturing sector NACE Rev.2 | 196,055 | |
| **EI(scaled)=** | **5.936** | EI(unscaled) / Highest value × 10 |

*Contribution to the $(HHI_{WGI})_{EU}$ and $(HHI_{WGI})_{EU\text{-}t}$*

| Country | Share of production | WGI(scaled) | Contribution to $(HHI_{WGI})_{EU}$ | T (trade variable) | Contribution to $(HHI_{WGI})_{EU\text{-}t}$ |
|---|---|---|---|---|---|
| Brazil | 85% | 5.08 | 3.67 | 1 | 3.67 |
| Canada | 13% | 2.26 | 0.04 | 1 | 0.04 |
| **Sum** | | | **3.71** | | **3.71** |

*Contribution to the $(HHI_{WGI})_{GS}$ and $(HHI_{WGI})_{GS\text{-}t}$*

| Country | Share of production, SOP(GS) | WGI(scaled) | Contribution to $(HHI_{WGI})_{GS}$ | T (trade variable) | Contribution to $(HHI_{WGI})_{GS\text{-}t}$ |
|---|---|---|---|---|---|
| Brazil | 92% | 5.08 | 4.30 | 1 | 4.30 |
| Canada | 8% | 2.26 | 0.01 | 1 | 0.01 |
| **Sum** | | | **4.31** | | **4.31** |

**Sources:** [12, 15]

of this research is proposing a numerical evaluation method for critical raw material supply chains. By taking niobium as an example material, it offers an analytical computational framework where critical raw material supply chains can be examined in-depth.

Besides, a comprehensive overview of the niobium supply chain is presented together with potential recycling processes. Following the principles of CE, this overview can be regarded as a closed-loop supply chain that contributes to the resource reservation of niobium. “Think Globally, Act Locally” used to be a motto for CE implementation, which indicates that stakeholders should consider the global environmental status and take action in their own communities at a local scale [33]. Adding to this motto, this research provides conceptual proof that urges global actions on CRM. Based on this study, it can be seen that CRM supply chains often require multinational collaborations across vast geo-political scales. Only local actions are insufficient to stimulate a systematic CE transition on such a global supply system. Therefore, we raise attention to the multi-scale CE transition and call for more research to quantify and demonstrate the impact of circular interventions on CRM supply chains at a global level.

The results provide performance insights into the environmental and criticality implications of different scenarios, which can be interpreted as potential policy recommendations resolving the challenges of CRM supply chains. Additionally, this study constitutes a call for action for both public and private actors. To reach a higher recycling input rate, future policy interventions that can enhance technological innovations are in demand. Legislators in the EU should make use of possibilities to implement policies in the context of the European Green Deal to promote the secondary material market. Therefore, the EU’s dependence on CRM-production countries can be reduced.

**Table 10** Calculation of supply risks under future scenarious

| Item | Value |
|---|---|
| (a) Linear scenarios | |
| SI(SR)= | 0.98 |
| IR= | 1 |
| EoL-RIR= | 0 |
| **SR=** | **3.93** |
| (b) Resource-based scenarios | |
| SI(SR)= | 0.98 |
| IR= | 1 |
| EoL-RIR= | 12.85% |
| **SR=** | **3.43** |
| (c) Technology-based scenarios (100%) | |
| SI(SR)= | 0.98 |
| IR= | 1 |
| EoL-RIR= | 20.96% |
| **SR=** | **3.11** |
| (c) Technology-based scenarios (85%) | |
| SI(SR)= | 0.98 |
| IR= | 1 |
| EoL-RIR= | 17.82% |
| **SR=** | **3.23** |
| (c) Technology-based scenarios (70%) | |
| SI(SR)= | 0.98 |
| IR= | 1 |
| EoL-RIR= | 14.67% |
| **SR=** | **3.35** |
| (d) Government-based case | |
| SI(SR)= | 0.98 |
| IR= | 1 |
| EoL-RIR= | 30% |
| **SR=** | **2.75** |
| Calculation method | |
| $[(HHI(WGI\text{-}t))GS \times IR / 2 + (HHI(WGI\text{-}t))EU \times (1 - IR / 2)] \times (1 - EOL(RIR)) \times SI(SR)$ | |
| Source | |
| (EC, 2020a) | |

## Limitations and Future Research Directions

The research limitations exist in four aspects. First, from the methodological perspective, EIO modelling is a linear modelling approach that captures the overall material flow structure of the system without considering supply–demand uncertainties and complexities. Second, the computations are carried out mainly based on secondary data. Some numbers of niobium production are based on estimates and industry averages only, which could introduce imprecisions in the modelling results. Third, the research only analyses the individual effects of each scenario while more efforts need to be devoted to investigating

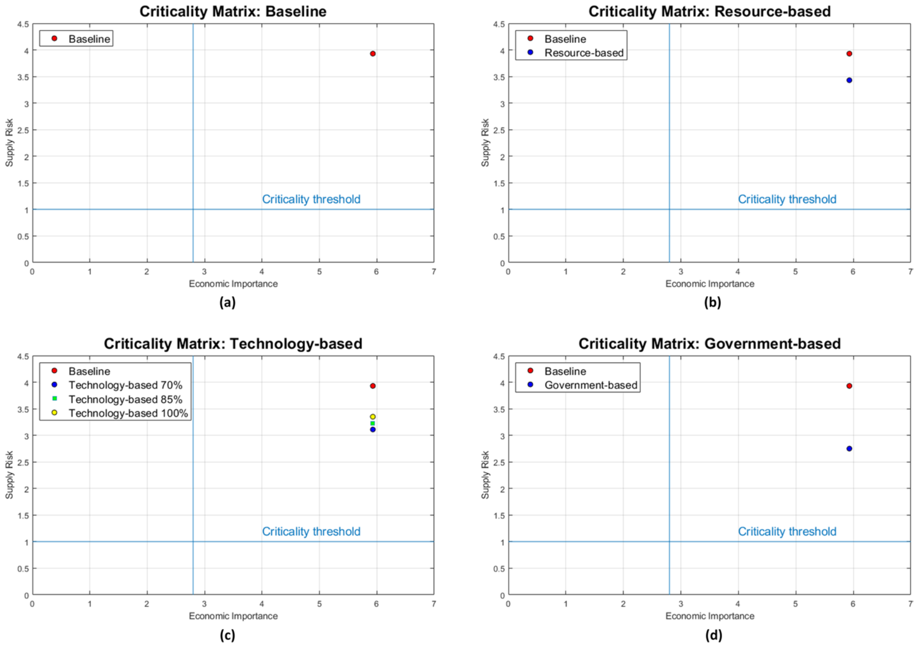

**Fig. 4** Scenario analysis results: (**a**) Linear scenario; (**b**) Resource-based scenario; (**c**) Technology-based scenario; (**d**) Government-based scenario

combined effects of multiple scenarios. Finally, the proposed modelling method should be applied to examine the criticality of other types of materials in order to ensure the method's validity and generalisability. Therefore, future research is required to overcome these limitations and focus on (1) dynamic input–output modelling involving supply–demand uncertainties as an embedded factor, (2) rigorous and comprehensive data collection of critical raw material consumptions, (3) combined-scenario analysis guiding the formulation of mixed-policy packages, and (4) cross-case validation based on different types of critical materials.

Furthermore, we suggest to incorporate a temporal lens to examine future policy interventions. The CE policy-making often follows a five-stage policy cycle covering (1) agenda setting, (2) policy formulation, (3) policy decision-making, (4) policy implementation, and (5) policy evaluation [43]. There is usually a significant time gap between each stage of policy-making whereas the initial strategy might fall short to tackle the uncertain and dynamic real situation. Currently, the proposed method only presents a static performance overview of the niobium supply chain. It sets up a preliminary assessment structure and provides a flexible basis to incorporate more features in future research. We aim to improve the model and add a time-based perspective to analyse the global impact so that decision-makers are able to capture the potential evolution progress of policy interventions. Aligned with the research directions pointed out by prior studies [28, 36], more research is required to showcase how the criticality and circularity of a critical material supply chain can change over time and space.

## Conclusion

Niobium is a type of CRM that requires immediate action to reserve. The goal of this study is to assess the extent to which a CE strategy impacts niobium's criticality as well as the environmental performance of the niobium supply chain. The research adopts an integrated approach by combining EIO modelling with the EU's criticality assessment matrix. The results provide a comprehensive analysis of the niobium supply chain and its potential for improvement. Specifically, the resource-based, technology-based, and government-based scenarios all demonstrate the potential to reduce the supply risk and environmental impacts of niobium production. The findings emphasise the importance of adopting more sustainable practices, improving recycling technologies, and implementing government policies to enhance the overall sustainability of niobium supply chains. Additionally, these results offer insights into the broader context of CRM and the significance of recycling in reducing supply risks and environmental consequences. Further research and action are needed to achieve a more sustainable and less critical niobium supply chain.

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