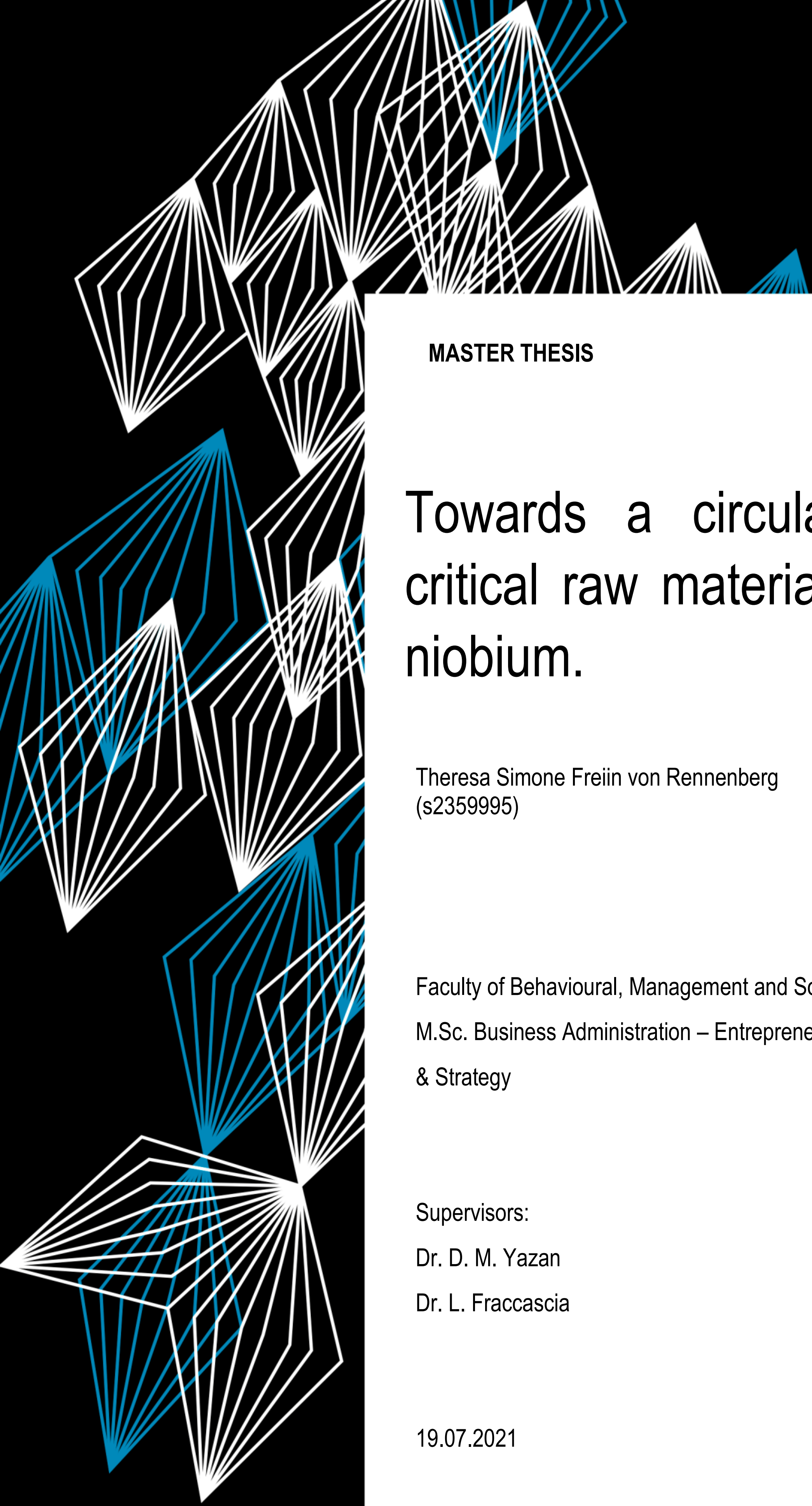

MASTER THESIS

Towards a circular economy of critical raw materials: The case of niobium.

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With this thesis my master studies will be finished, and I am grateful for having had this opportunity to develop academically, professionally and personally.

Abstract

The central research goal of this thesis was to assess how the implementation of a circular economy strategy through urban mining impacts the criticality of the critical raw material niobium as well as the generation of waste and emissions along its supply chain. To find an answer to this question a scenario analysis with three different scenarios for varying possible future paths was established in order to explore imminent developments which impact the niobium supply chain and trigger circular economy. As a method to measure the changes in environmental implications along the supply chain enterprise input-output modelling (EIO) was adopted. The results of the EIO model showed how the amount of inputs, outputs and by-products changed in each scenario. In a final step, the supply risk was calculated for each scenario in accordance with the European Commission's criticality assessment framework to evaluate how circular economy affects niobium's criticality under differing conditions. The results show that urban mining is a viable strategy to both strongly reduce niobium's criticality and to mitigate its supply chain's negative impact on the environment. The European Union would prevent a shortage of supply by becoming less dependent on Brazil which produces 92% of all niobium products globally but is also a country which faces strong economic, environmental, social and political issues. However, joint efforts of academia, politics and the economy are needed to reduce the supply risk as well as the environmental implications. Even though circular economy has a high potential to reduce the supply risk in all scenarios, an even higher recycling input rate or a mix of a recycling and a substitution strategy is necessary to reduce the supply risk below the criticality threshold of 1 and offset niobium's criticality.

Key words: Critical raw materials, critical metals, niobium, ferro-niobium, circular economy, circular economy policies, urban mining, criticality assessment, supply risk, recycling

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List of Abbreviations

BOF	Basic oxygen steelmaking furnace
CBMM	Companhia Brasileira de Metalurgia e Mineração
CRM	Critical raw material
EAF	Electric arc furnace
EC	European Commission
EI	Economic importance
EIO	Enterprise Input Output
ELV	End-of-life vehicle
EOL-RIR	End-of-life recycling input rate
EU	European Union
FeNb	Ferro-niobium
GDP	Gross domestic product
GHG	Greenhouse gas
GJ	Gigajoule
GVA	Gross value-added
HDI	Human Development Index
HHI	Herfindahl-Hirschmann-Index
HSLA	High-strength low-alloy
ICP-MS	Inductively coupled plasma mass spectrometry
I-O	Input Output
IR	Import reliance
l	Litre
Mercosur	Southern Common Market
Nb	Niobium
NGO	Non-governmental organization
SI	Substitute index
SOP	Share of production
SR	Supply risk
t	Tonne
WGI	World Governance Index

1. Introduction

Raw materials are needed in any producing industry and are thus crucial to the economy and society. The consumption of finite materials such as metals, fossil fuels and minerals is still on the rise and projected to double within the next 60 years (OECD, 2018). Therefore, a responsible handling of raw materials will become more and more important in the near future (European Commission, 2017). One group of materials whose availability is already problematic are critical raw materials (Isildar et al., 2019; European Commission, 2020a). These materials are characterised by their high importance for the economy and by a high risk regarding their supply. Per definition, supply risk of a material is the risk of an interruption in its supply and depends on the governance and trade policy of the raw material's producing countries. The substitution and recycling of a critical raw material can reduce its supply risk. The higher the economic importance and the higher the supply risk of a material, the higher the criticality of this material (European Commission, n.d.). Some models focusing on assessing the criticality of materials such as the Yale method created by Gradel et al. (2012) add to the two dimensions of supply risk and economic importance a third category, the environmental implications on ecosystems and human beings.

One of the 30 critical raw materials identified by the European Commission (EC) is niobium. It was first classified as a critical raw material in 2011 in the European Union's (EU) initial list of critical raw materials and has been confirmed as such in every subsequent EU list of critical raw materials to date (European Commission, 2020a). Its criticality has increased from a score of 2.8 in 2011 to a score of 3.9 in 2020 (European Commission, 2020a, p. 65). Niobium (Nb) with the atomic number 41 is a chemical element and a ductile soft metal of group 5 of the periodic table. It occurs worldwide, however, in higher concentrations it can be mainly found in Nigeria, the Democratic Republic of Congo, Russia, Australia, Canada, and Brazil. Over 90% of the worldwide reserves are located in Brazil; Brazil and Canada are the only two main producers (Institute for Rare Earths and Strategic Metals, 2021; European Commission, 2014). In fact, 85% of the EU supply of niobium originates in Brazil, in a global context 92% of niobium is sourced in Brazil (European Commission, 2020a, pp. 5 & 8). Moreover, 75% of the Brasilian niobium reserves are located in a single mine in Minas Gerais, operated by CBMM (Companhia Brasileira de Metalurgia e Mineração [CBMM], 2019; Dolganova et al., 2020). The supply risk of niobium is based on its high concentration of production in one country, its production being mainly performed by one company, an uncertain recycling rate and a moderate substitutability (Royal Society of Chemistry, 2021; Deloitte, 2015; European Commission, 2014; U.S. Geological Survey, 2015).

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 (Minerals UK, 2011; Alves & dos Reis Coutinho, 2019). A low concentration of 0.01 to 0.1% of niobium can already significantly enhance the mechanical strength of steel (Institut für seltene Erden und strategische Metalle, n.d.; PROMETIA, 2017). The three main use cases for niobium are infrastructure (45%), energy (17%), and mobility (23%) (European Commission, 2020a). As niobium strengthens stainless steel, it is widely used in the construction industry for beams and girders for buildings, bridges, and other infrastructure. In the energy sector it is mostly used for the construction of oil and gas pipelines (Royal Society of Chemistry, n.d.). However, it is recently also increasingly being implemented in the clean energy sector, e.g., to enhance the performance of solar cells (Baktash et al., 2020; Nunes et al., 2020). Thirdly, niobium is used in the mobility sector, especially in the automotive industry in HSLA steel as a light-weight strengthening material for car parts (European Commission, 2014; Golroudbary et al., 2019).

Finally, superalloys account for approximately 8% of the global niobium demand. Due to its high melting point, it is used in superalloys at a concentration of 5% for thermal turbines, jet engines, rockets, and the nuclear energy industry (European Commission, 2014; Alves & dos Reis Coutinho, 2019; Kurlyak, 2016; Tkaczyk et al., 2018).

Besides being a crucial material to the economy, the use of niobium holds further issues. Niobium is one of the critical raw materials with the highest forecasted demand growth, second only to lithium (European Commission, 2020a) and according to the European Commission its demand will keep rising at an annual growth rate of 8% (European Commission, 2014; European Commission, 2020a). Since 2000, the trade of niobium has already nearly tripled (Dolganova et al., 2020). However, the recycling rate remains relatively low at 20 to 30% (Royal Society of Chemistry, 2021; European Commission, 2014). Additionally, no valid substitute for niobium exists as possible substitute materials imply increased costs and/or a decreased performance (European Commission, 2014, Tkaczyk, 2018). Various studies show that along the whole supply chain of the production of niobium, from mining, processing, production to consumption and finally end of life, greenhouse gases (GHG) are emitted, and the environment is negatively impacted (Golroudbary et al., 2019; Ibn-Mohammed et al., 2016).

In sum, niobium is classified as a highly critical raw material for bearing a high supply risk, being a crucial raw material for various major economic sectors and the negative environmental implications of niobium production.

The objective of this thesis is to investigate an approximation to a circular economy for the use of niobium to analyse how the criticality and the negative environmental impact of the metal can be mitigated. The main research question which shall be answered is:

> *To what extent does the implementation of a circular economy strategy for niobium-containing high-strength low-alloy steel under varying conditions impact niobium's criticality for the European Union as well as the generation of waste and emissions along the supply chain?*

To answer this question, an Input-Output analysis and a criticality assessment integrated in a scenario analysis will be conducted.

1.2 Theoretical and practical contributions

The aim of this thesis is to establish possible future scenarios of a circular use of niobium in HSLA steel to analyse how the criticality of the material is impacted under varying conditions. In these scenarios, the end of life products of the niobium supply chain will be the source of new niobium-containing high-strength steel. The practical contribution consists of elaborating a feasible and sustainable solution for the current issues related to the niobium supply chain and to meet the rising demand for the material in the European Union over the next decades (European Commission, 2014). The focus lies on creating substantiated forecasts of material, waste, and emission flows along the niobium supply chain for the near future to elaborate a feasible supply chain management.

Three different main scenarios based on current developments will be analysed to show different possible future outcomes. These scenarios consider variables which impact the companies operating in the niobium supply chain: a supply shortage of niobium, the introduction of a new recycling technology and governmental policies. The first scenario demonstrates how a sudden shortage of niobium due to an interruption of the niobium supply chain in the processing stage impacts the criticality of niobium. This scenario builds on the already discussed fact that niobium is as a raw material with an exacerbating criticality (Royal Society of Chemistry, 2021; European Commission, 2014; European Commission, n.d.). The European Commission classifies especially the stage in which ferro-niobium is processed as the most critical step to cause a bottleneck for the European Union (European Commission, 2020a). Therefore, it will be assumed that in this stage a halt of exports from Brazil where the majority of ferro-niobium is produced (Alves & dos Reis Coutinho, 2019; Dolganova et al., 2020) occurs. The second scenario examines the implementation of a technological innovation which leads to a higher recyclability of niobium. In the third scenario, the European Union will implement a circular economy strategy. Policies will obligate companies in the niobium supply chain to work towards a circular economy and source more raw materials from secondary sources. This scenario builds on the "European Green Deal", the EU's answer to the growing environmental and climate-related challenges. Part of the Green Deal measures is the implementation of policies to mobilise the economy towards a climate neutral and circular economy (European Commission, 2019).

As a contribution to theory, this thesis adds to the currently existing literature on life cycle assessments of the niobium supply chain (Dolganova et al., 2020; Alves & dos Reis Coutinho, 2019) by assessing how the current challenges related to niobium production may evolve and be addressed in the future. This thesis will not only establish one theoretical forecast but explore three possible future scenarios. In these scenarios, the potential impact of different driving variables for a more circular use of niobium in the European Union will be analysed, the material flows, and emissions related to the supply chains will be calculated. As a contribution to practice, the feasibility and impact of a circular use case of niobium on its criticality under varying circumstances will be evaluated and concrete recommendations for action for companies and European governments will be formulated.

2. Theoretical framework

2.1 Critical raw material classification

One definition of CRMs which is predominantly used in current literature is the definition by the European Commission (Isildar et al., 2019; Massari & Roberti, et al., 2013; Glöser et al., 2015), which defines critical raw materials as follows: "Critical raw materials are those which display a particularly high risk of supply shortage in the next 10 years, and which are particularly important for the value chain." (European Commission, 2011, p. 12). This definition includes two dimensions by which CRMs can be classified, supply risk and economic importance (European Commission, 2011). According to the European Commission (2011), supply risk (SR) is the risk of a disruption of the supply of a material and is influenced by various factors, among them the global supply concentration, substitutability, import reliance, recycling rate, country governance of the country of origin and possible trade restrictions. The economic importance (EI) of a material reflects to what extent a material is essential for an economy, measured by the value added of sectors using the material (European Commission, 2020a). On a corporate level, the economic importance can be measured by the revenue that is impacted by the material (Graedel et al., 2012).

With these two criteria a criticality matrix is established which is a common tool of raw material criticality assessment. By means of the matrix, both supply risk and economic importance are quantified, and critical raw materials can be ordered in the two-dimensional matrix instead of elaborating a less informative hierarchical risk ranking (Glöser et al., 2015). The threshold for criticality lies at a value of 2.8 for economic importance and 1 for supply risk. When a material scores 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 most critical raw materials for the European Union, as can be seen in the following figure (European Commission, 2020a).

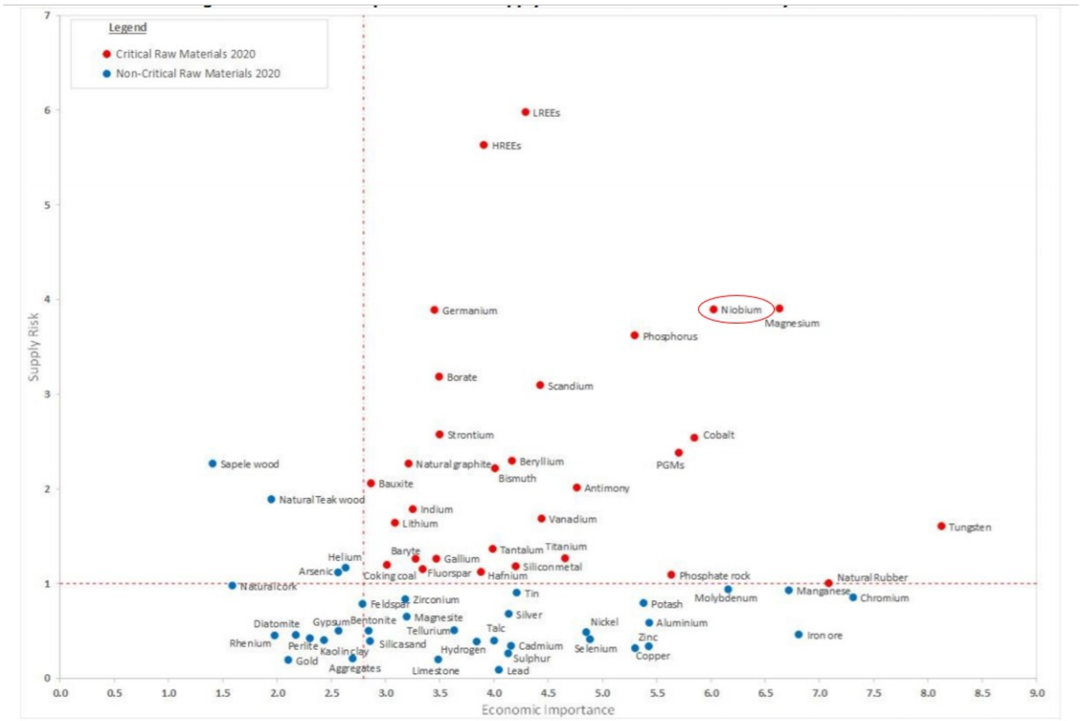


Figure 1: Criticality Matrix 2020 (European Commission, 2020a, p.3)

In addition to the first two dimensions, a third dimension has gained importance considering critical raw materials, which is environmental implications. Firstly, CRMs are essential for sustainable products and green technology, e.g., for renewable energy and emission-free vehicles, and therefore important in order to reach carbon neutrality (European Commission, 2020a; Isildar et al., 2019). Secondly, the sourcing and processing of CRMs is often related to negative environmental impacts (Graedel et al., 2012; Nuss et al., 2014). Graedel et al. (2012) have elaborated a criticality assessment framework for metals which develops the two-dimensional matrix and considers environmental impacts as a third dimension which has to be taken into account when evaluating the criticality of raw materials. The result is a three-dimensional criticality space with the three axes supply risk, economic importance or as Graedel et al. (2012) phrase it, vulnerability to supply restriction, and environmental implications in which critical raw materials can be positioned (Graedel et al., 2015). 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. This simplified approach is adopted in order to avoid an impractical full life-cycle assessment of each end-use product while still covering the main environmental issues related to the use of a certain metal along its supply chain (Graedel et al., 2012). 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.

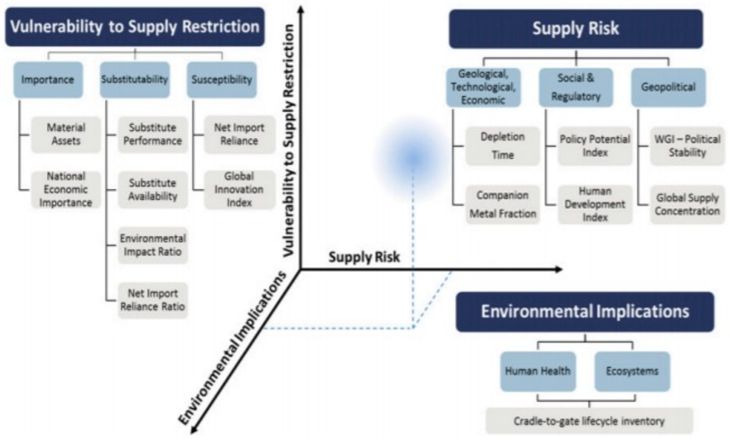


Figure 2: Three-dimensional criticality space (Graedel et al., 2015, p. 4258)

In contrast to the European Commission's framework, the methodology developed by Graedel et al. (2012), considers more diverse influence factors on each dimension. For example, both frameworks take into account the geopolitical factors WGI and global supply concentration to quantify supply risk as well as the regulatory factors policies and possible trade restrictions. However, the method by the EC considers neither social factors nor geological factors such as depletion time. In the European framework, the economic importance is defined by the sectors using a material and the value added created by these sectors. Also, the cost and performance of substitutes are considered as an influential factor on the economic importance. Graedel et al. additionally take into account the environmental impact ratio of a substitute and its net import reliance ratio. Furthermore, the impact of susceptibility on the economic importance is measured by the net import reliance and the global innovation index in the methodology created by Graedel et al. (2012). Finally, Graedel et al. (2012) include a third dimension which emphasises the impact of environmental implications on the criticality of a material. Even though the European Commission has highlighted the importance of critical raw materials for clean technologies and consequently, environmental protection, the impact of the production and processing of a critical raw material on its environment along the supply chain has not yet been addressed by the EC's method (European Commission, 2020a). A final difference between the two methodologies lies in the data the two models take into account for their criticality assessments. While Graedel et al. focus on global data and assess the criticality of a metal on a global level, the EC's method focusses on data regarding the European Union, e.g., the recycling rate in the EU and the economic importance of a metal for the EU's economy and not the recycling rate and economic importance on a global level (Graedel et al., 2012; European Commission, 2020a).

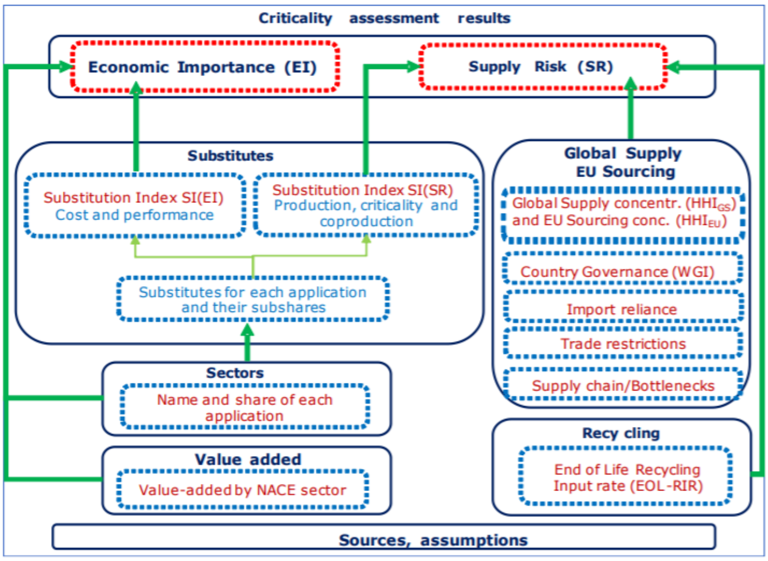


Figure 3: Overall structure of the EC's criticality methodology (European Commission, 2020a, p. 20)

2.2 Niobium supply chain

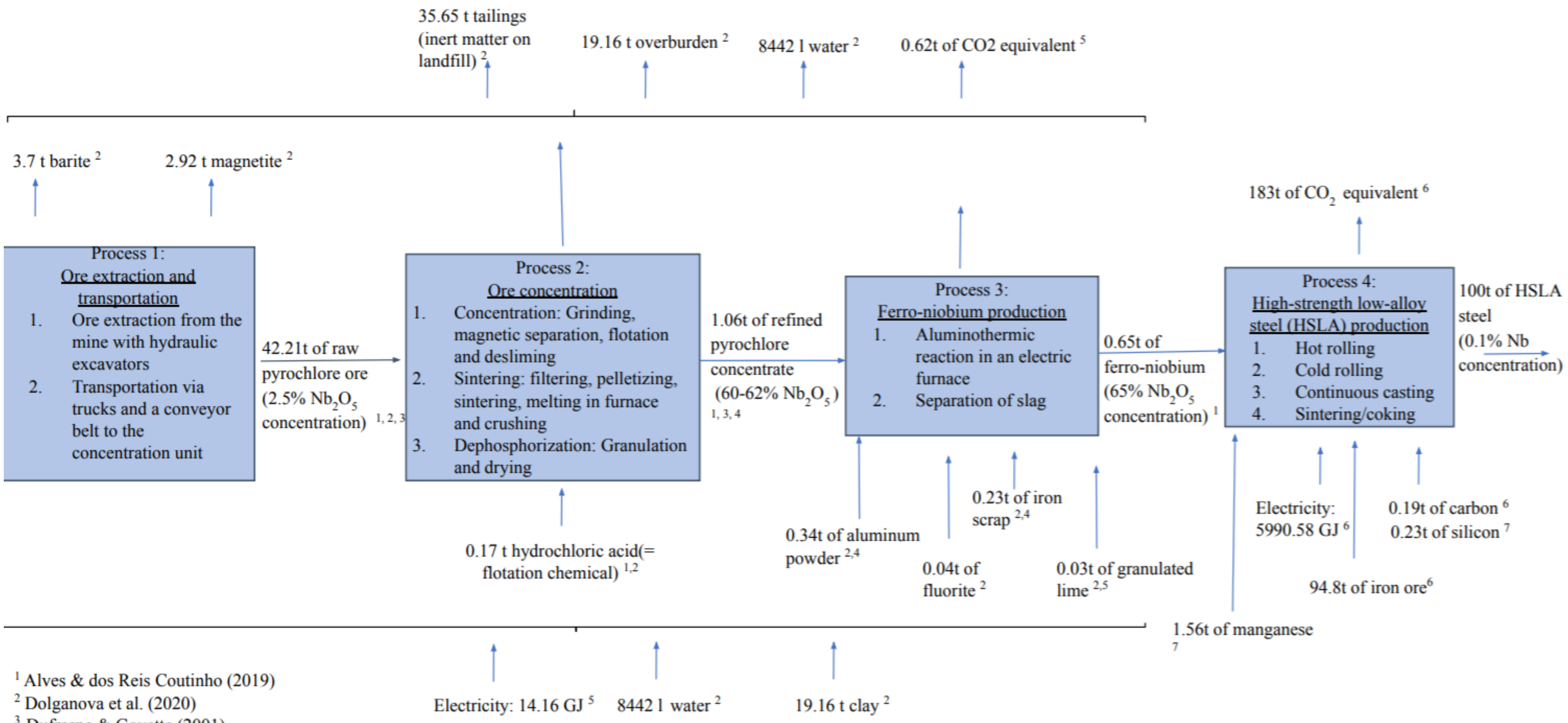
The basic input material for all main industries using niobium is ferro-niobium. Thus, the first step to understand the niobium supply chain and its impacts is to analyse the production of ferro-niobium. 75% of the Brazilian niobium reserves are located at the open-pit mine operated by the biggest producer of niobium products and technology, CBMM, in Araxá in the province of Minas Gerais (Dolganova et al., 2020). The main source for niobium is pyrochlore ore but it also occurs in other ores such as columbite and tantalite, usually in the form of niobium oxide (Nb_2O_5) (National Institute of Materials Science, 2003; Alves & dos Reis Coutinho, 2019; Dufresne & Goyette, 2001). Ferro-niobium production can be divided into three main steps, including ore extraction, ore concentration and aluminothermic reaction. For each of these steps, various input materials are required and by-products as well as emissions and waste occur. In the first step, the raw pyrochlore ore with a concentration of approximately 2.5 % of Nb_2O_5 is extracted from the mine by the means of hydraulic excavators and transported by trucks and a conveyor belt to the concentration unit (Alves & dos Reis Coutinho, 2019; Dolganova et al., 2020). This stage bears the highest risk of negatively impacting the mine's direct surrounding environment. In the process, radioactive materials and heavy metals are moved to reach the niobium deposit. Hazardous chemicals such as hydrocarbons penetrate the soil and may thus lead to soil contamination and its sterilisation. The inappropriate disposal of hazardous waste can lead to the contamination of the groundwater. Also, rivers and other watercourses are endangered due to the erosion of the exposed surfaces around the mine. The dispersion of dust caused by the activities in and around the mine can negatively affect the air quality. Furthermore, the building of the mine and the infrastructure around it leads to an irretrievable change in landscape and landform (Globe Metals and Mining, 2020). To obtain the refined pyrochlore ore with a niobium oxide concentration of 60 to 62% needed for the ferro-niobium production, the raw ore undergoes three processes, firstly, concentration through grinding, magnetic separation, flotation and desliming. The result is a pyrochlore concentrate with a niobium oxide concentration of 55 to 60%. In the second process, the concentrate is subjected to sintering which includes filtering, pelletising, and grinding by which the concentrate is agglomerated and separated from sulphur and water. Eventually, the concentrate reaches the dephosphorisation unit where it is refined in an electric furnace to remove iron-phosphorus components of the ore and finally granulated and dried (Alves & dos Reis Coutinho, 2019).

The final pyrochlore concentrate passes on to the metallurgy unit where it is mixed with iron, aluminium powder, metallic powder, fluorite, iron oxide hematite and granulated lime. In an electric furnace the materials are processed through an aluminothermic reaction, as a result standard ferro-niobium with a niobium concentration of approximately 65% is obtained (Alves & dos Reis Coutinho, 2019; Dolganova et al., 2020; Albrecht et al., 2011).

Ferro-niobium production is a material-intense process. To obtain one ton of FeNb 65 tons of raw pyrochlore ore need to be processed (Dolganova et al., 2020) and 21.86 gigajoules of energy are consumed (CBMM, 2019). Further main input materials during the three processes are hydrochloric acid, water, energy, aluminium powder, and iron oxide. During concentration, the magnetic separation leads to approximately 6.7 tons of waste, desliming and flotation cause another 3.3t of waste. After the aluminothermic reaction the ferro-niobium is separated from 1.8t of metallurgical slag which goes to landfill. Finally, the production of ferro-niobium also causes a variety of atmospheric emissions, such as lead, sulfur dioxide, hydrochloric acid, sulfur oxide and greenhouse gases (Alves & dos Reis Coutinho, 2019). For the production of one tonne of ferro-niobium, 0.96 tonnes of CO_2 are emitted (CBMM, 2019) and in total 55t of tailings are produced which proceed to be disposed on a landfill site (Dolganova et al., 2020). The finished ferro-niobium is then imported into the EU to be further processed (PROMETIA, 2017; European Commission, 2015).

The next step in the niobium supply chain is the production of high strength low alloy (HSLA) steel. HSLA steels account for 90% of niobium usage, in this type of steel niobium is added in the form of ferro-niobium as a strengthening component (PROMETIA, 2017; Golroudbary et al., 2019). HSLA steels are low carbon steels which contain low concentrations of alloying materials (Huang et al., 2018). Besides niobium, other elements such as molybdenum, titanium and vanadium are used as alloying materials in HSLA steels, however, the effect of niobium in HSLA steels is the most studied one (Schulz et al., 2017). In case of niobium, a concentration of less than 0.1% is needed to enhance the mechanical strength of the steel (Schulz et al., 2017; PROMETIA, 2017). HSLA steel is predominantly used in the automobile industry (PROMETIA, 2017; Golroudbary et al., 2019), pipelines and infrastructure (Huang et al., 2017; PROMETIA, 2017), usually with a niobium concentration between 0.04 to 0.1% (PROMETIA, 2017; Golroudbary et al., 2019). The production of HSLA steel consists of four processes, hot rolling, cold rolling, continuous casting, and sintering (Golroudbary et al., 2019). This thermo-mechanically control process leads to the required resistance of the material to be used in cars, infrastructure, and pipelines (Patterson & Lippold, 2020; Huang et al., 2017). Also, the production of HSLA steel causes CO_2 emissions, for the output of one tonne of HSLA steel 1.83 tonnes of CO2 are being emitted (Golroudbary et al., 2019). In the EU, 31% of finished niobium products are then used in the construction sector, 28% are processed in the automotive industry and 24% are built in pipelines (PROMETIA, 2017).

In conclusion, the production of primary niobium-containing HSLA steel causes a high amount of CO_2 emissions, is an energy-intensive process, and is related to the production of by-products which cannot be further used and therefore, are disposed of as landfill waste. Furthermore, the direct environment of the mine is exposed to the risk of being contaminated by hazardous materials and of an irreversible change of the landscape. An overview over the inputs and outputs along the niobium supply chain can be found in the flow diagram below.



[1] Alves & dos Reis Coutinho (2019)
[2] Dolganova et al. (2020)
[3] Dufresne & Goyette (2001)
[4] Albrecht et al. (2011)
[5] CBMM (2020)
[6] Golroudbary et al. (2019)
[7] Patterson & Lippert (2020)

Figure 4: Niobium supply chain flow diagram (own depiction)

2.2.3 Recycling

To recycle niobium, it is not necessary to recover the pure element. Niobium used in HSLA steel is mainly brought back to steel making (Tkaczyk, 2018; Kurlyak, 2016). After the collection of steel scrap from end-of-live 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 are consumed and 0.18 tonnes of CO_2 equivalent are emitted per tonne HSLA steel recycled. In comparison to the HSLA steel production stage, recycling only consumes 10% of the energy consumed in the production stage (Golroudbary et al., 2019).

2.3 Social-economic and geopolitical situation

After having analysed the ecological impact of niobium production along the supply chain, it is crucial to understand the social, economic, and political surroundings of niobium production to assess the full impact of the material on its environment and to identify further factors which contribute to niobium’s criticality. The focus lies on Brazil as the main niobium-producing country. To demarcate the complexity of this extensive topic, economic indicators such as the GDP, unemployment rate and the Gini Index as well as the key indicators World Governance Index and Human Development Index which are also considered in criticality assessment, will be examined.

Brazil’s economy is still characterised by the recession the country has undergone between 2015 and 2016 from which the economy slowly recovered until the Covid-19 pandemic in 2020 caused a new GDP decline of -4.06%. Also, the general government debt has increased steadily in the last years, from 78% in 2016 to 99% of the GDP in 2020. Another consequence of the pandemic is an increasing unemployment rate which reached 13.2% in 2020 and is projected to rise up to 14.5% in 2021 (International Monetary Fund, 2021; Santander Trade, 2021). This situation is further aggravated by the fact that approximately 41.6% of the working population have informal jobs (Santander Trade, 2021). Furthermore, Brazil faces a strong income disparity with an estimated Gini Index of 53.4 in 2019 (World Bank Group, 2021). In 2018, 9.2% of the Brazilian population lived in poverty, which means that this proportion lived on less than 3.20 US-Dollars per day (World Economic Forum, 2018).

Brazil is a federal, presidential republic. Since January 2019, Brazil's president is the far-right politician Jair Bolsonaro. His main goals at the beginning of his office were the fight against corruption, the control of violent crimes and economic recovery. Initially, the economy responded positively (Santander Trade, 2021). However, since the first months of the Covid-19 pandemic, Brazil has become an epicentre for the virus and the lack of containment strategies has led to negative health, social and economic consequences for the population (Zilla, 2020). Since the start of the pandemic, Brazil has had three different health ministers due to conflicts about the management of the crisis (Santander Trade, 2021). In July 2021, Brazil was the country with the third highest number of Covid-19 cases worldwide, with over 19 million cases and more than 530,000 deaths (BBC News, 2021).

Brazil scores moderately in the World Governance Index (WGI) dimensions which reflects a neither strong nor weak governance. The WGI considers six indicators, Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law and Control of Corruption, to assess a country's governance. Brazil scores low especially in the dimension of political stability and absence of violence/terrorism with a percentile of 24.76 out of 100, where 100 corresponds to the highest rank (World Bank, 2021), which emphasises the lack of a stable government.

The Human Development Index (HDI) measures the progress in human development in three categories, health, education and living standards and is published annually by the United Nations Development Programme. The HDI was established to assess a country's development not only by economic growth but by the development of its population. In 2019, 189 countries were assessed, and Brazil was ranked on the 84th place, between Colombia (rank 83) and China (rank 85), with a score of 0.765 (United Nations Development Programme, 2021).

Minas Gerais (engl. General Mines), the province where most niobium is sourced (Dolganova et al., 2020) is located in the south-east of Brazil and is the country's second-largest province in population. The region is rich in minerals, mining is the sector which contributes most to the province's wealth (Encyclopedia Britannica, 2021) and makes Minas Gerais one of the richest regions in Brazil. However, the pandemic has also had a strong impact on this region and has led to an excess mortality (Amaral et al., 2020).

In conclusion, Brazil is currently facing severe economic, social, and internal political challenges due to the Covid-19 pandemic and the preceding recession. The increasing debt and the GDP loss emphasize the seriousness of the economic crisis Brazil is currently undergoing.

The Gini Index and unemployment rate reflect the existing issues and disparity in Brazil's society. The failed crisis management of the pandemic and the volatility in Bolsonaro's government highlight the political instability. Even though both the WGI and the HDI show mediocre results when it comes to assessing Brazil, it must be noted that both indicators do not yet take into account latest data from 2020 and 2021 which reflect the most recent developments.

2.4 Circular economy and urban mining for critical raw materials

The central concept in this thesis is circular economy, an economic system in which "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" (den Hollander et al., 2017, p. 517). In a circular economy no more waste is produced as all materials are infinitely reused (den Hollander et al., 2017). Opposed to a linear model, in which products are produced, used, and discarded at their end of life, in a circular economy, products are designed in a way that they can be either repaired, reused, returned, or recycled at their end of life (World Economic Forum, 2014). The European Commission has lately published a circular economy action plan in which they strive for a more sustainable but also more competitive European economy by implementing a circular economy. In a circular economy scenario not only the generation of waste is avoided but also the emission of greenhouse gases can be reduced, and economic growth is decoupled from the use of new resources (European Commission, 2020b). In case of critical raw materials, implementing the principles of the circular economy hold 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 (El Wali et al., 2019; Araya et al., 2020; Ottoni et al., 2020).

With regard to circular economy, the concept of urban mining has become central. Urban mining is a circular economy strategy according to which raw materials are sourced from already existing objects and infrastructure (German Environment Agency, 2020; Ottoni et al., 2020, Tesfaye et al., 2017). Especially durable goods such as cars, technical devices, buildings, and landfill sites are used as "urban mines" to serve the demands of the economy (German Environment Agency, 2020; Giurco et al., 2014). Key studies dealing with urban mining have already emphasized the potential benefits of urban mining, especially to master the rising amount of e-waste (Zeng et al., 2018, Tesfaye et al., 2017) and in this context also to recover critical raw materials from this waste stream (Ottoni et al., 2020). 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 used at their end-of-life stage instead of entering waste management (German Environment Agency, 2020). Due to urban mining, a circular product flow is 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 (Ottoni et al., 2020; Tesfaye et al., 2017).

As previously mentioned, the demand for niobium is on the rise (European Commission, 2014) while the criticality regarding its supply and environmental impact is increasing (European Commission, 2020a). In order to meet this rising demand for niobium and reduce the dependency on suppliers and the environmental impact, urban mining can be a feasible strategy as high-strength steel containing niobium is used in goods which are commonly used for urban mining, e.g., infrastructure such as buildings and pipelines or cars (German Environment Agency, 2020; Giurco et al., 2014). 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 (Cunningham, 1998). This enables a more reliable and accurate forecasting of future material streams in the niobium supply chain.

3. Research design

3.1 Data collection

As already pointed out by various articles, data on the supply chain and life cycle of niobium and ferro-niobium is still scarce (Dolganova, 2020; Alves & dos Reis Coutinho, 2019). Therefore, data on energy consumption, greenhouse gas emissions, material use and waste occurring along the niobium supply chain will be retrieved from various sources, for instance from data provided by CBMM, the biggest producer of niobium technology and various scientific papers. To ensure the accuracy of the data included it will be cross-checked from various sources. The import numbers of ferro-niobium into the European Union are taken from PROMETIA's factsheet on niobium and tantalum (PROMETIA, 2017). For the criticality assessment data will be acquired via the ESTAT database which includes the necessary data on the sectors using niobium products in the European Union. Data regarding the shares of the sectors in niobium consumption as well as data on the trade variables and substitution index will be taken from the EC's reports on CRMs. Finally, data on the World Governance Index will be retrieved from World Bank. A detailed overview of all sources for each variable can be found in Appendix I.

3.2 Data analysis

This thesis integrates an input-output analysis and a criticality assessment into a scenario analysis. The scenario analysis is a widely used tool to forecast the economy's development in a defined period of time. Within this framework, the future is constructed in a systematic way (Swart et al., 2004). It is a central planning tool for companies to observe developments relevant for their industry or specifically one company to prepare for an uncertain future (Wack, 1985). Different scenarios manifest varying images of the future described by a set of possible outcomes (Pallottino et al., 2005). Scenarios include the definition of a problem and current conditions, the identification of processes that trigger change and assumptions on how problems can be solved (Swart et al., 2004). In this thesis, each scenario investigates a different process which stresses the need for or catalyses circular economy. Hence, a comprehensive view on possible future developments for a circular use case of niobium can be established and consequently lead to new insights to finally construct solutions on how the criticality of niobium may be mitigated.

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 will be applied. I-O models have already been used in numerous ways to investigate approaches related to circular economy, e.g., for industrial symbiosis (Yazan & Fraccascia, 2020) or for life cycle impact assessments of recycled materials (Shi et al., 2019), and are a common method to analyse supply chains (Wang et al., 2020). In I-O models, material flows between different sectors of one economy are aligned and interdependencies between the sectors can be analysed (Leontief, 1973). In this paper, the approach of an Enterprise Input-Output (EIO) model will be adapted. The EIO model is a type of I-O models which serves as an accounting and a 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. Moreover, 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 (Yazan & Fraccascia, 2020; Albino & Kühtz, 2004). Here, EIO models will be established to model circular economy cases for the niobium supply chain in different scenarios.

3.2.1 EIO modelling

To achieve this model, the material flows between the sectors will be entered into an enterprise input-output table to compute intermediate flows, final demand, external resources needed in the production process as well as waste and by-products emitted in the process. A basic physical input-output table consists of four main components, two matrices and two vectors, in which n equals the number of sectors. In the intermediate flow matrix Z (n*n) the output from one sector i becomes the input for another sector j. The second component is the final demand vector f (n*1) which reflects the final demand of sector i. The technical coefficients matrix A (n*n) manifests the required main output quantity of sector i to produce one unit of main output of sector j. The total output vector x (n*1) condenses the total output of sector j. In the calculation Z, f and x are estimated in order to calculate A (Leontief, 1973).

Table 1: Example of a physical Input-Output table, own depiction

Intermediate Flows Matrix Z	**unit**	**P1: Process 1**	**P2: Process 2**	**P3: Process 3**	**Final Demand f**	**Total Output x**
P1: Process 1	t	z_{11}	z_{12}	z_{13}	f_1	x_1
P2: Process 2	t	z_{21}	z_{22}	z_{23}	f_2	x_2
P3: Process 3	t	z_{31}	z_{32}	z_{33}	f_3	x_3

The EIO table is complemented by further components to enable a sustainability analysis; the primary input coefficient matrix R (s*n where s is the number of primary inputs), the total primary input use vector r (s*1), the waste and by-products matrix W (m*n where m is the number of wastes and by-products) and the total waste and by-product emission vector w (m*1). R contains the quantities of the primary inputs k, these are raw materials, natural resources and energy resources needed to produce one unit of the main output j. W includes the quantities of secondary products l, waste and by-products, generated in the production of main product j. Vector r denotes the quantity of a primary input k needed to produce one unit of the main output and vector w defines the quantity of secondary product l emitted (Yazan & Fraccascia, 2020).

Table 2: Example of an Enterprise Input-Output table, own depiction

Intermediate Flows Matrix Z	**unit**	**P1: Process 1**	**P2: Process 2**	**P3: Process 3**	**Final Demand f**	**Total Output x**
P1: Process 1	t	z_{11}	z_{12}	z_{13}	f_1	x_1
P2: Process 2	t	z_{21}	z_{22}	z_{23}	f_2	x_2
P3: Process 3	t	z_{31}	z_{32}	z_{33}	f_3	x_3

Primary Resources Matrix R	**unit**	**P1: Process 1**	**P2: Process 2**	**P3: Process 3**	**Total Primary**
R1: Primary input 1	t	r_{11}	r_{12}	r_{13}	$\sum r_{1j}$
R2: Primary input 2	t	r_{21}	r_{22}	r_{23}	$\sum r_{2j}$
R3: Primary input 3	t	r_{31}	r_{32}	r_{33}	$\sum r_{3j}$

Waste & By-products Matrix W	**unit**	**P1: Process 1**	**P2: Process 2**	**P3: Process 3**	**Total Waste W**
W1: Waste 1	t	w_{11}	w_{12}	w_{13}	$\sum w_{1j}$
W2: Waste 2	t	w_{21}	w_{22}	w_{23}	$\sum w_{2j}$

3.2.2 Criticality assessment

In a final step, the criticality of niobium for each scenario will be assessed, to find an answer to the central research question by evaluating how the implementation of a circular economy strategy impacts the criticality of niobium under varying circumstances. For this purpose, the EC's methodology will be adopted, considering the dimensions economic importance and supply risk and focussing 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 ($Total\_GVA_w$) with the substitute index for EI (SI_{EI}).

$$EI_{unscaled} = Total\_GVA_w \times SI_{EI}$$

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 2-digit level. The result is then multiplied by 10 to obtain the value for EI on a scale from 1 to 10.

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

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 (WGI_{scaled}) which can be obtained from the World Bank. The result of this multiplication is the "contribution to the Herfindahl-Hirschmann-Index WGI (HHI_{WGI}). This calculation is conducted with SOP both on global (GS) and EU (EU) supply level for each production country.

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

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

The HHI_{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.

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

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

The sum of the HHI_{WGI-t} of the individual production countries equals the total HHI_{WGI-t}.

The supply risk is then calculated as follows:

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

IR is the import reliance, based on to what extent 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 wastes 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 recycling of end-of-life products (European Commission, 2020a).

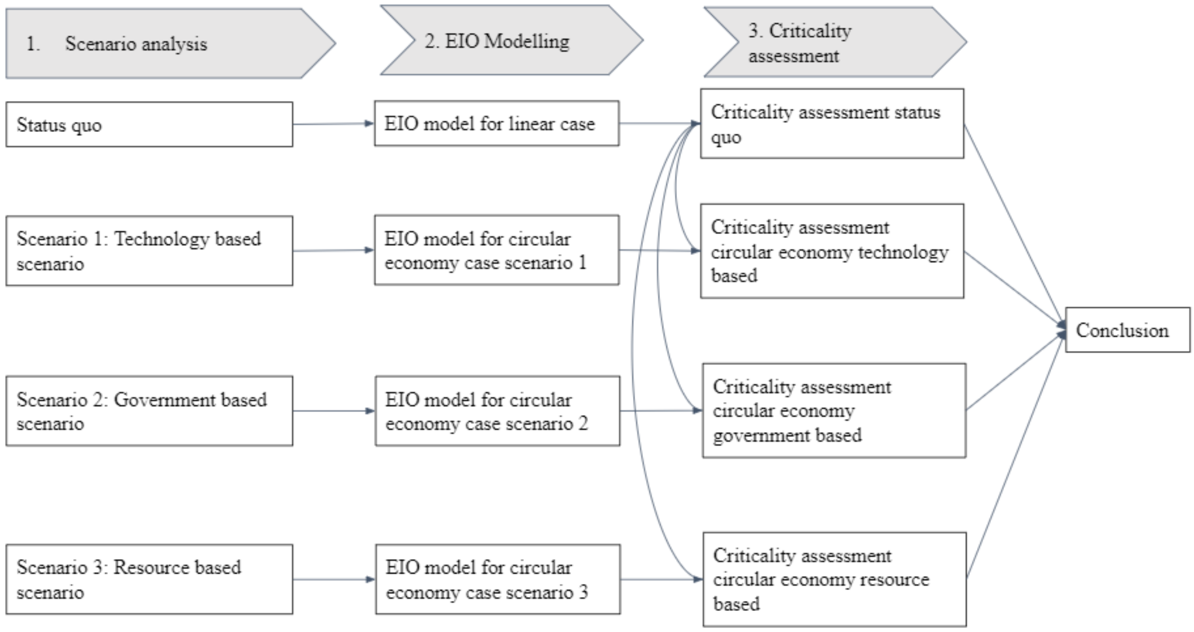


Figure 5: Overview over the research process (own depiction)

3.3 Outline and planning

To lay the foundations for a subsequent analysis, the theoretical principles on critical raw materials, circular economy, urban mining, and current issues concerning the niobium supply chain were described based on relevant current literature related to these concepts. As a preliminary basis for the EIO analysis, a flow diagram of the niobium supply chain was already developed in the theoretical framework (see p. 11) to give a first overview over the material and waste streams related to the individual steps of the niobium supply chain in the status quo. In the next step, the three scenarios will be defined considering imminent trends towards circular economy and the looming crisis of a niobium shortage. Based on the theoretical knowledge, the scenarios, and the flow diagram, the EIO analysis for each scenario will be conducted including all of the relevant variables regarding the supply chain, input materials, output materials, waste, and emissions. In a last step, the criticality of niobium will be assessed.

The results from the EIO analysis and the criticality assessment will be discussed in the light of the theoretical background summarized in the first part to elaborate an answer to the overarching research question. Finally, recommendations for action for European legislators and the sectors using niobium in their output will be formulated and suggestions for possible future research will be presented.

4. Analysis

4.1 Scenario definition and analysis

In the following, the three scenarios which will be explored in this thesis are defined in detail. Each scenario builds on incipient or imminent developments which may occur in the near future and have an impact on the niobium supply chain. Afterwards, circular economy cases for each scenario will be developed adopting EIO modelling to evaluate how circular economy can impact the criticality of niobium under varying conditions.

4.1.1 Linear case

The linear case reflects the status quo, in which 100% of HSLA steel is produced with ferro-niobium sourced in Brazil. As mentioned before, no reliable data exists to determine the functional recycling rate of niobium in the EU (Deloitte, 2015; European Commission, 2014). In their CRM reports the European Commission uses the recycling indicator 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, for criticality assessment (European Commission, 2020a). The EOL-RIR for niobium lies at 0 and therefore, for the status quo a recycling input rate of 0 will be assumed.

4.1.2 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. This scenario builds on the already discussed high supply risk of niobium (Royal Society of Chemistry, 2021; European Commission, 2014; European Commission, n.d.). The European Commission rates especially the stage in which ferro-niobium is produced as the most critical step to cause a bottleneck for the European Union (European Commission, 2020a). Therefore, a sudden decline in ferro-niobium production and export which to a large extent takes place in Brazil, will be assumed in the resource based scenario.

The causes for such a scenario are related to the factors which contribute to niobium's supply risk. According to the criticality assessment method of the European Union, the supply risk is influenced by various variables. Firstly, the EU has an import dependency of 100% for niobium as no niobium is sourced in Europe. Furthermore, 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 (European Commission, 2020a; European Commission, 2014, Tkaczyk, 2018).

Secondly, Brazil's country governance has an impact on the supply risk of niobium. In the EC's criticality assessment, the scaled World Governance Index is used to rate the governance for 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. The WGI considers six dimensions, among them political stability, government effectiveness and control of corruption. For Brazil, a scaled WGI of 5.08 was determined which is relatively high and therefore increases the supply risk. In comparison, Canada has a scaled WGI of 2.26 and Austria a scaled WGI of 2.5. Countries with a similar scaled WGI as Brazil are Jordan (5.16), Serbia (5.05) and Turkey (5.34) (European Commission, 2020a).

Thirdly, trade restrictions impact a material's supply risk (European Commission, 2020a). The trade relationship between Brazil and the EU can be defined as ambivalent. On the one hand, the EU has reached a new agreement of trade with the Mercosur (Mercado Común del Sur/ Southern common market) states, Argentina, Brazil, Paraguay, and Uruguay in 2019 (European Commission, 2019) which continued the pre-existing movement towards free trade between the EU and Brazil (European Commission, 2018). This trade agreement is part of a new Association Agreement between the Mercosur states and the EU which is supposed to strengthen political and economic collaboration between the two regions (European Commission, 2019). On the other hand, the ratification of the Association Agreement has still not been performed and it is unlikely that the deal will be approved in the near future as several EU member states, and the European Parliament have expressed their opposition to the deal. This is due to negative environmental impacts related to the agreement and the Mercosur countries, in particular Brazil (Nadibaidze, 2020). Various NGOs as well as politicians from all over the EU, among them the German chancellor Angela Merkel and the French president Emmanuel Macron, have voiced their concern about the current environmental policies in Brazil (Caldeira Rodrigues, 2021; Nadibaidze, 2020; Hanke Vela, 2020). The focus of their criticism lies on Brazil's president Jair Bolsonaro and his cabinet who permit the deforestation of the Amazon rain forest and damaging activities which have already led to numerous far spreading wildfires. An agreement which includes an increase in imports of products related to deforestation, e.g., soybeans, from the Mercosur states without environmental guarantees from these countries is incompatible with the EU's value of sustainable development. Without environmental commitments made by the Mercosur countries or a renegotiation of the agreement it is unlikely that the deal will be ratified

(Nadibaidze, 2020, Hanke Vela, 2020). However, reopening negotiations would likely result in a tedious process as the negotiations for the current version of the agreement have already taken more than 20 years (Caldeira Rodrigues, 2021).

In conclusion, a complete termination of the trade relationships between the EU and Brazil is improbable in the near future. Nevertheless, as Brazil is already facing political instability, Bolsonaro and his government might use a limitation of the export of ferro-niobium products into the EU as leverage to avoid environmental commitments and a renegotiation of the Association Agreement. The EU depends to over 90% on the import of ferro-niobium products from Brazil and no equivalent substitute for niobium exists (European Commission, 2020a), therefore, this scenario would lead to a bottleneck and would leave urban mining as the major sourcing option for niobium.

In the past, export restrictions on a variety of critical raw materials have been imposed in different forms, e.g., export quotas, export taxes or minimal export prices. In particular China is known for imposing export quotas on CRMs such as molybdenum or rare earth elements (Korinek & Kim, 2010; Subin, 2021; European Commission, 2016). For instance, in 2007, China limited exports of molybdenum to 35,700 tonnes (Korinek & Kim, 2010). In 2012 and in 2014 respectively, China lost the case brought to the World Trade Organization which forced the country to suspend export restrictions on various raw materials, among them the critical materials fluorspar, magnesium, and bauxite (Deutsche Welle, 2012; European Commission, 2016).

In 2012, 19,000 tonnes of ferro-niobium were imported into the European Union (European Commission, 2015), in 2015 imports increased to more than 22,000 tonnes of ferro-niobium. According to the projected rise in demand of 8% the ferro-niobium demand in the European Union will be 43,200 tonnes in 2022 (PROMETIA, 2017; European Commission, 2014). Brazil covers 85% of the European niobium demand (European Commission, 2020a) and would therefore have to supply 36.720 tonnes 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 maximum 32.000 tonnes imposed by the Brazilian government can be mitigated through circular economy and how niobium's criticality will be impacted in the process. 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.

4.1.3 Technology based scenario

The technology based scenario analyses how the introduction of an innovative technology can lead to a higher recyclability and thus impact the criticality of niobium. To recycle niobium, it is not necessary to recover the pure element from a niobium product. Most niobium is used in HSLA steel and therefore mainly brought back to steel making, which makes its recycling process theoretically easy (Tkaczyk, 2018; Kurlyak, 2016). At present, niobium has a high recycling rate, more than 50% of the consumed niobium is introduced to a recycling process (Graedel et al., 2011). However, most of these recycling processes are non-functional according to Graedel et al. (2011) and the niobium cannot be re-used in its original application areas after having been recycled. In practice, the exact functional recycling rate of niobium in the EU remains unknown. However, it is assumed that the only functional recycling occurs for superalloy scrap and that niobium HSLA steel scrap is usually non-functionally recycled (Deloitte, 2015).

The main issue regarding the recycling process of niobium is the lack of identification of niobium containing steel before melting. Consequently, niobium containing steel is diluted with other steel types due to which it loses its strengthening properties and its applicability in the automotive, construction or pipeline industry, which leads to a downcycling process instead of a recycling process (Kurlyak, 2016; Deloitte, 2015; Ohno et al., 2015). Improved sorting and separation of HSLA steel from other steel scrap is needed to increase the efficiency of the recycling process (Globe Metal, 2020; Kurlyak, 2016; Ohno et al., 2015). 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 (Kurlyak, 2016; Golroudbary et al., 2019). Besides ELVs, pipelines will become promising urban mines for HSLA steel in the next twenty years as they have an approximate lifetime of 60 years and have been introduced in the 1970s (Kurlyak, 2016, Cunningham, 1998). Also, waste from construction and demolition are urban mines for HSLA steel. It is estimated that more than 50% of all metals worldwide in use are contained in buildings (van Beers and Graedel, 2007) and the infrastructure sector is the biggest consumer of niobium, accounting for 45% of the niobium demand in the European Union in 2020 (European Commission, 2020a). The importance of recycling demolition and construction waste in order to recover metals is rising due to high metal prices and the high potential recyclability of metals as well as for sustainability reasons (Koutamanis et al., 2018). The central challenge regarding the recyclability of buildings, however, is that most buildings differ in their composition as they are not, unlike vehicles, mass-produced (Gerst & Graedel, 2008; Koutamanis et al., 2018). Therefore, it is challenging to identify and correctly sort materials recovered from construction waste before introducing them into the recycling process which often leads to construction waste from buildings being downcycled, e.g., as road construction material (Koutamanis et al., 2018). Niobium was introduced to the construction sector in the 1980s and finds application in a variety of construction market segments such as buildings, skyscrapers and industrial complexes, wind towers, reinforcing bars and pre-stressed concrete wire rods. The lifetime of these types of infrastructure cannot be determined in a consistent manner as they not only depend on deterioration but also other reasons which lead to the demolition of infrastructure, e.g., when a facility is deemed to be out-of-date or no longer needed (Jansto, 2021).

At present, recycling technologies that enable an efficient recycling of niobium are lacking (Kurylak, 2016; Ohno et al., 2015). For critical raw materials like niobium, which find application in different products, better sorting and separation is needed to achieve a functioning recovery strategy (Zhang & Xu, 2018; Ohno et al., 2015). In the technology based scenario, the introduction and implementation of a technology which detects niobium containing HSLA steel in recycling facilities, determines the niobium concentration and separates it from other steel scrap will increase the sorting efficiency. As a result, less HSLA steel will be diluted with other steels which do not contain niobium or other concentrations of niobium and thus, the devaluation of HSLA steel during the recycling process can be avoided. Consequently, the HSLA steel can be reused for secondary production in the appropriate application areas.

In recent years, the recycling of critical raw materials has moved to the fore. One example for new disruptive technologies in this area is a technology developed by Geomega Resources, based in Canada, which focusses on the recycling of the rare earth elements neodymium, praseodymium, terbium, and dysprosium from magnet waste by separation (Barker, 2020). 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. Furthermore, the project led to the validation of an ICP-MS (inductively coupled plasma mass spectrometry) instrument, which identifies and measures nanoparticles of critical metals even at low concentrations (Recycling Product News, 2018). 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. Due to their short lifespan, ELVs will remain the major source for secondary HSLA steel in the next ten years and thus, the potential recycling volume is limited by this sector. With an average lifetime of 10 years (Cunningham, 1998), cars manufactured in 2014 will become available for recycling in 2024. In 2014, the demand for FeNb in the EU peeked and amounted to 43016 tonnes (PROMETIA, 2017). The demand share of the automotive sector in this year was approximately 28% (European Commission, 2015) and consequently, around 12,044.48 tonnes of FeNb were used in car parts in 2014's production. With a concentration of 0.1% of FeNb (PROMETIA, 2017), 12,044,480 tonnes of HSLA steel were produced for vehicles. For 2024, a FeNb demand of approximately 50,000 tonnes of FeNb is projected, which leads to a production of 50,000,000 tonnes of HSLA steel. Therefore, with a maximum potential recycling rate of 100% of all HSLA steel contained in vehicle parts, 24.08% of the HSLA steel demand can be covered with steel from secondary sources in 2024. However, the most recent recycling rate for ELVs from 2018 lies at 87% in the European Union and has not risen significantly since 2013 (Eurostat, 2021). Therefore, it will be assumed that the recycling rate for ELVs will remain stable until 2024. The recycling rate of ferrous scrap or steel scrap from ELVs is close to 100% (Federal Environment Ministry of Germany, 2010; WorldAutoSteel, 2021). With a recycling rate of 87% for ELVs in 2024, 10,478,698 tonnes of HSLA steel can be sourced from secondary sources which accounts for an EOL-RIR of 20.96% in relation to the European demand in 2024.

Table 3: 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	43,016.00	28%	12,044.48	12,044,480	0.10%	100%
	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	87%	10,478.70	50,000,000	10,478,697.6	20.96%

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

4.1.4 Government based scenario

In the government based scenario it will be analysed how governmental incentives in form of policies for a more sustainable management of companies in the niobium supply chain catalyses circular economy in the niobium supply chain and impacts the criticality of niobium. This scenario builds on the European Green Deal. The Green Deal is the European Union's answer to the growing environmental and climate-related challenges. According to the European Commission it is a "new growth strategy that aims to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of GHG in 2050 and where economic growth is decoupled from resource use." (European Commission, 2019, p. 2). The Green Deal is also meant as a plan towards the implementation of the sustainable development goals formulated in the United Nations 2030 Agenda. Central goals of the Green Deal are the supply of clean energy, sustainable construction, the reduction of pollution, the protection of ecosystems, the promotion of sustainable mobility, and the mobilisation of the industry for a circular economy. The European Commission has elaborated concrete measures to reach these goals over the next decades.

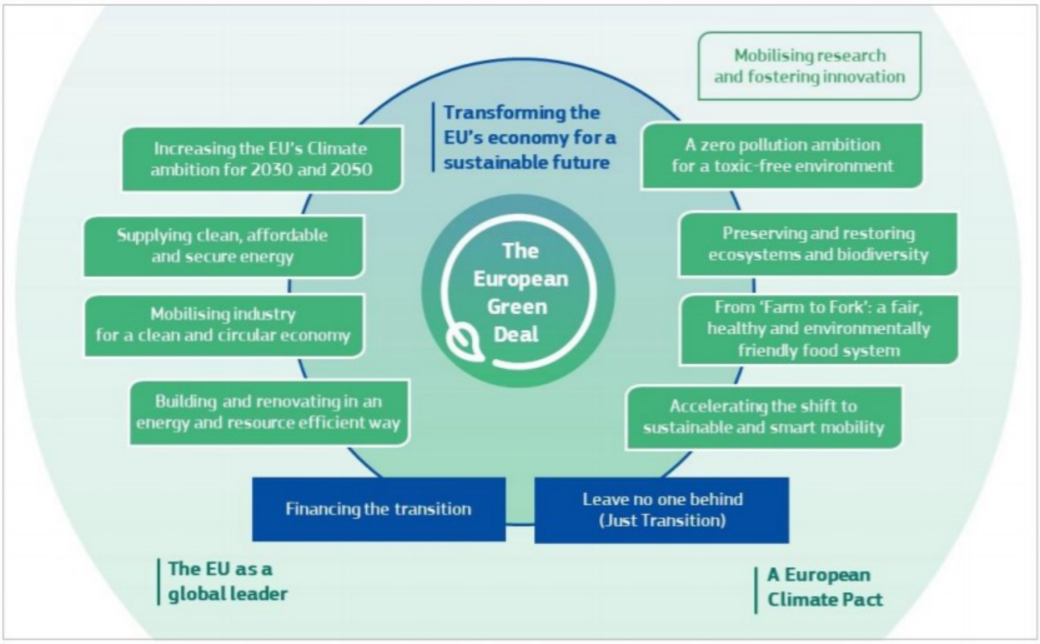


Figure 6: The European Green Deal (European Commission, 2019)

Considering CRMs, the Green Deal emphasizes the importance of circular economy and defines the sourcing of materials form secondary sources as a central strategy to ensure their supply and to create more sustainable supply chains. Part of the Green Deal measures is the implementation of policies for the mobilisation of the industry towards a climate neutral and circular economy. According to the European Commission, the market for secondary raw materials and by-products shall be promoted. Additionally, the commission considers the implementation of legal requirements for mandatory recycled content in certain products, among them vehicles and construction materials (European Commission, 2019).

Until today, the policy framework for circular economy in the European Union and its member states is fragmented and no overarching target for resource efficiency which binds all member states exists. With the introduction of various policy strategy documents over the last decade which are meant to promote circular economy, such as the Europe 2020 strategy (2010), the flagship initiative on resource efficiency and the resource efficiency roadmap (2011) and the circular economy package (2015), the European Commission has stressed the need for progress towards resource efficiency and proposed specific policies (McDowall et al., 2017; Domenech & Bahn-Walkowiak, 2019). However, the definitions of most of the goals set by the European Commission in these policy documents are rather vague, non-mandatory and qualitative, lacking concrete timeframes or quantitative goals all member states have to comply with (Domenech & Bahn-Walkowiak, 2019). It is left to the member states to decide how strongly, and with which instruments they pursue the implementation of these policies. Despite the numerous efforts of the European Commission only few member states of the EU have established dedicated strategies to achieve more resource efficiency in their economy (McDowall et al., 2017; Domenech & Bahn-Walkowiak, 2019). Especially a reluctance to the application of taxation as a tool to incentivise the economy towards more resource efficiency can be observed as states fear to compromise their economic competitiveness (Domenech & Bahn-Walkowiak, 2019). To sum up, a more coherent and specific policy framework which binds all member states to act is needed to reach the goals formulated by the EC in the European Green Deal and previous policy strategy documents. As stated in the Green Deal, the European Union is already considering the implementation of a regulation which predefines a minimum recycled content which certain products have to meet (European Commission, 2019). Also, 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 (EUWID, 2021).

The government based scenario manifests how the introduction of a specific and binding policy for a recycling input rate for critical raw materials in new products catalyses circular economy 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.

4.2 EIO analysis results

4.2.1 Linear case

In the status quo, a recycling input rate of 0% (European Commission, 2020a) and a niobium concentration of 0.1% in HSLA steel (PROMETIA, 2017) 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. Per 100 tonnes of HSLA steel produced, a total of 8442 litres of water, 19.17 tonnes of clay, 6004.74 gigajoule of energy, 94.8 tonnes of iron ore and 1.56 tonnes of manganese are used. Further inputs with lower input amounts are hydrochloric acid (0.17 tonnes), aluminium powder (0.34 tonnes), fluorite (0.04 tonnes), iron scrap (0.23 tonnes), granulated lime (0.03 tonnes), carbon (0.19 tonnes) and silicone (0.23 tonnes). The waste and by-products generated in the production processes are 3.7 tonnes of barite, 2.92 tonnes of magnetite, 35.64 tonnes of tailings, 19.17 tonnes of overburden, 8442 liters of water and 183.63 tonnes of CO_2 equivalent per 100 tonnes of HSLA steel produced. While the water can be reintroduced to the production cycle, tailings and overburden go to landfill. Barite and magnetite are co-products and therefore sold as valuable outputs (Dolganova et al., 2020). All EIO tables can be found in Appendix II.

Table 4: 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

4.2.2 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 less input materials. The results can be seen in the following table 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.

Table 5: 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%

Also, the amount of by-products and emissions can be reduced in comparison to the status quo. In case of GHG emissions, the reduction accounts for 21.29 tonnes or 11.59% as the recycling process of niobium consumes significantly less energy and thus, generates less emissions. For the production of 1 tonne of primary HSLA steel, 59.91 GJ of energy are consumed and 1.83 tonnes of CO_2 are emitted; a total of 6.69 GJ of energy are consumed and 0.18 tonnes of CO_2 equivalent are emitted per tonne HSLA steel recycled (Golroudbary et al., 2019). In this scenario, 160.01 tonnes of CO_2 emissions are generated due to the production of 87.15 tonnes of primary HSLA steel while only 2.31 tonnes of CO_2 emissions are emitted for the production of 12.85 tonnes of secondary HSLA steel.

4.2.3 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 6: 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%

As initially a recycling rate of 100% is not probable, additionally 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%.

Table 7: 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 8: 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%

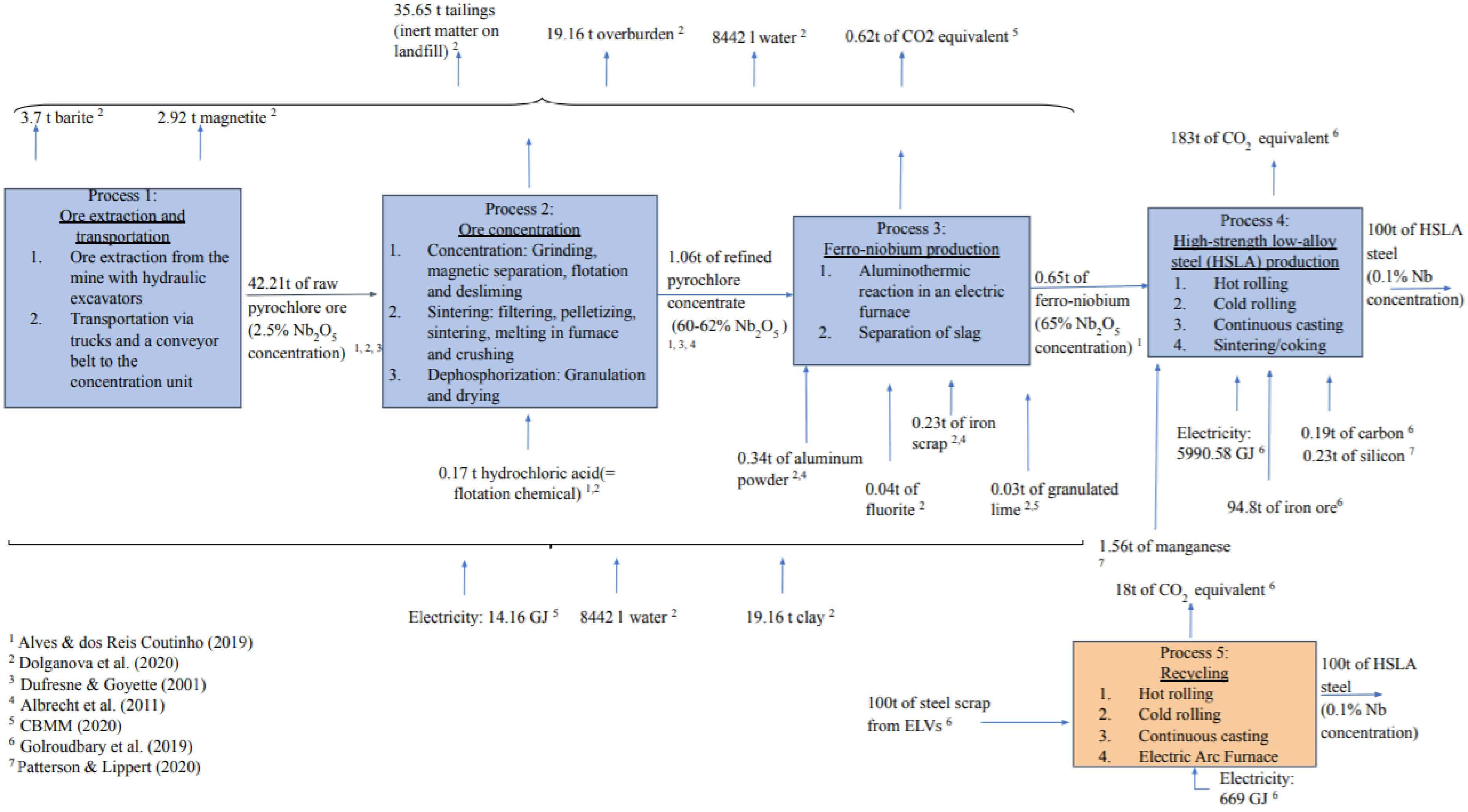
4.2.4 Government-based scenario

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 9: 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%

To visualize the transformed niobium supply chain, the fifth process step of recycling has been introduced to the flow diagram, as depicted below, comparing the inputs and outputs generated for 100 tonnes of primary HSLA steel and for the recycling of 100 tonnes of HSLA steel.



[1] Alves & dos Reis Coutinho (2019)
[2] Dolganova et al. (2020)
[3] Dufresne & Goyette (2001)
[4] Albrecht et al. (2011)
[5] CBMM (2020)
[6] Golroudbary et al. (2019)
[7] Patterson & Lippert (2020)

Figure 7: Niobium supply chain flow diagram, circular (own depiction)

4.3 Criticality assessment results

In the following, the economic importance and the supply risk are calculated. As EI is not impacted by circular economy it will only be calculated once, for the linear case. SR is calculated for each scenario, assessing how the change in recycling impacts SR and niobium's overall criticality.

4.3.1 Linear case

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.

Table 10: Calculation of the Total $GVA_{weighted}$ *for niobium using sectors in the EU*

Application	NACE sector GVA (M€)	2-digit NACE sector	Data source	Share	Data source Share	Contribution to EI (Share x sector GVA)
Construction (Steel)	148,351	C25 - Manufacture of fabricated metal products, except machinery and equipment	ESTAT; European Commission, 2020	45%	European Commission, 2020	66757.95
Automotive (Steel)	160,603	C29 - Manufacture of motor vehicles, trailers and semi-trailers	ESTAT; European Commission, 2020	23%	European Commission, 2020	36938.69
Oil & Gas	55,426	C24 - Manufacture of basic metals	ESTAT; European Commission, 2020	17%	European Commission, 2020	9422.42
Stainless steel	55,426	C24 - Manufacture of basic metals	ESTAT; European Commission, 2020	10%	European Commission, 2020	5542.6
Special Steel	44,304	C30 - Manufacture of other transport equipment	ESTAT; European Commission, 2020	3%	European Commission, 2020	1329.12
Total GVA weighted						**119990.78**

Table 11: Calculation of EI_{scaled} for niobium

Step	Value	Data source	Calculation
SI(EI)=	0.97	European Commission, 2020	
EI(unscaled)=	116391.0566		Total GVA weighted x SI(EI)
highest value of the manufacturing sector NACE Rev.2	196,055		European Commission, 2020
EI(scaled)=	**5.936653317**		EI(unscaled) / highest value x 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.

Table 12: Calculation of the 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-t))EU**
Data source	European Commission, 2020	Eurostat	World Bank	SOP(EU)2 * WGI(scaled)	European Commission, 2020	Contribution to (HHI(WGI))EU * T
	Brazil	85%	5.08	3.67	1	3.67
	Canada	13%	2.26	0.04	1	0.04
	Sum			**3.71**		**3.71**

Table 13: Calculation of the 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-t))GS**
Data source	European Commission, 2020	Eurostat	World Bank	SOP(GS)2 * WGI(scaled)	European Commission, 2020	Contribution to (HHI(WGI))GS * T
	Brazil	92%	5.08	4.30	1	4.30
	Canada	8%	2.26	0.01	1	0.01
	Sum			**4.31**		**4.31**

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.

Table 14: Calculation of SR for niobium, linear case

Step	Value	Data source	Calculation
SI(SR)=	0.98	European Commission, 2020	
IR=	1	European Commission, 2020	
EoL-RIR=	0	European Commission, 2020	
SR=	**3.93**		**[(*HHI*(*WGI-t*))*GS* x *IR* / 2 + (*HHI*(*WGI-t*))*EU* x (1 – *IR* / 2)] x (1 – *EOL*(*RIR*)) x *SI*(*SR*)**

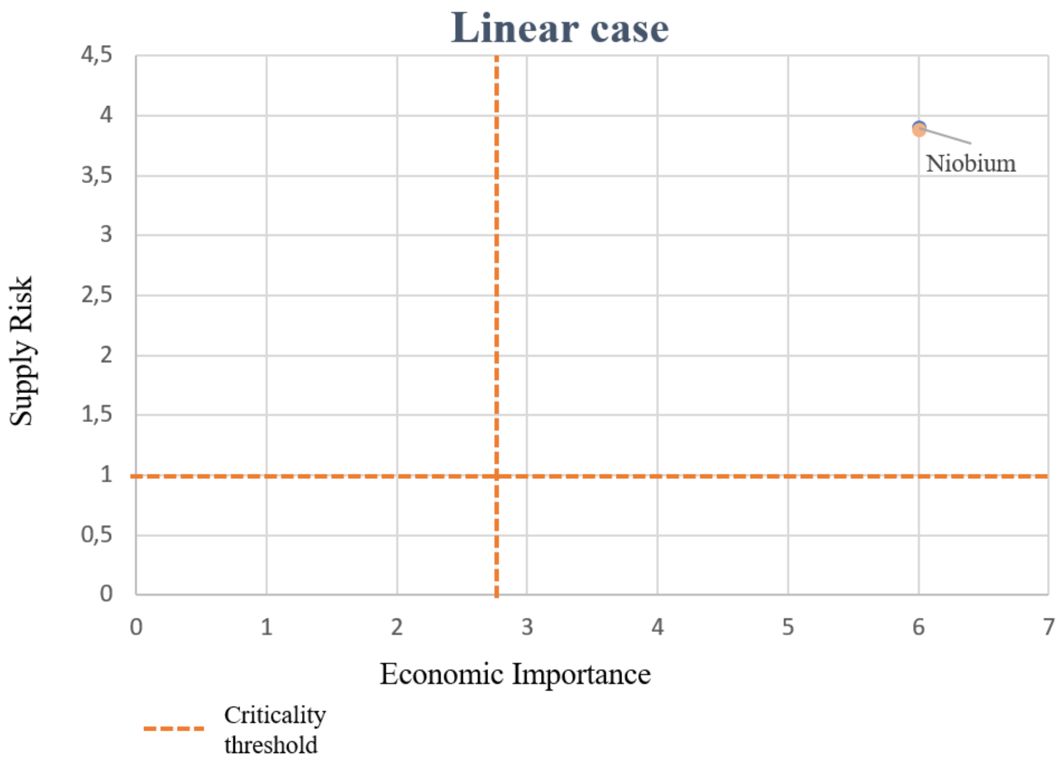


Figure 8: Criticality Matrix, linear case (own depiction)

4.3.2 Resource based scenario

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.

Table 15: Calculation of SR for niobium, resource based

Step	Value	Data source	Calculation
SI(SR)=	0.98	European Commission, 2020	
IR=	1	European Commission, 2020	
EoL-RIR=	12.85%	European Commission, 2020	
SR=	**3.43**		**[(*HHI*(*WGI-t*))*GS* x *IR* / 2 + (*HHI*(*WGI-t*))*EU* x (1 – *IR* / 2)] x (1 – *EOL*(*RIR*)) x *SI*(*SR*)**

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 (European Commission, 2020a).

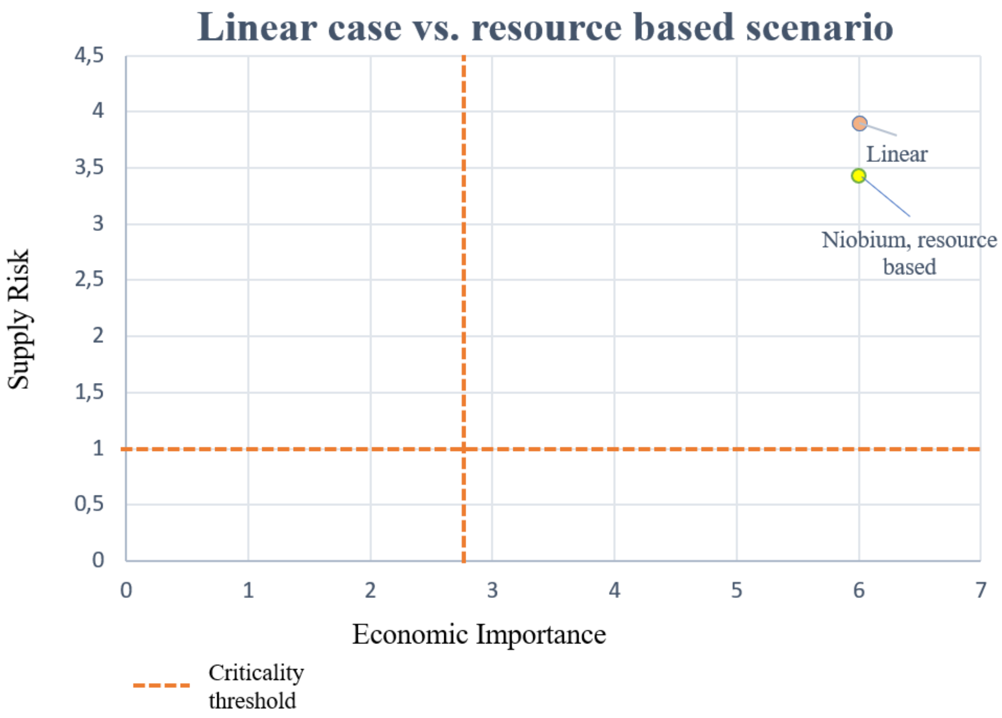


Figure 9: Criticality Matrix, resource based scenario (own depiction)

4.3.3 Technology based scenario

For the technology based scenario a sensitivity analysis was conducted. The following tables show how the supply risk changes when the recycling rate is respectively 100%, 85% or 70%.

Table 16: Calculation of SR for niobium, technology based, recycling rate = 100%

Step	Value	Data source	Calculation
SI(SR)=	0.98	European Commission, 2020	
IR=	1	European Commission, 2020	
EoL-RIR=	20.96%	European Commission, 2020	
SR=	**3.11**		**[($HHI(WGI\text{-}t)$)GS x IR / 2 + ($HHI(WGI\text{-}t)$)EU x (1 – IR / 2)] x (1 − $EOL(RIR)$) x $SI(SR)$**

Table 17: Calculation of SR for niobium, technology based, recycling rate = 85%

Step	Value	Data source	Calculation
SI(SR)=	0.98	European Commission, 2020	
IR=	1	European Commission, 2020	
EoL-RIR=	17.82%	European Commission, 2020	
SR=	**3.23**		**[($HHI(WGI\text{-}t)$)GS x IR / 2 + ($HHI(WGI\text{-}t)$)EU x (1 – IR / 2)] x (1 − $EOL(RIR)$) x $SI(SR)$**

Table 18: Calculation of SR for niobium, technology based, recycling rate = 70%

Step	Value	Data source	Calculation
SI(SR)=	0.98	European Commission, 2020	
IR=	1	European Commission, 2020	
EoL-RIR=	14.67%	European Commission, 2020	
SR=	**3.35**		**[(*HHI(WGI-t))GS* x *IR* / 2 + (*HHI(WGI-t))EU* x (1 – *IR* / 2)] x (1 − *EOL(RIR)*) x *SI(SR)***

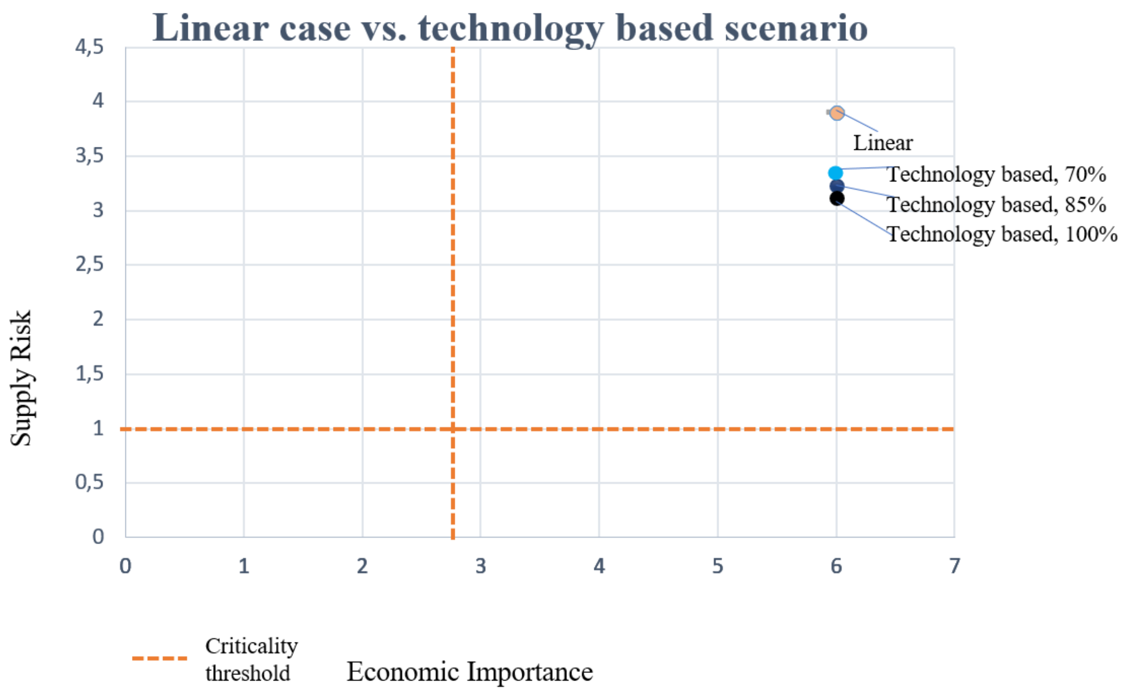


Figure 10: Criticality Matrix, technology based scenario (own depiction)

4.3.4 Government based scenario

The government based scenario is the scenario that lies furthest in the future and with the highest EOL-RIR (30%). This impacts the supply risk as follows.

Table 19: Calculation of SR for niobium, government based

Step	Value	Data source	Calculation
SI(SR)=	0.98	European Commission, 2020	
IR=	1	European Commission, 2020	
EoL-RIR=	30%	European Commission, 2020	
SR=	**2.75**		**[(*HHI(WGI-t))GS* x *IR* / 2 + (*HHI(WGI-t))EU* x (1 – *IR* / 2)] x (1 − *EOL(RIR)*) x *SI(SR)***

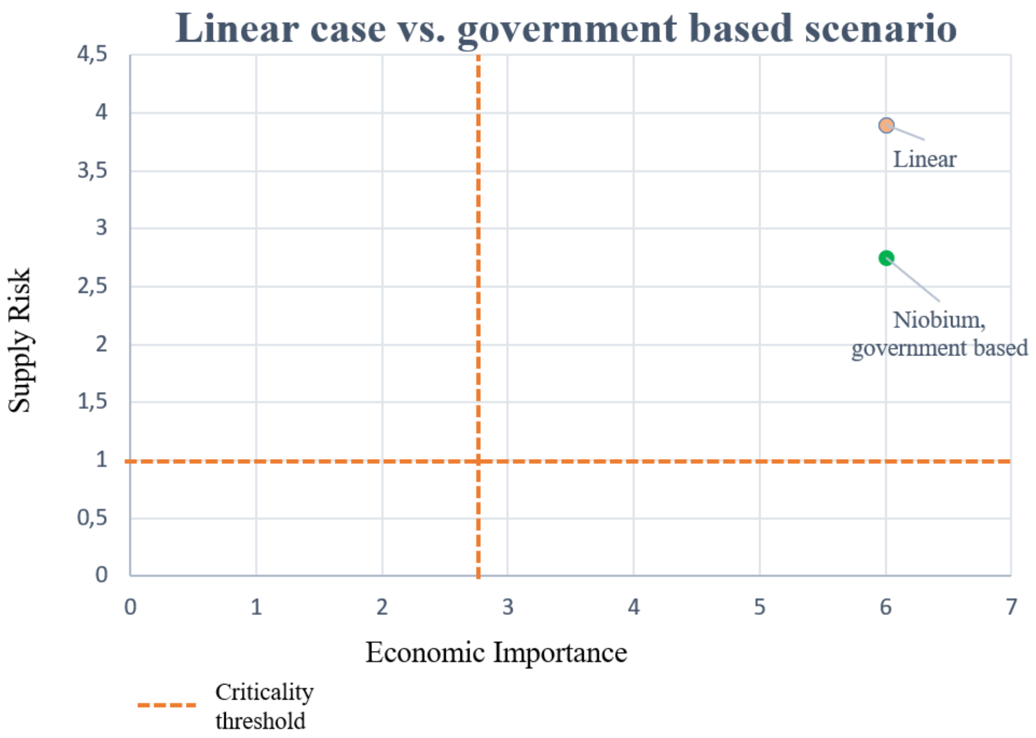


Figure 11: Criticality Matrix, government based scenario (own depiction)

5. Discussion

In each scenario the supply risk of niobium as well as environmental implications, i.e., emissions and waste generated along the supply chain, could be mitigated in comparison to the linear case. In the resource based scenario, the supply risk could be reduced by 0.5 points, from 3.9 to 3.4. However, niobium's overall criticality is still far from an uncritical state in this scenario. Also, the quantity of all by-products and emissions could be reduced by at least 11.59% due to the increased recycling input rate triggered through the bottleneck scenario. This reduction implies a relief for the direct environment of the niobium mine due to the reduction of landfill waste, such as tailings and overburden (Dolganova et al., 2020) as well as for the global environment due to the reduction of GHG emissions.

In the second scenario which analysed the introduction of an ICP-MS technology which enables a better sorting and recycling of steel scrap from ELVs, a maximum recycling input rate of 20.96% was calculated due to the limiting factor of available ELVs as urban mines. With a recycling rate of 100% of all available HSLA steel in ELVs a recycling input rate of 20.96% can be achieved and the supply risk can be reduced to 3.1 in the year. At a recycling rate of 85%, the EOL-RIR lies at 17.82% and the supply risk drops to 3.2 while at a recycling rate of 70% of all secondary HSLA steel available the EOL-RIR is reduced to 14.67% and the supply risk accounts for 3.4. Also, the quantity of by-products generated along the supply chain was lowered, for instance, GHG emissions declined by 18.91% (100% recycling rate), 16.07% (85% recycling rate) and 13.24% (70% recycling rate). Furthermore, the amount of tailings and overburden, the two by-products of the niobium supply-chain which cannot be reused and are discarded in landfill, could also be reduced by respectively 7.4 tonnes and 4 tonnes (100% recycling rate) 6.3 and 3.4 tonnes (85% recycling rate) and 5.2 and 2.8 tonnes (70% recycling rate) per 100 tonnes of HSLA steel produced.

Finally, the government based scenario had the biggest impact on niobium's supply chain and criticality, lying furthest in the future and implying the highest recycling input rate of all scenarios with an EOL-RIR of 30%. According to the EIO modelling in this scenario the GHG emissions are reduced by 27.06% which implies a total reduction of 50 tonnes of $CO_{2\text{-eq}}$ per 100 tonnes of HSLA steel produced. Tailings and overburden are respectively lowered by 10.7 tonnes and 5.8 tonnes. In the government based scenario, the supply risk drops to a score of 2.75. Even though this result manifests a significant reduction of niobium's supply risk by 1.15

points, niobium remains a critical raw material in this scenario, surpassing the criticality threshold of 1 by far (European Commission, 2020).

The main limitation for this thesis was the lack of current data which takes into consideration the latest developments caused by the Covid-19 pandemic in 2020 and 2021. Due to the resulting effects on the economy and the sectors which use niobium-containing HSLA steel a change in the demand in the European Union is highly probable. Furthermore, Brazil's WGI might have changed due to the political issues which Brazil has been facing as a result of the Covid-19 pandemic which has had a significant impact on the country's economy, society and politics (Zilla, 2020, Santander Trade, 2021, BBC News, 2021). However, newer data which covers the time period of 2020 and 2021 is not yet available and could therefore not be included to reflect on how these developments might have had an impact on niobium's criticality.

6. Conclusion

The central goal of this thesis was to assess how the adoption of a circular economy strategy impacts niobium's criticality as well as the generation of waste and emissions along the supply chain. To find an answer to this question three scenarios for different possible future paths were established to explore imminent developments which impact the niobium supply chain and trigger circular economy. For each scenario a different recycling input rate was assumed which was then incorporated in the EIO analysis. The results of the EIO model showed how the amount of inputs, outputs and by-products changed in each scenario. In a final step, the supply risk was calculated for each scenario according to the EC's criticality assessment framework to evaluate, how circular economy affected niobium's criticality under differing conditions.

In the theoretical framework, after having defined the concept of CRMs, the issues occurring along the niobium supply chain besides supply risk and economic importance were analysed and broken down into two categories: environmental impact and social-economic and geopolitical issues. Firstly, along the entire supply chain, especially during mining of niobium and production of HSLA steel, the environment is negatively impacted due to the generation of wastes which cannot be recycled or reused and the emission of GHGs (Dolganova et al., 2020; Golroudbary et al., 2019; Globe Metals and Mining, 2020; Alves & dos Reis Coutinho, 2019). Secondly, Brazil, the producer of over 90% of all niobium products worldwide, is facing grave economic, social and political issues which were further aggravated by the Covid-19 pandemic since 2020 (Zilla, 2020, Santander Trade, 2021, BBC News, 2021). Additionally, the Brazilian government does not take sufficient measures to protect the environment and to thereby lessen the environmental impact of the niobium supply chain (Caldeira Rodrigues, 2021; Nadibaidze, 2020; Hanke Vela, 2020). As a solution to the increasing criticality of niobium and the issues related to its supply chain, an urban mining strategy was explored. Niobium-containing HSLA steel is mostly used in long-lasting products, in vehicles, infrastructure and pipelines, which are viable urban mines due to their stable life-span and durability (German Environment Agency, 2020; Giurco et al., 2014). Therefore, urban mining was deemed a feasible strategy to tackle the current challenges related to the production of HSLA steel.

While establishing the scenarios it became clear that the main limiting factors for the production of secondary HSLA steel are the lack of a recycling technology which enables adequate sorting of different steel types and the currently limited amount of available urban mines. Firstly, most niobium containing HSLA-steel is recycled, however, due to the lack of sorting, it gets diluted in the recycling process when it is melted together with other steels. As a result, the niobium concentration declines, and the steel loses its strengthening properties (Graedel et al., 2011; Kurlyak, 2016; Deloitte, 2015; Ohno et al., 2015). Secondly, as most buildings and pipelines containing HSLA steel will not become urban mines for the next decade, the only urban mines currently available are ELVs. Consequently, the potential amount of secondary HSLA steel is limited to the amount of HSLA steel in ELVs (Kurlyak, 2016, Cunningham, 1998; Jansto, 2021). Furthermore, the lack of a policy framework to promote the market for secondary CRMs in the European Union was identified as another contributing factor to the low functional recycling rate of niobium (McDowall et al., 2017; Domenech & Bahn-Walkowiak, 2019). Finally, the possibility of a bottleneck due to trade restrictions imposed by the Brazilian government against the European Union was identified as the main current threat to the stability of the niobium supply chain (Nadibaidze, 2020, Hanke Vela, 2020; Caldeira Rodrigues, 2021; Korinek & Kim, 2010). Based on these factors, three scenarios were adopted to respectively explore how the implementation of a new recycling technology, the adoption of circular economy policies as part of the European Green Deal and a sudden bottleneck due to trade restrictions would lead to an increased EOL-RIR and impact the niobium supply chain.

These recycling input rates were then incorporated in the EIO analysis. The results from EIO models have shown that in each scenario the amount of inputs needed as well as waste and emissions generated could be decreased which is due to the strongly reduced resources consumed in the recycling process in comparison to primary production. The further ahead the scenario lies in the future, the higher the recycling input rate and thus, the lower the emissions and wastes created along the supply chain. Therefore, the adoption of an urban mining strategy leads to less tailings and overburden having to be disposed of on a landfill site, which lightens the negative environmental impact on the direct environment of the mine. Also, the generation of CO_2 and other GHGs is significantly decreased when an urban mining strategy is implemented due to which the contribution of the niobium production to climate change on a global level can be reduced.

In a final step, the supply risk and, thus, the change in niobium's criticality was evaluated for each scenario adopting the EC's framework for criticality assessment. In all three scenarios a significant reduction of the supply risk could be observed due to the increase in EOL-RIR. The higher the recycling input rate, the lower the supply risk and the lower niobium's overall criticality. Therefore, the lowest criticality could be achieved in the government-based scenario which implied the highest EOL-RIR of 30% and a decrease in supply risk of 1.15 points from

3.9 in the linear case to 2.75 in the circular model. These results show that the adoption of a circular economy strategy has a strong mitigating impact not only on the environmental implications, but also on the criticality of niobium. Also, through circular economy, the European Union becomes less dependent on Brazil as the main producing country of ferro-niobium. However, even a recycling input rate of 30% is not sufficient to completely offset the criticality of niobium as the criticality threshold of 1 for SR (European Commission, 2020a) is still exceeded.

This thesis contributes to academia by exceeding the scope of the current state of research on niobium which mainly focuses on life cycle assessments (Dolganova et al., 2020; Alves & dos Reis Coutinho, 2019) but rarely goes beyond the end-of-life state of products containing niobium to look for future strategies to improve the status quo (Golroudbary et al., 2019). Furthermore, the need for further research on CRMs is emphasized, as recycling as the only strategy will not solve the issues related to the niobium supply chain. Therefore, future research on the topic of CRMs might focus on the two main measures which can be taken to reduce criticality, recycling and substitution (European Commission, 2020a). In this thesis it has been manifested that a high EOL-RIR is necessary to offset the criticality of niobium. Consequently, further research on strategies, technologies and innovation which lead to a higher recycling input rate is necessary. In addition to recycling, research on possible substitutes for niobium as a strengthening component could further contribute to secure the production and supply of HSLA steel. Currently there is no viable alternative to niobium as all potential substitutes either involve higher costs and/or a lower performance than niobium. However, substitutes are important contributors to decrease a material's criticality and should therefore not be overlooked in research.

Additionally, this thesis constitutes a call for action for both politics and the economy. Until now, little effort has been made to decrease niobium's criticality. Legislators in the European Union should make use of possibilities to implement policies in the context of the European Green Deal to promote the market of secondary CRMs in the EU and thus lower the dependence on producing countries of primary CRMs. In the light of the high projected demand growth for niobium, a decrease in EI below the criticality threshold of 2.8 is extremely unlikely (European Commission, 2020a). Therefore, the legislator should focus on strategies which aim at decreasing SR and help prevent a bottleneck scenario and ensure a stable supply. Also, with the establishment of policies the legislator would not only protect economic growth but also the environment by decreasing the emission of GHGs and the production of wastes as this thesis has highlighted. Thus, a contribution towards the achievement of the United Nation's sustainability goals could be made.

The results have shown that urban mining is a viable strategy to both reduce niobium's criticality and mitigate its supply chain's negative impact on the environment. However, to achieve this goal, joint efforts of the companies acting in the niobium supply chain and the government are needed as not just the government is responsible to ensure the supply chains of CRMs. Also, individual companies should look for strategies which lower their vulnerability to a decline in supply and invest in innovations which increase the recycling input rate of niobium-containing HSLA steel. Furthermore, these companies could lower their carbon footprint by adopting a circular economy strategy for their raw materials.

In conclusion, urban mining is a feasible and sustainable strategy to positively impact niobium's criticality and mitigate its supply chain's environmental implications. Additionally, the European Union would become less dependent on Brazil, a country which faces strong economic, environmental, social and political issues and thus preventing a shortage of supply. However, joint efforts of academia, politics and companies are needed to reduce the supply risk as well as the environmental implications. Even though circular economy has a high potential in all scenarios to reduce SR, an even higher recycling input rate or a mix of a recycling and a substitution strategy is necessary to reduce SR below the criticality threshold of 1 and offset niobium's criticality.

7. References

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8. Appendix

Appendix I: Overview inputs and outputs

Table 20: Overview inputs, outputs, waste & by-products, their sources, adjustments and further use in the niobium supply chain

Input	**Quantity**	**Data source**	**Adjustments**	**Further use**
Water	8442 l	Dolganova et al., 2020	8442l in total for the first three processes, one third distributed to each process, adjusted to the production of 0.65t of FeNb	/
Clay	19.16 t	Dolganova et al., 2020	19.16t in total for the first three processes, one third distributed to each process, adjusted to the production of 0.65t of FeNb	/
Electricity	14.16 GJ	CBMM, 2019	14.16 GJ in total for the first three processes, one third distributed to each process, adjusted to the production of 0.65t of FeNb	/
Hydrochloric acid	0.17 t	Alves & dos Reis Coutinho, 2019; Dolganova et al., 2020	adjusted to the production of 0.65t of FeNb	/
Aluminium powder	0.34 t	Dolganova et al., 2020; Albrecht et al., 2011	adjusted to the production of 0.65t of FeNb	/
Fluorite	0.04 t	Dolganova et al., 2020	adjusted to the production of 0.65t of FeNb	/
Iron scrap	0.23 t	Dolganova et al., 2020; Albrecht et al., 2011	adjusted to the production of 0.65t of FeNb	/
Granulated lime	0.03 t	Dolganova et al., 2020; CBMM, 2019	adjusted to the production of 0.65t of FeNb	/
Manganese		Patterson & Lippert, 2020	adjusted to the production of 100 t HSLA steel	/
Iron ore		Golroudbary et al., 2019	adjusted to the production of 100 t HSLA steel	/
Carbon		Golroudbary et al., 2019	adjusted to the production of 100 t HSLA steel	/
Silicone		Patterson & Lippert, 2020	adjusted to the production of 100 t HSLA steel	/
Electricity		Golroudbary et al., 2019	adjusted to the production of 100 t HSLA steel	/
Output	**Quantity**	**Data source**	**Adjustments**	**Further use**
HSLA steel		100 t	/	/
Waste & by-products	**Quantity**	**Source**	**Adjustments**	**Further use**
Barite	3.7 t	Dolganova et al., 2020	adjusted to the production of 0.65t of FeNb	sold as valuable output

Magnetite	2.92 t	Dolganova et al., 2020	adjusted to the production of 0.65t of FeNb	sold as valuable output
Tailings	35.65 t	Dolganova et al., 2020	adjusted to the production of 0.65t of FeNb	Landfill
Overburden	19.16 t	Dolganova et al., 2020	adjusted to the production of 0.65t of FeNb	Landfill
Water	8442 l	Dolganova et al., 2020	adjusted to the production of 0.65t of FeNb	Reutilization
CO_2 equivalent	0.62 t	CBMM, 2019	adjusted to the production of 0.65t of FeNb	Emission
CO_2 equivalent	183 t	Golroudbary et al., 2019	adjusted to the production of 100 t HSLA steel	Emission

Appendix II: EIO tables

Table 21: EIO table, linear case

Intermediate Flows Matrix (Z Matrix)	unit	**P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb_2O_5 concentration)**	**P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb_2O_5)**	**P3: FeNb production, process output: ferro-niobium (65% Nb_2O_5 concentration)**	**P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)**	**Final Demand**	**X**
P1: Ore extraction & transportation	**t**	**0**	**42.21**	**0**	**0**	**0**	**42.21**
P2: Ore concentration	**t**	**0**	**0**	**1.06**	**0**	**0**	**1.06**
P3: FeNb production	**t**	**0**	**0**	**0**	**0.65**	**0**	**0.65**
P4: HSLA steel production	**t**	**0**	**0**	**0**	**0**	**100**	**100**

Primary Resources Matrix (R Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**R**
R2: Water	l	2814	2814	2814	0	8442
R3: Clay	t	6.39	6.39	6.39	0	19.17
R4: Electricity	GJ	4.72	4.72	4.72	5990.58	6004.74
R5: Hydrochloric acid	t	0	0.17	0	0	0.17
R6: Aluminium powder	t	0	0	0.34	0	0.34
R7: Fluorite	t	0	0	0.04	0	0.04

R8: Iron scrap	t	0	0	0.23	0	0.23
R9: Granulated lime	t	0	0	0.03	0	0.03
R10: Manganese	t	0	0	0	1.56	1.56
R11: Iron ore	t	0	0	0	94.8	94.8
R12: Carbon	t	0	0	0	0.19	0.19
R13: Silicone	t	0	0	0	0.23	0.23

Waste & By-products Matrix (W Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	W
W1: Barite	t	3.7	0	0	0	3.7
W2: Magnetite	t	2.92	0	0	0	2.92
W3: Tailings	t	11.88	11.88	11.88	0	35.64
W4: Overburden	t	6.39	6.39	6.39	0	19.17
W5: Water	l	2814	2814	2814	0	8442
W6: CO2 equivalent	t	0.21	0.21	0.21	183	183.63

Table 22: EIO table, resource-based scenario

Intermediate Flows Matrix (Z Matrix)	unit	**P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)**	**P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)**	**P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)**	**P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)**	**P5: Recycling of ELVs, secondary HSLA steel production**	**Final Demand**	**X**
P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)	**t**	**0**	**36.79**	**0**	**0**	**0**	**0**	**36.79**
P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)	**t**	**0**	**0**	**0.92**	**0**	**0**	**0**	**0.92**
P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)	**t**	**0**	**0**		**0.57**	**0**	**0**	**0.57**
P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)	**t**	**0**	**0**	**0**	**0**	**0**	**87.15**	**87.15**
P5: Recycling of ELVs, secondary HSLA steel production	**t**	**0**	**0**	**0**	**0**	**0**	**12.85**	**12.85**

Primary Resources Matrix (R Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs, secondary HSLA steel production**	**R**

R2: Water	l	2454.73	2454.73	2454.73	0	0	7364.18
R3: Clay	t	5.57	5.57	5.57	0	0	16.70
R4: Electricity	GJ	4.11	4.11	4.11	5221.16	85.97	5319.46
R5: Hydrochloric acid	t	0	0.15	0	0	0	0.15
R6: Aluminium powder	t	0	0	0.29	0	0	0.29
R7: Fluorite	t	0	0	0.03	0	0	0.03
R8: Iron scrap	t	0	0	0.20	0	0	0.20
R9: Granulated lime	t	0	0	0.02	0	0	0.02
R10: Manganese	t	0	0	0	1.36	0	1.36
R11: Iron ore	t	0	0	0	82.62	0.00	82.62
R12: Carbon	t	0	0	0	0.17	0.00	0.17
R13: Silicone	t	0	0	0	0.20	0.00	0.20

Waste & By-products Matrix (W Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs**	**W**
W1: Barite	t	3.23	0	0	0	0	3.23
W2: Magnetite	t	2.55	0	0	0	0	2.55
W3: Tailings	t	10.37	10.37	10.37	0	0	31.10
W4: Overburden	t	5.57	5.57	5.57	0	0	16.71
W5: Water	l	2454.73	2454.73	2454.73	0	0	7364.18
W6: CO2 equivalent	t	0.18	0.18	0.18	159.48	2.31	162.34

Table 23: EIO table, technology based scenario, recycling rate = 100%

Intermediate Flows Matrix (Z Matrix)	**unit**	**P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)**	**P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)**	**P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)**	**P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)**	**P5: Recycling of ELVs, secondary HSLA steel production**	**Final Demand**	**X**
P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)	**t**	**0**	**33.36**	**0**	**0**	**0**	**0**	**33.36**
P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)	**t**	**0**	**0**	**0.84**	**0**	**0**	**0**	**0.84**
P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)	**t**	**0**	**0**	**0**	**0.51**	**0**	**0**	**0.51**
P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)	**t**	**0**	**0**	**0**	**0**	**0**	**79.04**	**79.04**
P5: Recycling of ELVs, secondary HSLA steel production	**t**	**0**	**0**	**0**	**0**	**0**	**20.96**	**20.96**

Primary Resources Matrix (R Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs, secondary**	**R**

						HSLA steel production	
R2: Water	l	2226.29	2226.29	2226.29	0	0	6678.88
R3: Clay	t	5.05	5.05	5.05	0	0	15.15
R4: Electricity	GJ	3.73	3.73	3.73	4735.29	140.22	4886.70
R5: Hydrochloric acid	t	0	0.13	0	0	0	0.13
R6: Aluminium powder	t	0	0	0.27	0	0	0.27
R7: Fluorite	t	0	0	0.03	0	0	0.03
R8: Iron scrap	t	0	0	0.18	0	0	0.18
R9: Granulated lime	t	0	0	0.02	0	0	0.02
R10: Manganese	t	0	0	0	1.23	0	1.23
R11: Iron ore	t	0	0	0	74.93	0.00	74.93
R12: Carbon	t	0	0	0	0.15	0.00	0.15
R13: Silicone	t	0	0	0	0.18	0.00	0.18

Waste & By-products Matrix (W Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs**	**W**
W1: Barite	t	2.93	0	0	0	0	2.93
W2: Magnetite	t	2.31	0	0	0	0	2.31
W3: Tailings	t	9.40	9.40	9.40	0	0	28.21
W4: Overburden	t	5.05	5.05	5.05	0	0	15.16
W5: Water	l	2226.29	2226.29	2226.29	0	0	6678.88
W6: CO2 equivalent	t	0.16	0.16	0.16	144.64	3.77	148.91

Table 24: EIO table, technology based scenario, recycling rate = 85%

Intermediate Flows Matrix (Z Matrix)	**unit**	**P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)**	**P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)**	**P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)**	**P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)**	**P5: Recycling of ELVs, secondary HSLA steel production**	**Final Demand**	**X**
P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)	**t**	**0**	**34.69**	**0**	**0**	**0**	**0**	**34.69**
P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)	**t**	**0**	**0**	**0.87**	**0**	**0**	**0**	**0.87**
P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)	**t**	**0**	**0**	**0**	**0.53**	**0**	**0**	**0.53**
P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)	**t**	**0**	**0**	**0**	**0**	**0**	**82.18**	**82.18**
P5: Recycling of ELVs, secondary HSLA steel production	**t**	**0**	**0**	**0**	**0**	**0**	**17.82**	**17.82**

Primary Resources Matrix (R Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs, secondary**	**R**

						HSLA steel production	
R2: Water	l	2314.85	2314.85	2314.85	0	0	6944.55
R3: Clay	t	5.25	5.25	5.25	0	0	15.75
R4: Electricity	GJ	3.88	3.88	3.88	4923.64	119.19	5054.47
R5: Hydrochloric acid	t	0	0.14	0	0	0	0.14
R6: Aluminium powder	t	0	0	0.28	0	0	0.28
R7: Fluorite	t	0	0	0.03	0	0	0.03
R8: Iron scrap	t	0	0	0.19	0	0	0.19
R9: Granulated lime	t	0	0	0.02	0	0	0.02
R10: Manganese	t	0	0	0	1.28	0	1.28
R11: Iron ore	t	0	0	0	77.91	0.00	77.91
R12: Carbon	t	0	0	0	0.16	0.00	0.16
R13: Silicone	t	0	0	0	0.19	0.00	0.19

Waste & By-products Matrix (W Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs**	**W**
W1: Barite	t	3.04	0	0	0	0	3.04
W2: Magnetite	t	2.40	0	0	0	0	2.40
W3: Tailings	t	9.78	9.78	9.78	0	0	29.33
W4: Overburden	t	5.25	5.25	5.25	0	0	15.76
W5: Water	l	2314.85	2314.85	2314.85	0	0	6944.55
W6: CO2 equivalent	t	0.17	0.17	0.17	150.40	3.21	154.12

Table 25: EIO table, technology based scenario, recycling rate =70%

Intermediate Flows Matrix (Z Matrix)	unit	**P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)**	**P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)**	**P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)**	**P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)**	**P5: Recycling of ELVs, secondary HSLA steel production**	**Final Demand**	**X**
P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)	**t**	**0**	**36.02**	**0**	**0**	**0**	**0**	**36.02**
P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)	**t**	**0**	**0**	**0.90**	**0**	**0**	**0**	**0.90**
P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)	**t**	**0**	**0**	**0**	**0.55**	**0**	**0**	**0.55**
P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)	**t**	**0**	**0**	**0**	**0**	**0**	**85.33**	**85.33**
P5: Recycling of ELVs, secondary HSLA steel production	**t**	**0**	**0**	**0**	**0**	**0**	**14.67**	**14.67**

Primary Resources Matrix (R Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs, secondary HSLA steel production**	**R**

R2: Water	l	2403.41	2403.41	2403.41	0	0	7210.22
R3: Clay	t	5.45	5.45	5.45	0	0	16.35
R4: Electricity	GJ	4.03	4.03	4.03	5112.00	98.16	5222.24
R5: Hydrochloric acid	t	0	0.14	0	0	0	0.14
R6: Aluminium powder	t	0	0	0.29	0	0	0.29
R7: Fluorite	t	0	0	0.03	0	0	0.03
R8: Iron scrap	t	0	0	0.19	0	0	0.19
R9: Granulated lime	t	0	0	0.02	0	0	0.02
R10: Manganese	t	0	0	0	1.33	0	1.33
R11: Iron ore	t	0	0	0	80.89	0.00	80.89
R12: Carbon	t	0	0	0	0.16	0.00	0.16
R13: Silicone	t	0	0	0	0.20	0.00	0.20

Waste & By-products Matrix (W Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs**	**W**
W1: Barite	t	3.16	0	0	0	0	3.16
W2: Magnetite	t	2.50	0	0	0	0	2.50
W3: Tailings	t	10.15	10.15	10.15	0	0	30.45
W4: Overburden	t	5.45	5.45	5.45	0	0	16.36
W5: Water	l	2403.41	2403.41	2403.41	0	0	7210.22
W6: CO2 equivalent	t	0.18	0.18	0.18	156.15	2.64	159.32

Table 26: EIO table, government based scenario

Intermediate Flows Matrix (Z Matrix)	unit	**P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)**	**P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)**	**P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)**	**P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)**	**P5: Recycling of ELVs, secondary HSLA steel production**	**Final Demand**	**X**
P1: Ore extraction & transportation, process output: raw pyrochlore ore (2.5% Nb2O5 concentration)	**t**	**0**	**29.55**	**0**	**0**	**0**	**0**	**29.55**
P2: Ore concentration, process output: refined pyrochlore concentrate (60-62% Nb2O5)	**t**	**0**	**0**	**0.74**	**0**	**0**	**0**	**0.74**
P3: FeNb production, process output: ferro-niobium (65% Nb2O5 concentration)	**t**	**0**	**0**	**0**	**0.46**	**0**	**0**	**0.46**
P4: HSLA steel production, process output: HSLA steel (0.1% Nb concentration)	**t**	**0**	**0**	**0**	**0**	**0**	**70**	**70**
P5: Recycling of ELVs, secondary HSLA steel production	**t**	**0**	**0**	**0**	**0**	**0**	**30**	**30**

Primary Resources Matrix (R Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs, secondary**	**R**

						HSLA steel production	
R2: Water	l	1971.67	1971.67	1971.67	0	0	5915.00
R3: Clay	t	4.47	4.47	4.47	0	0	13.41
R4: Electricity	GJ	3.30	3.30	3.30	4193.70	200.70	4404.31
R5: Hydrochloric acid	t	0	0.12	0	0	0	0.12
R6: Aluminium powder	t	0	0	0.24	0	0	0.24
R7: Fluorite	t	0	0	0.03	0	0	0.03
R8: Iron scrap	t	0	0	0.16	0	0	0.16
R9: Granulated lime	t	0	0	0.01	0	0	0.01
R10: Manganese	t	0	0	0	1.09	0	1.09
R11: Iron ore	t	0	0	0	66.36	0.00	66.36
R12: Carbon	t	0	0	0	0.13	0.00	0.13
R13: Silicone	t	0	0	0	0.16	0.00	0.16

Waste & By-products Matrix (W Matrix)	**unit**	**P1: Ore extraction & transportation**	**P2: Ore concentration**	**P3: FeNb production**	**P4: HSLA steel production**	**P5: Recycling of ELVs**	**W**
W1: Barite	t	2.59	0	0	0	0	2.59
W2: Magnetite	t	2.05	0	0	0	0	2.05
W3: Tailings	t	8.33	8.33	8.33	0	0	24.98
W4: Overburden	t	4.47	4.47	4.47	0	0	13.42
W5: Water	l	1971.67	1971.67	1971.67	0	0	5915.00
W6: CO2 equivalent	t	0.15	0.15	0.15	128.10	5.40	133.94