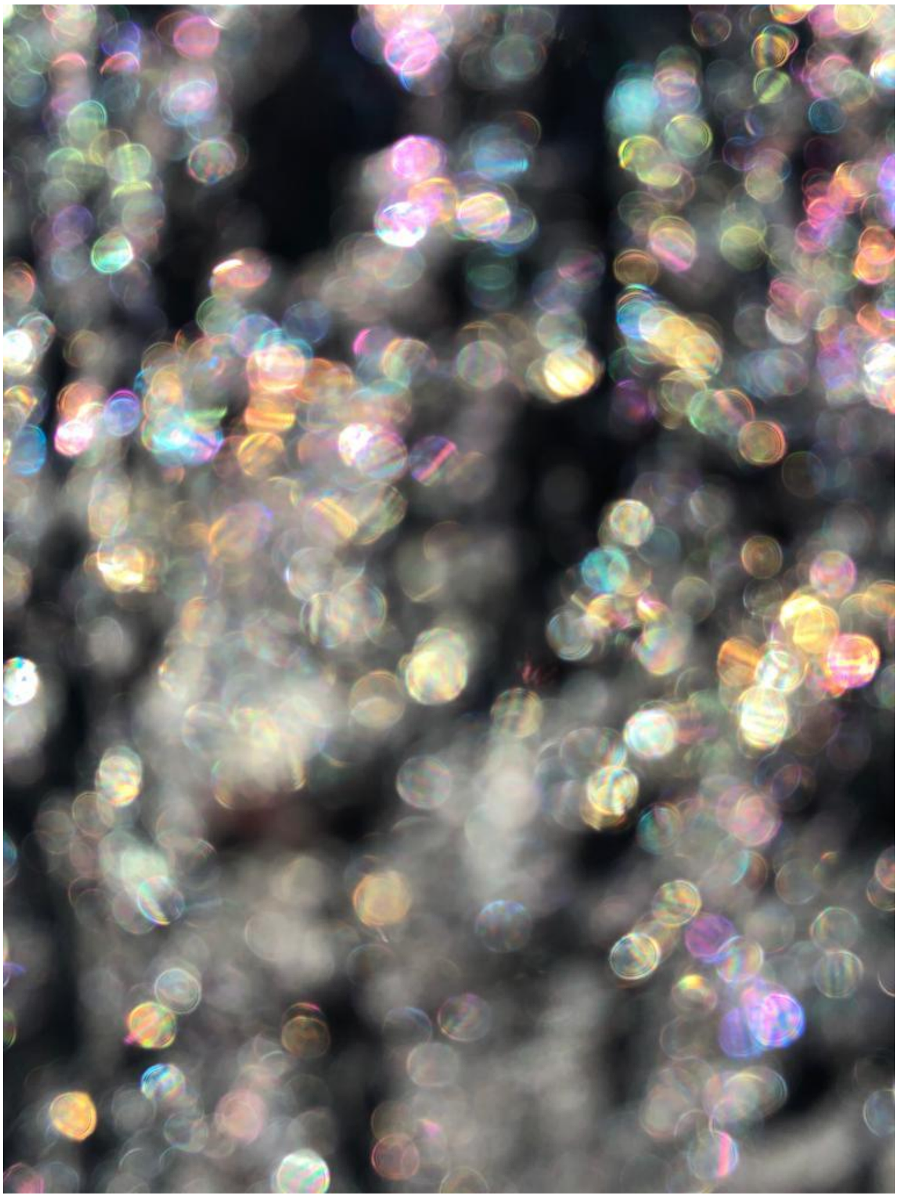
THE SILICON CARBIDE INDUSTRY IN THE SPOTLIGHT

ENERGY INTENSIVE INDUSTRIES (EIIS) AND THE SUSTAINABILITY TRANSITION



Close-up shot of a piece of silicon carbide in the sunlight (own picture)

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Abstract

Transitioning of energy intensive industries (EIIs) towards more sustainability forms an important building block in achieving the Paris climate goals. Silicon carbide (SiC) production is such an EII, though it has not yet received much attention in systemic research. This thesis attempts to fill this gap by studying how SiC flows through the global economy. The objectives are to describe the SiC supply chain, quantify its flows and analyse the supply chain's resilience. **Findings:** The global SiC production capacity constitutes 1 000 000 t per year. With 55.34% the Asia Pacific region is the biggest producer, followed by Europe with 32.7%, rest of world with 7.96% and North America with 4%. In order of quantity, abrasives, metallurgy, refractories, technical ceramics, other industrial uses, semiconductors and jewellery are the main applications of SiC. Around 5% of the material is recycled (USGS, 2021). High energy requirements in SiC production, as well as strict emission regulations are identified as the main supply risks. Substitution, use reduction, recycling and stockpiling can only minimally absorb supply disturbances at their current state. However, recycling is currently a popular topic in the industry and under development. In the mid-term, recycling activities might become a way to increase supply chain resilience. Another strategy that could lower pressure on the supply chain is using SiC production to balance the energy grid. That is, to produce when there is an oversupply of energy and to halt production when there is a shortcoming. **Implications:** This thesis shows that sustainability efforts in the SiC industry are not only environmentally desirable, but might also add to its supply chain's resilience. The case of SiC shows that small EIIs that have so far not received much attention can offer high returns in terms of knowledge gained.

Table of Content

Abbreviations

Abbreviation	What
CO_2	Carbon dioxide
CO_2-eq.	CO_2 equivalent
EII	Energy Intensive Industries
EOL	End-of-life
GaN	Gallium nitride
GJ	Gigajoules
Gt	Giga tons
HF	High frequency applications
IGBT	Insulated-gate bipolar transistor
Kt	Kilotons
LCA	Life Cycle Assessment
MOSFET	Metal-oxide-semiconductor field-effect transistor
PE	Power electronics applications
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals, EU regulation
RoW	Rest of World
Si	Silicon
SiC	Silicon carbide
t	tonnes
WBG	Wide Band Gap

1 Introduction

The transitioning of energy intensive industries (EIIs) towards more sustainability forms an important building block in achieving the Paris climate goals (Hildingsson et al. (2019); de Bruyn et al. (2020)). Approaches such as material efficiency strategies can help reduce emissions (Baars et al., 2022) and make EIIs more sustainable. However, sustainability transitions also bear the risk of problem shifting when taking a too narrow perspective. That is, industries might adapt to regulation and changes that lead to more pollution or energy use somewhere else. Especially as EIIs usually form part of a complex supply chain which operates in a global environment, a systemic perspective is necessary to avoid problem shifting. Thus, to understand where sustainability strategies might have the largest impact, it is necessary to look at the bigger picture.

One tool that applies such systemic thinking is material flow analysis (MFA). MFA can help assess the potential of different material efficiency strategies (Baars et al., 2022). Larger EIIs such as iron and steel, cement, fertilizers or aluminium have already received considerable attention with regards to their decarbonisation options (de Bruyn et al., 2020) and approaches exist which investigate them from a systems perspective, e.g. Cao et al. (2017) for cement or Liu and Müller (2013) for aluminium. However, smaller EIIs often remain under the radar of researchers and policy-makers.

One such smaller industry is silicon carbide (SiC) production. Its energy intensity is illustrated by the fact that the only producer of SiC in the Netherlands is the 8th largest individual consumer of electricity in the country (Xavier & Oliveira, 2021). The highly energy intensive and polluting production of SiC shows a need for change towards more sustainability. Still, research on SiC tends to focus on its chemical and material properties, with one recent exception, a report by the Dutch Environmental Assessment Agency on the decarbonisation options of the Dutch SiC industry (Xavier & Oliveira, 2021). Thus, no comprehensive efforts exist that investigate SiC from a systems perspective.

This study aims to address this knowledge and data gap by answering the research question: *"How does SiC flow through the global economy?".* In investigating this question, this research aims to describe the SiC supply chain, quantify its flows and analyse its supply chain by taking a resilience perspective.

With rising energy prices, EIIs come under pressure and might face supply issues. The supply chain is analysed to provide insights into potential threats to supply and investigate potential sustainability strategies and their effects on the supply chain. For instance, environmental regulations might form a supply risk or volatile supply chains might hinder sustainability efforts. Again a systems perspective is beneficial, as in complex systems such as global supply chains, a disruption in one place can have effects elsewhere (Sprecher et al., 2017). For these reasons, systemic sustainability efforts need to take the supply chain into account.

Instead of directly assessing sustainability strategies, I aim to create a knowledge base upon which other researchers can build. Knowledge on the whole (global) SiC production and its use cases should help policy-makers and researchers with designing sustainability strategies. This is done by synthesizing information from primary and grey literature. Further gaps are filled by conducting expert interviews. Results are presented in the form of a MFA and a supply chain resilience analysis.

The following section provides background information on SiC and its production process. It is followed by a methods and data section. Afterwards, the results of the material flow analysis and the supply chain resilience analysis are presented. The discussion summarizes and interprets the results and discusses limitations of the research. The thesis closes with concluding remarks and recommendations for future research.

2 Background

This section provides some background on how SiC was discovered and on its appearance and characteristics. Following, the production process and energy requirements for production are described. This helps to further understand SiC as a material and the sustainability challenges it faces.

2.1 What is SiC?

SiC is a chemical compound made up of silicon and carbon. It was discovered in 1891 by Edward G. Acheson while trying to produce artificial diamonds (Britannica, 2022). Only a few years later, Henri Moissan found naturally occurring SiC in Arizona in the Canyon Diablo meteorite (Britannica, 2022). It is also due to him that the mineral got its name “moissanite”. Different terms are used in different industries to refer to silicon carbide. For instance, the company founded by Acheson refers to the material as “carborundum”, whereas the jewellery industry uses “moissanite” to specifically refer to the mineral.

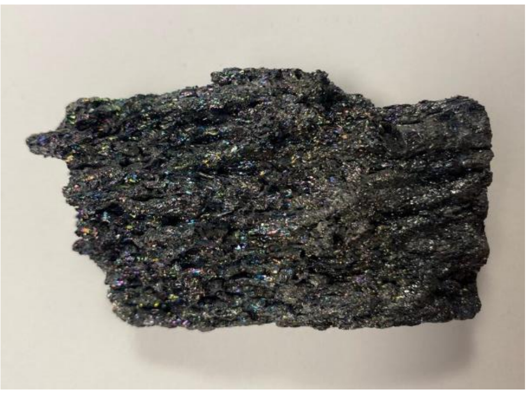

Figure 1 Picture of a SiC crystal (own picture)

Besides the different names, SiC occurs in many forms and shapes. For instance, SiC can be classified based on its different polytypes, grain sizes and purities. A further distinction can also be made between alpha and beta SiC, where the difference between the two depends on the location of the material during the production process (Tanaka, 2011). Pure SiC is colourless (Wecht, 1977), but the colour of the material depends on its impurities. Some companies also differentiate between green and black SiC, which depends on the level of impurity of the raw materials ([I])[1]. **Figure 1** shows the picture of a SiC crystal. Different types of SiC are used for different purposes and applications. For the purpose of this thesis the type of SiC is not further distinguished and SiC is viewed as a whole.

SiC distinguishes itself as a material with valuable characteristics for many applications. Namely, the material stands out due to its hardness, high temperature properties, high thermal shock resistance, low thermal extension, high corrosion resistance and high electrical conductivity (ESD SIC bv, 2022). On the Moh scale, which measures the hardness of materials, SiC is the third hardest material on Earth. Due to its hardness SiC is a valuable abrasive material and its high heat temperature properties make it useful in the refractories industry.

2.2 Production process

Since natural deposits of SiC are scarce, practically all of the SiC in use is produced synthetically. The most common process to produce SiC is the Acheson method. Its two main ingredients are silica sand (or quartz) and petroleum coke. The purity of both materials determines the quality of the produced SiC. The Acheson process is mainly used to create SiC for abrasives, metallurgical and refractories industries (Xavier & Oliveira, 2021). **Figure 2** shows a schematic overview of the SiC production process

[1] See Table 1, page 13 for reference overview of interview partners

as currently applied by the Dutch SiC producer ESD SIC bv. It needs to be noted that this plant is recognized as the most environmentally friendly producer of SiC in the industry (Xavier & Oliveira, 2021).

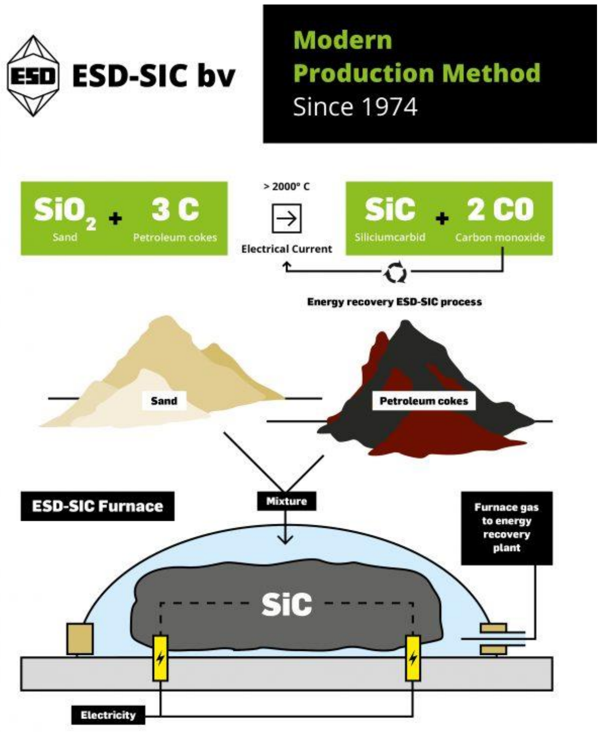

Figure 2 SiC production as currently applied by Dutch SiC producer (ESD SIC bv, 2022)

The production process is highly energy intensive as it requires high temperatures, the temperatures differing per plant and process (Xavier & Oliveira, 2021). For instance, traditional furnace installations consume between 22 and 28 GJ of energy to produce one tonne of 100% pure SiC (European Commission (2007); in Xavier and Oliveira (2021)). Energy consumption did improve somewhat over the last decades, as in 1974 this was still 27-28.8 GJ per tonne of SiC (Fuchs, 1974). However, creating high temperatures also leads to high emissions. For instance, even the Dutch production process which is recognized as most environmentally friendly in the industry still emits around 130 kt of greenhouse gases each year (Xavier & Oliveira, 2021). There are different ways to make the production process more environmentally friendly, such as fuel substitution or changes to the process design (Xavier & Oliveira, 2021). Next to high energy consumption, dust explosions, also known as blazer incidents can be an issue during production. For example, a local media outlet in the Netherlands reported six of these incidents for 2020, which is well below the average of 40 per year in the past (Drent, 2021a). SiC production also has to deal with SiC fibres which are suspected to increase cancer risks and led to a dispute between the province of Groningen and the Dutch SiC producer on how to include this risk in the production permit (Drent, 2021b).

The production of SiC for the semiconductor and jewellery industry do not use the Acheson method as they require much higher purities. Instead, they use SiC to grow a single crystal boule, often with the Lely method (Tanaka, 2011). However, which process current manufacturers apply is hard to find as information on the production process is kept confidential. This is because the knowledge required to produce SiC semiconductors is very high (Karlsson & Robertsson, 2022), which can form an important competitive advantage for companies. Thus, the differing applications of SiC as well as the differences in the production process between industries make it difficult to precisely evaluate energy requirements. This thesis does not further investigate the production process, but focusses on the flow of the material.

3 Method and Data

In the following, the methods material flow analysis (MFA) and supply chain resilience analysis are introduced and discussed. Following, data collection is presented.

3.1 Material Flow Analysis (MFA)

This section starts by discussing some theoretical background of MFA, followed by describing the system boundaries applied in this study. In the next section the treatment of uncertainties is discussed. The final section presents a meaningful categorization of end-uses of SiC.

MFA “quantifies the ways in which the materials that enable modern society are used, reused, and lost” (Graedel, 2019, p. 12188). The tool is a central method of the field of industrial ecology (Graedel, 2019). It is an analysis approach based on mass balancing. Everything that enters the system boundary eventually either needs to leave it or accumulate as a stock in the system. Bringezu & Moriguchi (2002), based on Bringezu and Kleijn (1997), distinguish between six types of MFA. They differ mainly in their objects of primary interest, namely, either substances, materials, products, firms, sectors or regions (Bringezu & Moriguchi, 2002). This thesis applies an MFA with a materials focus, namely looking at SiC.

An MFA system contains three main elements, processes, flows and stocks (Brunner & Rechberger, 2016). A process can be any kind of transport, transformation or storage of material (Brunner & Rechberger, 2016). A flow is material mass per time and a stock is a material reservoir that is part of a process (Brunner & Rechberger, 2016). An MFA system is defined by its temporal and geographical boundaries (Brunner & Rechberger, 2016). The geographic scope can vary from very small scale of individual households to that of the global economy, the latter being what is applied in this thesis. A global perspective is chosen due to low data availability on SiC in general and low quality trade data, which makes setting a country or region as a geographic system boundary difficult. All material production and use of SiC is therefore taken into account.

The temporal boundary in this thesis is one year, making it a static MFA. Ideally, in a static MFA one specific year would be represented in the model. However, in this case this is difficult for several reasons. First, low data availability means that data from a wide time span is used, which makes it difficult to set one specific year. Second, the covid-19 pandemic might make the most recent data unrepresentative of the general system. This means that production was often below pre-pandemic levels. While this is on the one hand a development that is important to consider in the system, with the pandemic being a state of emergency, it also does not give a realistic picture. Third, especially the semiconductor industry is growing quickly. This makes choosing a pre-pandemic year difficult, as this might result in growth in the sector not being taken into account.

Due to these factors, no specific year is chosen as that would be misleading. Instead, the model is constructed for a generalized contemporary year, mainly covering a period of the last five years. Generally, the data from the USGS on silicon carbide shows, that the market is rather stable, at least in the last 28 years for which the USGS reports data. The limitations of choosing no specific year are considered in the uncertainty analysis and are also discussed in section 5.5). In the following analysis the time of this MFA is referred to as “current”. The MFA is carried out in STAN 2.7 (Cencic & Rechberger, 2022).

3.1.1 Uncertainty in MFA

The lack of data mentioned before does not only influence methodological choices such as the geographic focus and the time span, but also has an impact on the results in general. Generally, MFAs are always confronted with the issue of uncertainty (Džubur et al., 2017, p. 464).

There are several ways in which uncertainty can be taken into account in MFA. One of them is the fuzzy set-based approach by Džubur et al. (2017). The approach is based on the assumption that values in MFAs can best be expressed as fuzzy sets. To do so, a classification is developed by Džubur et al. (2017) based on which data sources are put into categories based on their assumed reliability. The framework is based on earlier work by Hedbrant and Sörme (2001) who came up with an approach classifying data with uncertainty intervals and work by Laner et al. (2014) who elaborated on it and compared a probabilistic with a fuzzy set approach (Laner et al., 2015) based on which Džubur et al. (2017) developed their framework. In the framework, the data sources are ranked according to a classification table and depending on their score they get an uncertainty factor assigned (Laner et al., 2015).

Life-Cycle Assessments (LCA), another traditional Industrial Ecology tool, also has to deal with considerable uncertainties. For this purpose the pedigree matrix has been developed (Weidema & Wesnæs, 1996). Similar to the just discussed framework it is also a table which assigns scores to data points. However, it is not about the data source quality (reliability) only, but also takes completeness, temporal correlation, geographical correlation and further technological correlation into account. The usefulness of the pedigree matrix for MFA has also been recognised by Laner et al. (2016) who also note that not only the data quality, but also its representativeness should be taken into account. The addition of expert estimate evaluations in Laner et al. (2016) is valuable for MFA uncertainty assessments.

While the fuzzy set approach is well developed for the application in MFA, it only takes one dimension of uncertainty into account. In cases where data availability is high and the main concern is the reliability of the source, this is a well suited approach. However, in this case data is rather limited and uncertainty comes from many different aspects, hence making the more holistic pedigree matrix better suited.

In this thesis, an adjusted version of the pedigree matrix, based on work by Laner et al. (2016) is used to describe uncertainties in the MFA in a semi-quantitative way. Laner et al. (2016) use the pedigree matrix for data points taken from literature or other sources and have developed an extra category for data points coming from expert estimations. The uncertainty levels are translated to colour codes which are used to visualise the uncertainties in the MFA system diagram. The uncertainty levels, together with more explanation and justifications can be found in the 8.1 in the appendix. A semi-quantitative treatment of uncertainties is chosen. Quantifying uncertainties by representing flows and stocks as ranges would either result in very broad and therefore seemingly meaningless ranges or it would give a false sense of data certainty.

3.1.2 Where is SiC used?

For the MFA it is important to find a meaningful categorization for where SiC is used. Otherwise it can lead to double counting or missing important SiC flows or stocks. However, the simple question of where SiC is used is actually not easy to answer. Does it refer to the industry, country or application where it is used and does usage refer to the industrial process that used SiC or rather to the end-product? These questions can be answered in many different ways. What is most important is that the categorization is useful for its purpose. One can either have a high resolution and go into detailed fields of application or apply a low resolution and summarize end-uses as much as possible. In this case a low resolution is chosen, due to two main reasons. First, a too high resolution quickly becomes chaotic with a large number of stocks and flows and the overview is easily lost. While such a high resolution is useful to get a lot of details of the system, the purpose of this thesis is to rather describe the SiC flow from a systemic perspective, which makes a low resolution with a better overview more suited. Second, it is again a question of data availability, the higher resolution the system, the more data is needed, which is time consuming and would be outside the scope of this thesis.

Kim and Malik (2020) give a useful overview of different applications of SiC: abrasives, mechanical seals, catalytic supports, heating elements, carbon and silicon sources for steel production, filters for molten metals and gases, and foundry crucibles, semiconductor processing parts, mirror materials for astronomical telescopes, matrices for nuclear fuel particles and claddings, power electronic devices, and turbine components. One use missing in this enumeration is that of SiC in the jewellery industry as a diamond alternative. The categorization by Kim and Malik (2020) however is rather detailed and would have high data resolution requirements. This is why for the purpose of this analysis a lower resolution categorization is used. Throughout the research process the following categorization proved to be the most useful: **semiconductor industry** (power electronic devices and other SiC semiconductors), **jewellery**, **abrasives**, **technical ceramics** (filters for molten metals and gases, foundry crucibles and turbine components), **refractories**, **metallurgy** (carbon and silicon sources for steel production) and **other uses** (heating elements, mirror materials for astronomical telescopes, matrices for nuclear fuel particles and claddings). Some of the applications listed by Kim and Malik (2020) might also fall under one of the other categories, depending on how one defines these categories.

In general, SiC as a material belongs to ceramics due to its production process and the definition of the scientific field of ceramics (Wecht, 1977). Wecht (1977) for example clusters refractories and abrasives under the ceramics category. However, in this thesis the two are separate categories, which is mainly due to the different production processes and types of uses which results in different lifetimes and different recycling potentials. Separating them, means that these differences can be better illustrated in the MFA. Nonetheless, it needs to be noted that due to these unclear boundaries between these sectors, there is a risk of double counting, due to different reporting or understanding of the sectors. In general, the categories in this thesis are not clear-cut and overlap exists. The categorization needs to be regarded with caution. In the following each end-use category is introduced individually.

3.1.2.1 Semiconductor

SiC in the semiconductor industry is currently mainly used to replace Si as a semiconductor material in chips. SiC is mainly used for chips in power converters. It is also used as a substrate for GaN chips in high frequency applications such as 5G and radars. The most common SiC packages are IGBTs and MOSFETs, and also diodes for power converters.

3.1.2.2 Jewellery

SiC crystals are used as a diamond alternative in jewellery. One company for a long time had a patent on the process to make SiC gems. However, in 2016 this patent expired in a majority of countries (Charles & Colvard, 2020).

3.1.2.3 Abrasives

Abrasives are “manufactured materials that have been heated or treated chemically in order to remove material by rubbing action or impact” ([m]). Due to its hardness and chemical inertness, SiC is a useful abrasive material. SiC as an abrasive is used in different forms, either as a powder abrasive or in grinding or cutting wheels. The lifetime of abrasives is generally short due to wear-off effects during its application. The grain size of SiC is particularly relevant for the abrasive industry. The Federation of European Producers of Abrasives (FEPA) has also established a standardization for these grain size categories. However, this standardization applies only to Europe, in the US for example, other standards are used ([r]).

3.1.2.4 Refractories

Refractories are materials that can stand temperatures of 1300 °C or more ([n]).This makes SiC with its high heat resistance a suitable refractory material. No real melting point can be observed for SiC, but dissociation and sublimation starts in a reduced atmosphere at around 2000°C (Wecht, 1977). Three main industries that use SiC refractories are waste incineration plants (also biofuel plants), cement production and steel industry ([n]). These industries use SiC in the form of walls that usually protect metal from heat.

3.1.2.5 Ceramics

A broad set of products falls under this category. One example are diesel particulate filters. Other ceramic uses that use SiC are hermetically sealed pumps, sealing and regulatory disks, (switching) valves and others (technical-ceramics.com, 2022). In an info sheet CeramTec shows three examples of technical ceramics offered by them, shown in **Figure 3**. For its use in ceramics, SiC's general wear, temperature and chemical resistance is beneficial as well as its hardness.

Figure 3 Three types of technical ceramics using SiC as produced by CeramTec (CeramTec, 2022)

3.1.2.6 Metallurgy

SiC in metallurgy has mainly two uses. The first is using SiC as an alloy addition to increase the carbon content in steel. The other is using SiC as an alternative source of fuel, replacing ferrosilicon. The second use, replacing ferrosilicon has become more attractive in the very recent past due to steeply rising ferrosilicon prices.

3.1.2.7 Other uses

This category covers uses of SiC that are not covered by any of the other categories. It is used to show that there are also some applications that might not fall under any of the previous categories, but it is also used as a balancing flow in the MFA.

3.2 Supply Chain Resilience Analysis

In addition to the physical flow of the material, the supply chain of SiC is analysed. In this section the theoretical background of supply chain resilience analysis and particularly the definition of resilience is discussed. In addition, I provide a description of how supply chain resilience is applied in this thesis.

First, it is important to define what is meant by the term resilience. Resilience is used in many different disciplines, such as ecology, engineering or psychology, which also use different definitions of resilience and focus on different aspects of the concept. The definition most appropriate in the case of this thesis is the one by Sprecher et al. (2015) who apply the resilience concept to material supply chains and define it as: "the capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available." (p. 2)

Defining a specific quantity necessary to satisfy the demands of society is difficult and can be a very personal evaluation. What might be indispensable to some, might not be of any need to others. Generally, as Sprecher et al. (2015) note for their case study of NdFeB, a certain elasticity in supply and demand is needed, so that disruptions can get absorbed by the system. This is also how resilience is regarded in this research. Quinlan et al. (2016) mention the identification of risks, opportunities and alternate strategies as a common objective of resilient assessment (p.681). Meerow and Newell (2015) point out that more resilience research from an Industrial Ecology perspective would contribute to a better understanding of the relation between resilience and sustainability, as resilience would often be seen as a necessary part of a sustainable system. However, resilient systems might also create lock-in effects as discussed by Sprecher et al. (2015). This might mean that desirable long-term change might be inhibited by resilience. Meerow and Newell (2015) also discuss how resilience could have detrimental effects for sustainability. Their main claim is that Industrial Ecology as a discipline could positively contribute to the understanding of the relation between sustainability and resilience. This is why this thesis applies resilience thinking in an Industrial Ecology context, to get a better understanding of the relationship between a resilient supply chain and sustainability opportunities.

Besides defining the term, it is also important to discuss how resilience can be analysed. The Resilience Alliance (2010) has established a framework with five steps. These five steps are: describing the system, understanding system dynamics, probing system interactions, and evaluating governance, and finally acting on the assessment (Resilience Alliance, 2010, p. 5). This analysis mainly covers the first two steps of the framework. The resilience of the supply chain is studied in a qualitative way. The supply chain and important mechanisms and dynamics of the supply chain are described, but resilience is not quantitatively measured.

In order to describe and understand the supply chain, the framework by Sprecher et al. (2017) is used. The framework contains questions in seven categories: system disturbance, stockpiling, diversity of sources, substitution, use reduction, recycling and feedback loops.

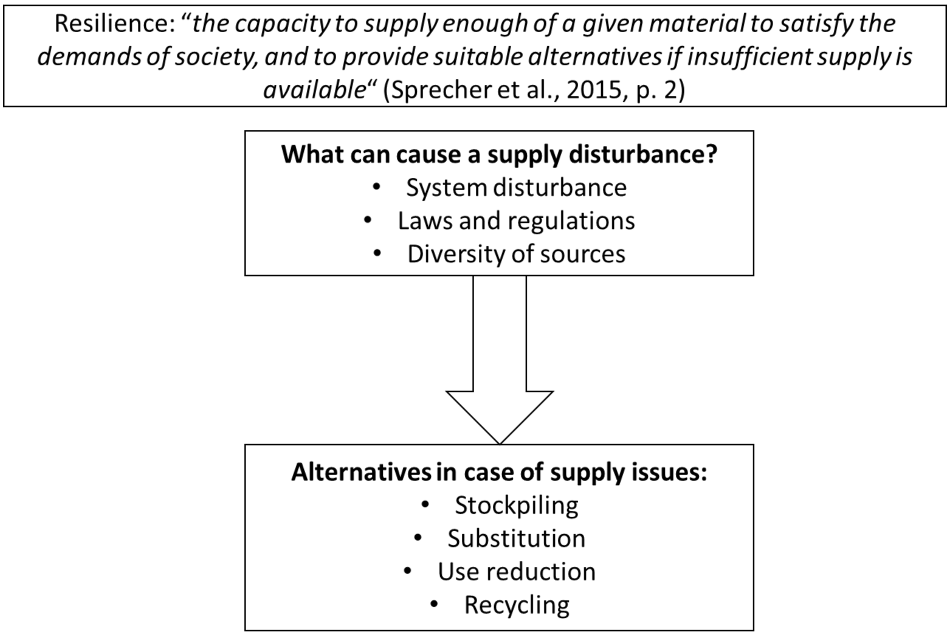

Figure 4 Supply Chain resilience analysis method flow diagram

Figure 4 shows the approach of the supply chain resilience analysis. First, the causes of what could disturb supply are described. This covers the categories of supply disruption, diversity of sources and laws and regulations. Next, the ways in which disturbances can be dealt with are investigated, namely stockpiling, substitution, use reduction, and recycling. The goal of applying this framework is to analyse the interaction between sustainability and supply chain resilience and how one can contribute to the other.

3.3 Data gathering

As a complete picture of flows of SiC is difficult to obtain through primary sources, this research relies on data triangulation, meaning using three different types of data sources, namely interviews, academic literature and grey literature. Interviews form the most direct source and help to fill knowledge gaps in academic and grey literature and help to validate insights derived from the literature.

3.3.1 Interviews

Around 90 companies and experts were contacted, which resulted in 18 interviews on the SiC industry and supply chain. The companies were selected first by contacting the ones that appeared in online searches on the topic and after the first few contacts and interviews, participant selection further continued through snowball-sampling. One channel through which companies from the semiconductor industry were approached, was by going to PCIM Europe, a fair for *Power Electronics, Intelligent Motion, Renewable Energy and Energy Management* that took place in Nuremberg, Germany between May 10th and 12th 2022. During this fair especially big companies in the semiconductor industry were approached on the search for more interview partners. Furthermore, the fair offered a great opportunity to talk to and learn from industry experts about the topic of SiC in electronics.

As the SiC market is rather small, with not many actors and information is often kept confidential, it is chosen to anonymise all interviewees. Table 1 provides an overview of the background of the interviewees, when the interview took place and a letter which is used to refer to the interview. More information on the interviews can be provided by the researcher on request.

Table 1 Interview overview

Description	When	Reference
Small German abrasives manufacturer	01.04.2022	[a]
Manufacturer of ceramics products in Europe	08.04.2022	[b]
European researcher on SiC for the semiconductor industry	11.04.2022	[c]
SiC association	05.05.2022	[d]
European research project on SiC supply chain for semiconductor applications	09.06.2022	[e]
Steel producer	13.05.2022	[f]
SiC semiconductor company 1	28.06.2022	[g]
SiC semiconductor company 2	20.05.2022	[h]
SiC semiconductor company 3	19.05.2022	[i]
Re-seller of SiC for abrasive products	18.05.2022	[j]
Re-seller of SiC for abrasive products	kw22	[k]
European SiC producer	written	[l]
Geological Survey	written	[m]
German Refractories producer	14.06.2022	[n]
German researcher on SiC in ceramics and SiC recycling	14.06.2022	[o]
German SiC recycling company for slurry recycling	24.06.2022	[p]
German abrasives association	written	[q]
Non-European abrasives association	14.07.2022	[r]
Conversations with various people at PCIM	11.05.2022	[s]

The interviews consisted of two main parts. The first part of the interview consisted of company- and sector- specific questions with the goal to gather data for the MFA and to understand the system. These questions varied widely per interview based on the background and expertise of the interviewee. The second part was semi-structured and mainly targeted at data collection for the supply chain resilience analysis. This part used the question framework developed by Sprecher et al. (2017). It covered the seven resilience concepts: system disturbances, stockpiling, diversity, substitution, use reduction, recycling and feedback loops. These seven categories also formed the basis for the coding process.

3.3.2 Grey literature

This data source is rather diverse as it includes a broad field of literature that is covered under the term grey literature. Table 2 shows the most important documents used. Some of them were used as direct sources for the analysis, others were used as background reading to better understand the SiC market.

Table 2 Grey Literature sources overview

Description	Reference
Report by Netherlands Environmental Assessment Agency (PBL) and TNO on the decarbonisation options of the Dutch SiC industry.	(Xavier & Oliveira, 2021)
Industry market report on the SiC market. Only outdated sample version could be accessed. Though due to the non-academic and non-transparent nature of data collection, the information need to be viewed with some caution.	(Grandview Research, 2019)
Report on SiC in semiconductor industry. Information for investors.	(Goldman Sachs, 2019)
US Geological survey, reports on manufactured abrasives. Production capacities per country, substitution, options, recycling and general trends are reported.	(USGS, 2021)
Annual company report, reporting on moissanite. Company that held patent on production process for jewellery for long time.	(Charles & Colvard, 2020)
Silicon Carbide & More Newsletter on industry developments. Reporting on the opening of new plants or new demand developments, but also on laws and regulations affecting the market. The earliest edition that is found is from summer 2003 and the last version that could be found is from April 2015.	(Kennedy, 2005)

3.3.3 Academic literature

This type of data source covers a broad range of articles and are cited wherever used. Table 3 shows the most important documents used. Some of them were used as direct sources for the analysis, others were used as background reading to better understand the SiC market.

Table 3 Overview academic articles

Description	Reference
Article on the SiC market in general from the early 1970s.	(Fuchs, 1974)
Book on SiC used for refractory purposes, though starts with general introduction of SiC.	(Wecht, 1977)
Article that gives an elaborate view on the SiC market, particularly on the different production processes from the perspective of the ceramics industry.	(Tanaka, 2011)
LCA study on Si, SiC and GaN in electric vehicle power electronics, with cradle-to-gate perspective.	(Warren et al., 2015)
Review article on SiC power devices and their application, providing general overview.	(She et al., 2017)
Master thesis that analyses the SiC semiconductor supply chain from the perspective of a large automotive company.	(Karlsson & Robertsson, 2022)

4 Results

The results section is structured around two main parts. The first part presents the results of the MFA, the second part covers the results of the supply chain analysis.

4.1 MFA

The MFA section consists of two main components. It starts off with a review of how SiC has flown through industry and society in the past. Better understanding the flows of SiC in the past can help to uncover dynamics over time, which can help to better understand the current flows of SiC. After a historical review of SiC, the results on the current flows of SiC follow.

4.1.1 Comparing SiC now and in the past

SiC has already been used in past decades. Fuchs (1974) and Wecht (1977) provide valuable insights on SiC from a more systemic perspective on the SiC market of the 1970s. Insights on production capacity per world region are provided as well as some insights on the different end-uses and types of SiC (Fuchs (1974) and Wecht (1977)). **Figure 5** shows the production capacities per region for 1973 based on Fuchs (1974) and the current shares. The data for the current shares is based on various sources, the calculation steps and sources can be found in 8.2 in the Appendix.

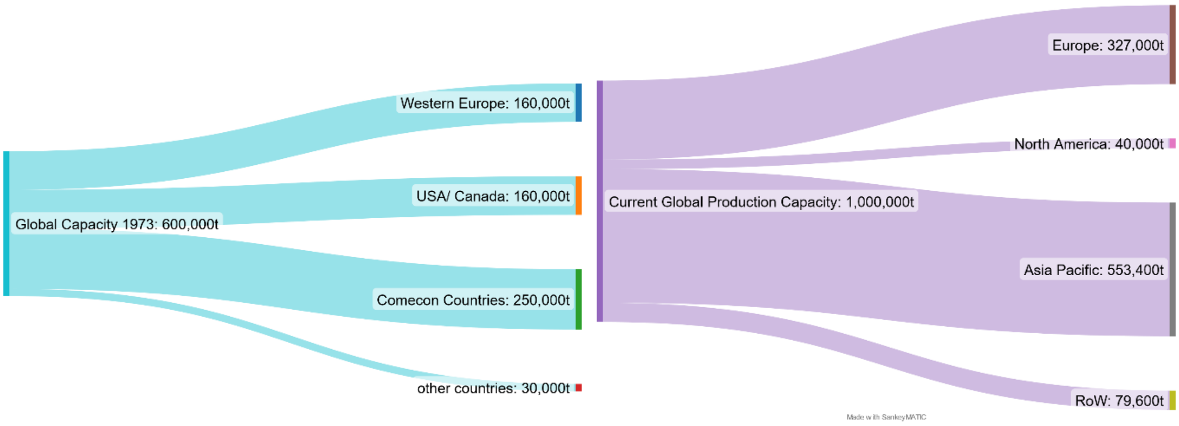

Figure 5 Sankey diagram global SiC production in 1973 (Fuchs, 1974) and current capacity in tons per year

Comparing the two figures, it can be seen that the world production capacity increased. The capacity for USA/Canada in 1974 is higher than the current capacity of North America. This indicates that in this region capacity might have decreased. Also interesting to observe is that the regions with the biggest production capacity changed. While in 1974 it were the Comecon countries (countries from the former Soviet bloc) that had the highest production capacity, currently it is Asia Pacific that is dominating the capacity. In 1974, the Asia Pacific region did not yet play a role, while currently the Comecon capacity is likely split between Europe (Eastern European countries) and some falling under the rest of world (RoW) countries.

The capacity before 1970 is also interesting, Fuchs (1974) notes that in 1960 the West-European production capacity was only 75 000 tons per year. Comparing it to the 1970s numbers (160 000t in Western Europe) this shows an important increase in capacity in that period. In 1973 the Elektroschmelzwerk Delfzijl (ESD) was founded in the Netherlands, which is the only producer of SiC in the Netherlands and an important global player in the SiC market. This shows that the 1970s period seems to have been a period of growth in the SiC market and SiC becoming more important and widely used.

Table 4 Sectors using SiC 1977 (Wecht, 1977)

Uses (rank ordered)	For what	Type of SiC
Ferrous metallurgy	Deoxidation of steel and for easier processing of the steel	90% SiC content (sometimes even less)
Ceramic Industry	Abrasives and Refractories	95-99% SiC content in rare cases also 90%
Electrical heating elements and resistors	Using electrical characteristics of SiC	99,5-99,9% SiC content
Other uses	Nuclear or special electrical uses in form of single crystals (no economic significance yet)	99,9% or more SiC content

Table 4 shows the sectors using SiC, ordered by their size based on the reports of Wecht (1977). This can unfortunately only be presented qualitatively, as no percentages or other quantitative size indications of the uses are given. It is only noted that the electrical heating elements and resistors follow the other two uses with a big distance (Wecht, 1977). Wecht (1977) notes that there were no public statistics about the SiC production.

Public statistics at least for the US, become available from 1996 in the mineral commodity summaries. In this reporting SiC is covered under “manufactured abrasives”. The earliest data reported is from 1994. The data shows that generally the SiC market is rather stable in the past 20 or more years. There are two main noteworthy changes. The first one is the rapid increase in capacity in China in 1996, when capacity increased from 250 000t to 450 000t per year. The other observation to note is the variability of the capacity of the US and Canada capacity in 2001 and 2003. The decrease in 2001 can be explained by the only Canadian producer ending its production (USGS). Except for these comparably drastic changes, the SiC capacity based on this data seems stable over the last two decades.

4.1.2 Current data

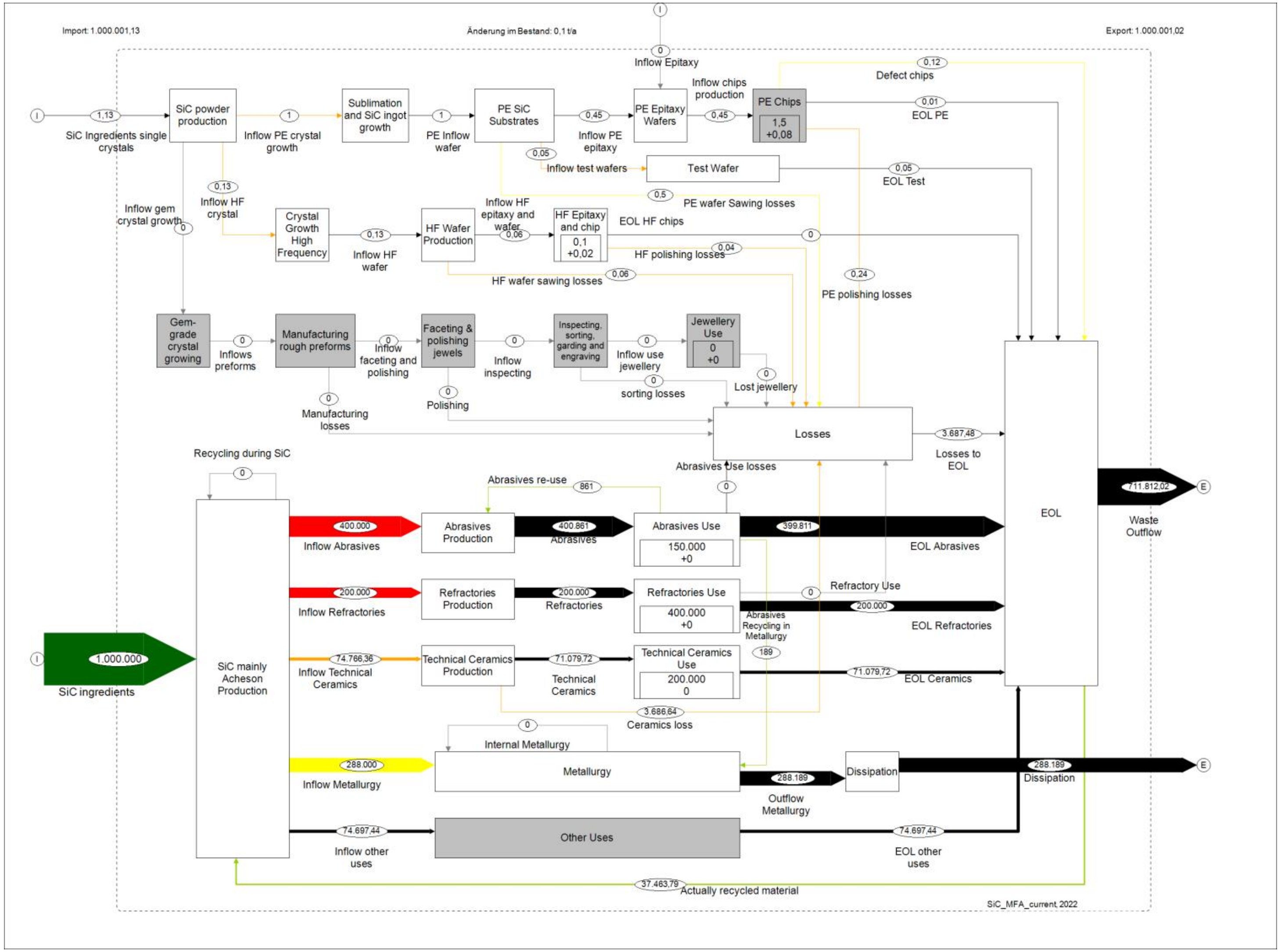

Figure 6 SiC Global MFA, system visualization in STAN

Figure 6 shows the MFA in visual form made in STAN. Coloured flows represent the results of the uncertainty analysis (dark green: 1, light green: 2, yellow: 3, orange: 4, red: 5). The black flows are not directly based on data but logically follow from earlier flows. Flows or processes in grey are assigned zero as a quantity, as their existence is known but no data was available to quantify them. This section discusses the MFA structure, followed by results split per end-use category.

Overall, the system can be divided in two main parts. The first one covers the industries that use SiC in single crystal form (semiconductors, jewellery). The second one covers the other industrial uses that use SiC that is produced through other means, e.g. with the Acheson process (abrasives, refractories, technical ceramics, metallurgy, other).

The flows and processes for the latter industries follow a similar structure. SiC first flows into the specific production process. This is modelled as a separate process as there are likely losses during production and it is the stage where recycled material can flow into. After the production process, the material flows into a use process. Following, all material that is not lost flows into the EOL process. The specific flows of the abrasives, refractories, ceramics and metallurgy industries are further discussed below.

The EOL flows are difficult to estimate for all industries, regardless of the production process. This is because the sectors cover a range of products with varying lifetimes. Chips for example are used in many different products. Similarly, the lifetime of refractories can vary between hours and years depending on where they are used. Only the metallurgy outflow is straightforward to estimate, due to the dissipation. Due to this lack of data and differentiation, the outflows equal the inflows that are left after subtracting losses and recycled material. The use processes are all modelled with a stock.

Based on reporting by the USGS (2021), total recycling is assumed to be 5%. The USGS however, does not know what type of SiC is recycled by whom and how, as the percentage is based on estimates given to them by survey participants. Therefore, it is not clear where the recycling takes place and whether the 5% are of the total production or total EOL material, an assumption had to be made. In the MFA it is assumed that 5% of material that ends in the EOL process is recycled and goes back to the production process. This also means that it is not specified from which use the material is coming and where it could be used again. The system contains few recycling flows since they are only modelled if the concrete flow is described by an interviewee or could be found in literature with enough detail (with information from where to where it is going). Generally, many sectors have relevant recycling potential (see section 4.2.2.4 for a more detailed description of recycling). The following subsections address industry-specific flows in more detail.

4.1.2.1 Semiconductor

This section discusses both power electronics (PE) and high frequency (HF) chips within semiconductors. Since the SiC crystal growth processes differ between the two (even though they use the same SiC Polytype [g]), they are divided into two different process chains in the MFA diagram. However, the production process for both types of chips is relatively similar for the remaining parts. Namely, SiC powder with high purity is used to produce a single crystal SiC boule (see Figure 7). This boule is then cut into thin wafers, which results in material losses of around 50%. Some companies are working on different ways to cut the wafers to decrease said losses. Infineon, for instance, applies a cold split process, which can decrease the losses during cutting by one third ([g]). The lost material currently seems to go to waste. Some of the wafers are also not further used due to impurities such as micropipes in the material. Instead, these are then used as test wafers to try out different production steps. These test wafers can be reclaimed and re-used several times before they go to waste.

Figure 7 SiC Crystal boule, 6 and 8 inch, picture taken during PCIM 2022

The next step applies an epitaxy layer to the SiC wafer substrates. Layers of crystal material are put on top of the substrate which fulfil the actual semiconductor chip function. For PE chips, the epitaxy layer consists of SiC. HF rely on GaN chips instead. Thus, for the PE chips, another inflow of SiC is added to this production step. Unfortunately no data on the exact quantity could be found. In this case however, the impact on the analysis is limited as the epitaxy layer is very thin, which would result in minimal amount of material inflows, even if recorded correctly. After another polishing step with an additional loss of half to two thirds of the material, the wafers are cut into individual chips. An uncut wafer and some cut chips can be seen in Figure 8. The chips can be used in different packages, e.g. IGBTs or MOSFETs. Still, some chips do not make it into a package due to defects and immediately go to waste.

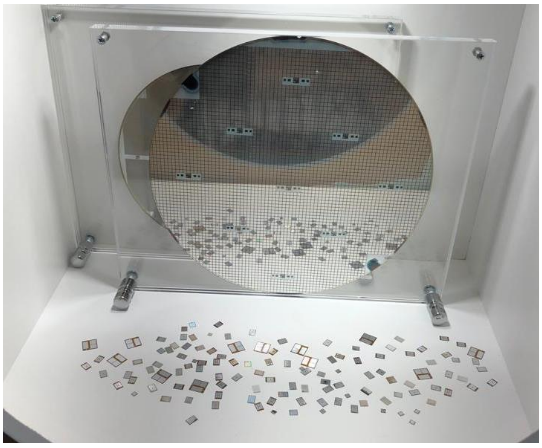

Figure 8 Wafer before cutting and individual chips in front, picture taken during PCIM 2022

The packages are then used for different applications and industries and depending on these specific uses also have varying lifetimes. In the MFA diagram, the HF process is simplified and due to the missing epitaxy inflow, the epitaxy and chips production process are summarised in one process. No interview partner was aware of ongoing efforts to recycle individual chips or packages (see section 4.2.2.4.1). Additionally, most did not see it as a realistic option for the future. Especially as the chips are mixed with many other materials they are small and the SiC content of individual chips is low.

4.1.2.2 Jewellery

The jewellery production uses the same single crystal boules as the semiconductor industry. The annual report from Charles & Colvard (2020) (a jewellery manufacturer) names the supplier of their boules and it is a company that also supplies the semiconductor industry. The MFA represents the production steps based on the production process described in the annual report by Charles & Colvard (2020). Unfortunately, no data could be found for how much SiC is used in the jewellery industry or is lost during its production. Therefore, no numbers could be assigned to it in the MFA. The flows of losses are added as the production steps suggest that there is most likely material lost. However, this could not be verified. It is assumed that the gems do not go to waste but mainly stay in use, or as a hibernating stock in drawers in households. The only way that it leaves the system is through jewellery being lost. The processes and flows related to the jewellery industry should be seen as a reminder for the existence of the use.

4.1.2.3 Abrasives

Due to a lack of data, the material going into the abrasives sector is calculated from the difference between summing up inflow into the other sectors and the global production capacity. This results in 400 kt of material in the abrasives sector. The abrasives production chain has two noteworthy recycling flows. They are both based on the specific application of SiC in the sawing process of Si wafers for solar panels. The SiC that is left in the sawing sludge is extracted. 82% of the SiC is re-used in the same application, 18% can no longer be used for cutting as the grains are too small or round. That material is then used in steel making ([p]).

The abrasives use process is modelled with a stock, mainly to illustrate the accumulation of material resulting from SiC abrasives used in private households. SiC abrasives in industrial applications have lifetimes below one year. However, in households they can last much longer due to less intense usage ([r]).

4.1.2.4 Refractories

In the MFA it is assumed that 200 kt of SiC are used in the global refractories industry. Finding data on the quantity of SiC in the refractories industry is difficult. Due to that reason an assumption has to be made. The number used is based on data by Wecht (1977) who notes 21 kt of SiC used in the German refractories industry each year (note that this is based on his 1977 perspective). The German refractories association notes that Germany produces one third of all European refractories (Deutsche Feuerfest Industrie e. V., 2022). Based on this, the 21 kt are multiplied by three to get a European estimate. It is then assumed that the shares per region in the SiC production would be the same for the refractories production which results in 192,660 kt per year. To not give a false sense of accuracy, the number is rounded to 200 kt.

For refractories no recycling is reported. However, that does not mean that it might not already take place. The refractories use process is modelled with a stock, as some refractory products last longer than a year. The lifetimes of refractories vary widely. In steel-making, refractories only last 30 minutes to a week, whereas they last five years in waste incineration and three years in cement production ([n]). Therefore, a stock build-up of refractories in use exists. During use, material of the refractories is lost in some sectors ([n]). It is not known how much is lost in all refractory uses, which means that the loss flow could not be quantified.

4.1.2.5 Ceramics

As there is no data available for how much SiC is used globally for technical ceramics, again an assumption needs to be made. This is calculated on the basis of Briggs (2011) who notes 8000t of ceramics use in the US. I assume that the SiC ceramics production shares are similar to the global SiC production share division. How the shares are calculated can be seen in the appendix in section 8.2. In this case the shares based on the Grandview Research (2019) data are used, because in the final calculation the share of the US production is very low. This is because the US imports a lot of SiC. The Grandview Research data on the other hand gives the market volume, which is likely to also include imports and gives a better basis for the ceramics total production.

For ceramics there is one loss flow reported. One interviewee reported a loss of around 20% while producing SiC ceramics. While this might differ per ceramics product, I assume that this applies to all ceramics, though the uncertainties around this need to be considered.

4.1.2.6 Metallurgy

The inflow to metallurgy is based on data from 2013 from Grandview Research (2019). The report states that steel and energy are the largest end-use sector and would use 28.8% of all SiC (Grandview Research, 2019). Though in the case of this MFA, abrasives are the biggest end-use. This is mainly due to a different categorization of end-uses. However, due to this different categorization the uncertainty around the suitability of 28.8% of SiC going into metallurgy, needs to be remembered. Metallurgy also has another inflow which is recycled material from abrasives. It is known that recycling within metallurgical production takes place, which includes SiC, though quantities could not be found for the specific case of SiC. The SiC used in metallurgy dissipates and flows out of the system.

4.1.2.7 Other uses

Due to the uncertainties regarding the categorizations of end-uses a general assumption is made that 100 kt of SiC go into no further defined uses. As these uses are not known, the process is not modelled with a stock, though accumulation of material might take place. All material from this process goes to the EOL process.

4.2 Supply Chain resilience

The supply chain resilience is analysed in three steps. First, the potential causes of supply disruptions are described. Second, the potential for alternative supply is analysed. In this section the most important results are described and analysed. A summary of all results for each category from the interviews can be found in the appendix in section 0. While the MFA shows that only a small share of global SiC production, 1t of 1 million tonnes, is used for semiconductors, still considerable attention is put on the semiconductor specific supply chain resilience aspects. This is because SiC semiconductors for example help to reduce losses in power conversion or increase the range of electric vehicles (Goldman Sachs, 2019). These are important properties that will help to increase energy efficiency in the long term, which contributes to emissions and energy saving in the long term. Unhindered supply of SiC for the semiconductor industry is therefore important for energy efficiency ambitions.

4.2.1 Potential supply disturbances

Currently there are only around 20-30 competitors in the SiC production market according to a SiC association ([d]). This shows that it is rather difficult for companies to establish a diversity of suppliers. For the US, the USGS (2021) reports that there are two companies that produce SiC at two plants in the US at the moment. Not only the number of SiC producers is relevant, but also which type of SiC they produce. Not all producers produce the same type of SiC. As a steel company noted, their choice of SiC is rather limited due to their strict requirements of the aluminium content in the material. They report that so far they have only identified two sources that can supply material with these requirements, and they are now working with one of the sources ([f]). Another interviewee noted that the purer the SiC you want, the more difficult it is to get ([n]).

4.2.1.1 War in Ukraine and share of China in global production

The location of SiC producers is relevant to identify potential supply threats. For stakeholders in Europe and the US, the Ukraine war and the high share of production in China are particularly relevant.

The war in Ukraine already has an effect on the supply chain. A steel manufacturer was told by its supplier that due to the war in Ukraine they could not get the quartz sand from Ukraine and therefore supply was disrupted for some time ([f]). However, as the steel company only requires rather small quantities this did not have a huge effect ([f]). A big SiC producer is located in Russia. This means that currently a big supplier is falling away, as a German refractories producer notes ([n]). This causes supply issues for companies that get most of their supply from Russia as a re-seller of SiC reports ([j]).

The high supply share of China in the SiC production market is another concern. Dramatic supply issues can emerge if no SiC comes from China anymore (e.g. due to problems in the harbours) as noted by the SiC association ([d]). An interviewee from the refractory industry reports that getting supply from China got increasingly difficult after covid, mainly due to transportation ([n]). In the report by Grandview Research (2019) it is reported that on the one hand they expect the Chinese government to introduce policies that will increase SiC production, however they also expect export restrictions to affect the SiC supply.

4.2.1.2 Energy and emissions

Energy availability and emissions regulation appear to be another threat to the supply of SiC. Energy availability has two components. Sufficient availability of energy is an important requirement for the location of a SiC plant. SiC production can put energy grids under pressure due to the high demand of energy. If the electricity becomes more expensive than SiC itself, then in the short term some producers start selling the electricity instead ([d]). In the semiconductor industry, rising energy prices might actually fuel SiC demand. An interviewee from a semiconductor company said that they believe that increasing energy prices only further the need for more efficiency and therefore increase demand for SiC ([h]).

Besides the availability of energy, also the costs of energy are of importance. Some SiC plants are therefore build close to hydropower dams e.g. in Brazil for energy availability reasons. However, one interviewee mentioned a situation in Brazil where missing rain caused rising energy prices and states that anything that could disrupt electricity or transport could disrupt the supply chain ([f]). Next to energy, also emissions are an important factor.

A European SiC producer said that problems with SiC supply would mainly be due to environmental regulations on emissions, high electricity costs, transportation costs, the covid pandemic and the war in Ukraine. ([l]). The interviewee names three bottlenecks in the supply chain, namely, energy prices, green sources for energy and raw material and CO2 prices and emissions reduction ([l]). Another interviewee voiced similar concerns about their SiC producer, saying that production had to be decreased due to emissions and energy regulations, even though demand is high ([n]). This interviewee also reported that because of the supply issues, they have to select their customers and cannot take all orders anymore and focus on their regular customers. According to them, the lack of raw material also limits growth potential of companies in their sector (refractories) ([n]). One interviewee generally stressed the need to find alternative routes of production besides the polluting and energy intensive Acheson process ([o]).

4.2.1.3 Semiconductor specific risks

As the supply chain for semiconductors looks a little different than that of other industrial applications, also the potential disturbances are a bit different. SiC in the semiconductor industry is rather novel and the supply chain is still building up. Production capacity is an issue in the SiC semiconductor industry. This makes qualifying more than one source of supply difficult, even though the goal for the future is to qualify three or four sources as one semiconductor producer reported ([h]). The same interviewee is optimistic that by around 2024 there should be a good balance between supply and demand, due to a lot of recent investment from suppliers in the production capacity ([h]). Another interviewee from a European research project on the SiC supply chain states that supply is likely not to increase at the same pace as demand ([e]). The interviewee also expects an equilibrium of supply and demand at some point, though expects that demand is likely to always be slightly higher than supply ([e]). However, the problem of production capacity seems to not lie with SiC as a material itself but rather in the crystal boule growth process. This process takes a long time. This means that any disturbance during that process can have long term effects. This is illustrated by the effects of the covid pandemic on the supply chain. Growing the boules from which the wafers are then cut is a process that not only has high energy requirements but that is also taking a long time (a matter of weeks), longer than for Si, (time: [i], [e] and [h]). Wafer production normally runs all day, but due to the pandemic had to shut down. However, restarting the production takes around three months to get up and running again ([s]).

4.2.1.4 Laws and regulations

Laws and regulations can also cause supply disruptions. One relevant legal aspect specific for the semiconductor industry is IP protection which means that suppliers ask their clients to sign that they only use the material for the intended purpose and do not reverse engineer it to grow additional material ([h]). Breaking such an agreement could have an impact on the supply chain as potentially illegal sources of crystal boules grown by reverse engineering could “flood” the market. Another legal aspect from a US or European perspective is not re-selling a product that can be used for military activities to a foreign entity such as North Korea or Iran. In case of the semiconductor industry this is because the material can also be used as a semi-insulator which is relevant for military applications. ([h]). For some technical ceramics applications this is also relevant as they can also be used in military applications as one ceramics producer reported ([b]). Due to its application also in military uses, SiC could potentially become the subject of geopolitical conflicts.

4.2.2 Alternative routes of supply

There are four main ways analysed in the framework that can help to overcome supply disruptions, stockpiling, substitution, use reduction and recycling. Especially the last three categories are highly sector dependent, and therefore they need to be discussed individually for different end-uses. Another way to counter supply disruptions might be to build a new SiC production plant. To start a new plant, an interviewee from a SiC association mentions that permissions would be the decisive factor but that they expect that it would take around a year to go from plan to realisation ([d]). Another interviewee mentioned that if a new plant would open now, it would at least need to fulfil the high standards of the Dutch SiC producer, which is said to be the most sustainable SiC producer ([k]). Another important factor for SiC plants is the availability of electricity ([d]).

4.2.2.1 Stockpiling

Stockpiling can help to balance out disruptions. In the semiconductor industry, stockpiles are not really present. Due to the low production capacity and growth of the industry a semiconductor company said that stockpiling is currently not possible and currently works on a principle of weeks ([h]). However, building up a stockpile would be a goal for the future ([h]). For stockpiling in the future it is important to think about where it should take place. The interviewee from the semiconductor company said that if only one voltage is produced, the buffer should be located at the stage after the polishing of the wafer and putting the epitaxial layer. If there is a need to switch between voltages in the production, it would make most sense to build up a stock with polished wafers before the epitaxial layer is applied ([h]).

In the rest of the supply chain stockpiles also do not seem to be a common thing. The USGS reports that there are no stockpiles of SiC as an abrasive. The US got rid of its SiC stockpiles in 1999 (USGS, 2000). A European SiC producer notes that while some companies might keep stockpiles it is not likely due to the high demand in the market ([l]). They themselves do not keep stockpiles ([l]). A re-seller of SiC points out that stockpiles at foundries are difficult as stocks take space (e.g. building warehouses) which costs money ([k]).

This shows that there are no significant stockpiling activities taking place in the SiC supply chain and that this therefore does not seem a viable option to react to possible supply disruptions.

4.2.2.2 Substitution

In the case of the semiconductor industry SiC currently serves as a substitute for Si. This means that Si could also be seen as a substitute for SiC, though only at the cost of losing the efficiency advantages of SiC. It needs to be noted that one cannot just easily decide to substitute one by the other as the whole system needs to be re-designed depending on whether it uses a Si or a SiC chip ([c], [i]). One interviewee stated that annually, less than 1% of all Si is being replaced by SiC ([h]). Next to Si and SiC also GaN can be seen as a substitute, at least for some applications. Though one interviewee states that the transition from Si to SiC is easier than that from SiC to GaN which would be more expensive, takes more time and generally means bigger change ([h]). GaN chips also use SiC substrates, which means from a material perspective GaN does not serve as a substitute as it still requires SiC. One interviewee states that currently no step backwards from SiC to Si can be observed ([h]).

A ceramics producer reported that SiC could maybe be substituted by using a completely new material but that it would not be possible to just replace SiC ([b]). Regarding the abrasives industry a re-seller said that complete substitution in grinding wheels does not yet seem possible ([j]). Another interviewee from the abrasives industry, said that the sector could not do without SiC ([q]). Alternative materials would not give the desired abrasive result as SiC ([q]). The USGS (2021) states that "natural and manufactured abrasives, such as garnet, emery, or metallic abrasives, can be substituted for fused aluminum oxide and silicon carbide in various applications."

For the steel industry, substitution depends on the purpose of SiC use. If SiC is used as a carbon source then one interviewee said that using more recarburizer and FeSi or even SiMn and recarburizer depending on the steel grade, could substitute SiC ([f]). Both a steel maker and a re-seller furthermore reported that SiC is currently considered as a substitute for ferro silicon in steel making due to rising prices of ferrosilicon ([f] and [k]). In case of the steel maker, this was still in an early trial phase, from the re-seller however it seemed that it is already applied in some plants ([f] and [k]). The substitutability of ferrosilicon and SiC does not only mean that SiC can be substituted by the steel industry, but it can also possibly be a risk to supply. If a lot of ferrosilicon is replaced by SiC this could noticeably increase demand. Whether this could disrupt supply could however not be analysed in this thesis.

Concerning the refractories industry one interviewee said that alternative materials are difficult due to the special characteristics of SiC ([n]). They said that if you look in the periodic table for materials with similar characteristics you would get to "adventurous" materials that are also not really available ([n])

Substitution is highly dependent on the specific applications. In most industries substitution seems difficult, especially in the long term. The steel industry is an exception in this.

4.2.2.3 Use reduction

A ceramics producer reported that 3D printing might in the future lead to less losses ([b]). A refractories producer said that reducing material use, thus making the product thinner, would lead to the need of earlier reparations ([n]). Making it thinner can also become risky e.g. in the steel industry where breaking refractories can lead to a steel leakage ([n]). Overall, interviewees said that the wall thickness is already optimised ([n]). In the semiconductor industry use could be reduced by reducing losses. One of the possible future developments in the semiconductor industry is the production of chips on re-usable substrates as for the functioning of the chip only the epitaxy layers are needed. However, this is still a subject of research and it remains to be seen how feasible it is ([g]).

Use reduction is not widely applied. At least from interviews in this thesis, use reduction does not seem to be a solution for supply disruptions.

4.2.2.4 Recycling

Generally, the reaction from many interviewees was that they find recycling a very important topic. Recycling can help to lower demand for primary SiC, but can also help to tackle the supply threats of energy demand and emissions. A SiC association representative said that recycling is a big challenge, but that energy reduction and a move towards circularity would be necessary for the future ([d]). A European SiC producer repeated this assessment and said that recycling plays an important role for CO2 emissions and energy consumption ([l]). The USGS mineral commodity summary factsheets report 5% recycling of SiC in its publications (USGS, 2021). The USGS however, cannot say where exactly the recycling is taking place.

Recycling during SiC production is possible during the melting process in the Acheson process and also by recycling off grades from the processing plants ([l]). There is also one SiC producer who has a patented process for scrap SiC recycling to produce 99% SiC. An expert in SiC recycling said that as always with recycling, the question is what and how you want to recycle. In the form of the component or rather as a powder? If wanting it as a powder the question still remains what you want to use it for, do you want it fine or coarse, which characteristics should it have and how pure should it be? ([o]). The interviewee also said that often the problem is that the powder is too fine to be used in any applications. Nonetheless, there is research being conducted on this and it seems possible to make this fine material also into a coarse powder again ([o]).

In the past, SiC recycling took place from the sawing slurry that forms during the Si wafer production for solar panels. The sawing works with SiC and results in a slurry containing Si, SiC, Glycol and some water. About 80-82% of the included SiC can be recycled and is reused for sawing. The other SiC has to be replaced. The remaining SiC is used in the steels industry ([p] & [o]). This recycling process was developed in Germany and a German company applied the process. The recycling company as well as many solar panel manufacturers were located in the east of Germany in close proximity of each other. However, around 2006, many solar panel manufacturers stopped production in Germany. Furthermore, the sawing process with SiC is being replaced by a sawing process with diamond wire. The German company SiC Recycling still does some slurry recycling for some of the companies that still produce solar panels in the region and that use SiC for the sawing process. They say that a lot of the slurry that is produced at the moment is not being recycled. However, they expect that in the next 3-5 years slurry recycling will be no longer needed. They are now looking for new business opportunities for SiC recycling.

4.2.2.4.1 Semiconductor recycling

In the semiconductor industry, recycling at EOL level would be in the form of chips. However, recycling of chips is described as extremely difficult by two interviewees ([i] and [h]). This is because at that stage the material is tightly mixed with other materials in the chip. Another interviewee who also does not expect any type of recycling of the chips now or in the future, notes that re-use could be possible but the economic feasibility of this is questionable, as chips in power electronics are worth less than 1€ ([g]). Currently the chips are disposed at the end of their lifetime ([g]). The only type of recycling already happening is during the production process and at the wafer level. If a wafer cannot be used for further production, all contaminations are removed in a reclaiming process. The cleaned wafer is then used as a test wafer and not for normal production ([h]). According to one interviewee, the test material is less than 5% of the overall SiC used ([g]).

4.2.2.4.2 Steel, abrasives and ceramics recycling

In steel-making, recycling of SiC does not seem to be possible as the material dissolves into its individual parts once added to the hot steel ([f]). However, there might be some scrap recycling within the steel making and recycling of steel itself is possible. Though also the recycling of scrap comes with some difficulties as due to the various alloy materials, scrap that is made during the production process can only easily be re-used by the same foundry (due to the unique "recipes" used by each foundry). Scrap re-use does happen as it is financially beneficial, as discarding of the material is also connected with costs. For the interviewee, re-working is also an important source of income ([k]).

For abrasives it looks a bit different. During an interview with a company that recycles different abrasive materials they reported that SiC does not play a role for them in recycling as there is too little material and too little applications ([j]). Additionally, often it is not possible as the SiC is bonded with bakelite which becomes toxic when burnt which means the SiC cannot be burned out for recycling ([j]).

Concerning ceramics, recycling depends on the specific ceramics product. One interviewee for example says that mechanical seals in pumps in cars for example are not worth to recycle as their original price is only in the range of 10 cents per piece. The car and pump would need to be dismantled to take it out and collect it. Currently this is not happening and the material just goes to the scrap press. The interviewee points out the need to find products or ways to easily collect the material. An example they give is kiln furniture, as it is easy to sort at the end of life. According to the interviewee there are already companies doing this in Germany who collect the material, grind it and then sell it to the refractories industry. He points out that this would mean some downcycling, but would be an acceptable option ([o]).

4.2.2.4.3 Refractories recycling

Regarding the refractories industry, recycling depends on the sector in which the refractory product is used. With one interviewee three sectors were discussed: waste incineration, steel making and cement production ([n]). With waste incineration the problem is what sticks to the boards after use and how can it be removed. Refractories in waste incineration were reported to have a lifetime of around five years and during its usage experiences very few material losses ([n]). The SiC used for this application is highly pure 98% SiC ([n]). The lifetime of refractories for steel production is said to be much shorter with only 30 min to 1 week. During use also around 50% of the material is said to be lost and at the end of the lifetime not much material is left as it goes into the slag ([n]). This makes recycling in this sector difficult. The material that is left is often grinded down and used as a slags conditioner ([n]). The lifetime of refractories used for cement production was reported as around three years and also around 50% of the material is lost during the production process ([n]). The material at the end of the lifetime goes to demolition waste disposal sites ([n]). The refractory producer reported that sometimes they do recycling themselves, but SiC would be rather secondary ([n]). In general, the interviewee reported that in the future with more recycling, the SiC producers would be the best place to carry out the recycling as one issue with recycling is the concern of oxidation resistance of the material which could best be checked and guaranteed by the SiC producers ([n]). If the oxidation resistance is not given, the SiC needs to be downgraded and for example be used in repair compounds ([n]).

Recycling is not yet widely applied and in the short term will likely not be able to contribute to dealing with supply disruptions. Expanding recycling capacity seems to be under development and the aim of many stakeholders.

5 Discussion

This research sets out to gather data and map SiC flows throughout the global economy, as well as analyse supply chain resilience. I find that the global SiC production capacity constitutes 1000 kt per year. With 55.34%, the Asia Pacific region is the biggest producer, followed by Europe with 32.7%, RoW with 7.96% and North America with 4%. In order of quantity, abrasives, metallurgy, refractories, technical ceramics, other industrial uses, semiconductors and jewellery are the main areas of application of SiC. Only around 5% of the material is recycled (USGS, 2021). High energy requirements in the SiC production as well as strict emission regulations are the main supply risks found. Substitution, use reduction, recycling and stockpiling can currently only very minimally absorb supply disturbances.

5.1 Role of semiconductors in supply chain

When researching SiC online, the semiconductor industry appears at the top. This illustrates SiC's popularity in the semiconductor industry as an up and coming technological innovation. However, quantity wise it is not noteworthy in relation to the SiC supply chain in its totality as only 0,000001% of the global SiC production capacity go towards the semiconductor industry. Thus, when researchers or policy makers look at energy saving policies in the SiC supply chain, the semiconductor industry will be the least important industry for potential change. The most interesting consideration in terms of energy saving for SiC in the semiconductor industry is to assess whether the switch from Si to SiC semiconductors actually saves energy over the complete lifecycle of the product. One interviewee also stated that one of the main risks he sees for SiC semiconductors development in the future would be if such a comprehensive assessment would show that SiC is not environmentally better than Si ([h]).

5.2 Information on SiC

Quantity-wise, the majority of SiC is employed in industries other than the semiconductor industry (abrasives, refractories, technical ceramics, metallurgy and others). However, also in these industries, SiC is not high on the agenda since the material is typically used in lower quantities compared to other inputs to the production process. Still, this does not imply that SiC is not important. For instance, SiC can be difficult to substitute in the short term due to its extraordinary hardness and heat resistance. Since SiC is low on the agenda of many stakeholders, information and data on SiC are scarce. Naturally, the main expertise on SiC lies with the SiC producers. However, they are reluctant to share information and I only had one producer answer questions in written form. Another interviewee explained that this might be a result of an oligopolistic global market with only 20-30 producers. High competition might thus make producers more careful in sharing information. However, this lack of information makes a comprehensive analysis of the flow of SiC and its supply chain more difficult. This implies that first, sustainability efforts such as recycling need to be researched on the basis of uncertain data. Second, the lack of data also in itself forms a vulnerability in the supply chain as potential weaknesses might be overseen and stakeholders might not be able to adequately prepare for disruptions.

5.3 Supply chain resilience

The supply chain analysis identifies several potential supply disturbances. They are: Low diversity in producers, the war in Ukraine, the high global production share of China, energy availability and price and emissions regulations. For semiconductors low production capacity is an additional risk. Furthermore, SiC uses that can also find military application face strict laws and regulations.

The analysis considers four ways to counter supply issues, namely stockpiling, substitution, use reduction and recycling. Mainly due to high demand, stockpiling barely takes place and is therefore unlikely to curb supply issues fully. Additionally, substitution seems difficult due to the specific characteristics of SiC. Thus, substitution is unlikely to address supply issues in the short term. Only in the steel industry are substitution options found (see page 24). As the analysis in this thesis shows, use reduction is currently not widely applied. It does not seem a viable option in the short-term as it is either not possible due to material use already being optimized or no attention being paid to the option.

Recycling is a promising field and could positively contribute to resilience in the long term. Actors are already actively looking into different recycling options. This shows a general openness for more recycling efforts and illustrates the potential for recycling. Also, there seems to be material available for recycling that as of now is not used. Opportunities for recycling are highly dependent on the specific end-uses of SiC. The economic viability of recycling efforts is also hugely dependent on the development of primary SiC prices, which in turn depend on the development of energy prices. That is, when SiC prices rise, recycling becomes more attractive. Still, it is important to keep the quality of recycling in mind. For instance, to not downcycle too early in the recycling chain. Thus, recycling of SiC in the metallurgical industry is not optimal as it cannot be re-used for another round of application, as is the case in other industries. As long as the material quality is high enough, downcycling should be avoided. Thus, stockpiling, substitution, recycling and use reduction are unlikely to significantly contribute to supply chain resilience in the short term. In the mid to long term this might change, especially if stakeholders would perceive a higher risk to unhindered supply. Independent, of perceived supply risk, recycling seems an attractive development for the supply chain due to its several beneficial contributions, such as reduced costs and environmental benefits.

5.4 Resilience and sustainability

Another strategy to contribute to supply chain resilience and help transition the SiC industry towards more sustainability is using SiC production plants as storage in the energy grid. This could serve to address aforementioned issues of energy needs and emissions. Renewable sources of energy often deliver unsteady supply of energy, for instance, PV panels cannot produce at night. But as already applied by the Dutch production facility, SiC plants can help balance the energy grid. The Dutch production plant is currently able to shut down the entire production process within two minutes when necessary (Xavier & Oliveira, 2021). When there is oversupply in the grid they can produce and when demand is high and supply is low they can halt production. This is beneficial to both the energy provider who makes sure that energy is sold when there is oversupply and the SiC producer who might face reduced costs (Movielinqs, 2017). Thus, the high energy needs of SiC production plants offers an opportunity and could help balance the energy grid. Regardless of these opportunities, the main focus should remain on lowering energy requirements altogether. As one interviewee mentioned, finding an alternative way of production besides the Acheson process might be necessary to lower energy needs ([o]).

Still, the question remains which locations are most suitable for SiC production from a systemic point of view. Locations with large amount of (renewable) energy seem the most fitting. This only holds if environmental standards are kept high in general e.g. in regards to pollution control. Also, transport routes should still be considered. For instance, if new locations mean that SiC needs to be transported over longer distances to users, then it might be environmentally less preferable. With rising energy prices and stricter regulations it remains to be seen whether SiC production in Europe remains a viable option. Moving the location of Sic production plants might also have implications for supply chain resilience in the short term for some countries. For instance, from a European perspective, moving more production to other regions will increase supply vulnerability. This shows that the choice of location cannot only depend on where renewable or cheap energy is available, but it includes many different aspects that need to be considered.

5.5 Limitations and future outlook

The lack of data and knowledge is the main issue this thesis is confronted with. It means that in many instances assumptions are made. Further, expert estimates often have to be relied upon, instead of transparently and reliably reported data. This causes high levels of uncertainties particularly in the MFA, which the visual (Figure 6) illustrates. It shows particular uncertainty with regards to the material inflow to the individual end-use categories. Moreover, the categorization of end-uses can have an impact on data quality. For instance, some products belong to multiple industries which makes the classification of end uses more difficult. Thus, the MFA may double count or leave out some important products. Additionally, the decision to not use a specific year, but a generalized contemporary “current” year, adds uncertainty to the analysis. However, it is still better to accept the uncertainty coming from choosing no concrete year, than to choose a specific year but use data that is distorted, e.g. through the impact of the covid-19 pandemic.

Not only is data on SiC scarce, but also all three data sources might have some inherent bias. For instance, grey literature and industry market reports might be influenced by commercial interests. Furthermore, interviews may be biased not only by the interviewee giving their own subjective view on things but also by the interviewer who can interpret replies differently from how they were intended. Additionally, the results face bias through the interview sample which is heavily Eurocentric with a particular focus on German companies. The researcher’s own language skills and knowledge have particularly opened opportunities to talk to German stakeholders. Since the MFA takes a global view, obtaining data from non-European interview partners would have likely led to some differing results. Particularly a Chinese perspective would have added valuable insights, as they are the biggest producer of SiC. However, interview partners from China but also other non-European countries were more difficult to reach. Still, efforts have been made to also reach out to global companies via email. Unfortunately, few companies reacted. Thus, the analysis offers more of a view into the German and Dutch SiC market. Another interesting thing to note is that all of the 18 interview partners were men. The SiC industry is technical by nature. One would thus already expect a similarly unequal gender representation as in other technical industries. However, even with a small sample it is noteworthy that not a single woman was represented among the interview partners. As the interviews were about the companies and not about the humans themselves, impact on the results is probably limited. However, it could still be the case that females would identify other factors that impact the dynamics of the supply chain and evaluate risks differently.

Different types of sources have different levels of bias, though no source will be completely unbiased. Awareness of these biases is a first and important step, for countering them. Nonetheless, my results present the first comprehensive analysis of SiC flows over the global supply chain. This can serve as a starting point for further research as more data becomes available. While it is not possible to quantify SiC flows minutely, in a reliable manner, the analysis still is useful to showcase broad trends. Therefore, the results help in understanding the structure of the SiC market and highlight where data and knowledge is lacking at the moment. This can also serve to determine avenues for further research.

An expansion of this work on acquiring knowledge and data on SiC is important to promote its sustainability transition for three reasons. First, more data can help establish business cases for recycling chains or help in discovering business opportunities by knowing where material becomes available for recycling that is valuable. Second, better data quality facilitates measuring progress of sustainability efforts. Third, more data can contribute to assessing the potential of the SiC industry to become more involved in industrial symbiosis activities. Industrial symbiosis is a concept where individual companies that are located in close geographic proximity collaborate to exchange materials, energy and/ or water in a way that is beneficial for all actors involved (Chertow, 2000). This could for example mean that company A shares residual heat with company B who in exchange shares waste with company A who can burn it to produce energy. Due to the high temperatures necessary for SiC production, this could offer potential opportunities to SiC producers. Furthermore, due to a lack of data and time, this thesis was unable to assess the potential effect that the substitution of ferrosilicon with SiC in metallurgy has on the supply chain. The question is whether the demand increase of SiC which might result from ferrosilicon substitution would present a challenge to the current SiC supply chain, or whether current production capacity is sufficient. This would still be an interesting route for future research.

6 Conclusion

This thesis shows the flow of SiC through the global economy and its use in different products and industries. Energy and emissions are identified as the biggest vulnerability of the SiC supply chain. Thus, transitioning towards more sustainable production and usage practices is not only beneficial from an environmental perspective, but also from a supply chain resilience viewpoint. This double incentive, along with the currently rising energy prices show the relevance of sustainability efforts.

This research identifies three potential strategies that address these sustainability and supply chain concerns. First, focusing attention on recycling options is a promising way forward. The SiC producers are to play an important role in recycling efforts. Recycling cannot only limit the input of materials and energy but also strengthen supply chain resilience, as it offers an alternative route of supply other than that of primary SiC. While there is notable recycling potential, it needs more attention and time before it has significant influence on the supply chain. Second, the role of SiC production plants in balancing energy grids provides an interesting opportunity for more sustainability in the supply chain. However, attention needs to be paid that the primary interest is still to reduce energy input as the cheap energy in times of oversupply might set the wrong incentives. Third, industrial symbiosis could positively contribute to the issues of emissions and energy. Thus, an interesting route for further research would be to map the flow of energy and other residual flows during SiC production in order to spot potential losses in the process and maybe eventually optimize it. Regarding supply chain resilience, the impact of substituting ferrosilicon with SiC on the SiC supply chain might be worth to further investigate as it could potentially put pressure on SiC supply.

The research shows that the studying even of small EIIs such as the SiC industry can provide valuable insights (e.g. potential it can have in energy grid) and that such industries might still contain relevant untapped potential for change. Further research on SiC can help develop more concrete sustainability recommendations. On the basis of this thesis, the focus of future research on the SiC industry should lie on recycling efforts and reducing energy input and emissions. In general, the case of SiC shows that particularly small EIIs that have so far not received much attention, can offer high returns in terms of knowledge gained.

7 References

Baars, J., Rajaeifar, M. A., & Heidrich, O. (2022). *Quo vadis* MFA? Integrated material flow analysis to support material efficiency. *Journal of Industrial Ecology*, jiec.13288. https://doi.org/10.1111/jiec.13288

Briggs, J. (2011). *Engineering Ceramics in Europe and the USA - An Overview of the Markets*. Ceramic Forum International. https://www.researchgate.net/publication/294643660_Engineering_Ceramics_in_Europe_and_the_USA_-_An_Overview_of_the_Markets

Britannica. (2022). Silicon carbide. In *Britannica.com*. https://www.britannica.com/science/silicon-carbide

Brunner, P. H., & Rechberger, H. (2016). *Handbook of Material Flow Analysis* (0 ed.). CRC Press. https://doi.org/10.1201/9781315313450

Cao, Z., Shen, L., Løvik, A. N., Müller, D. B., & Liu, G. (2017). Elaborating the History of Our Cementing Societies: An in-Use Stock Perspective. *Environmental Science & Technology*, *51*(19), 11468–11475. https://doi.org/10.1021/acs.est.7b03077

Cencic, O., & Rechberger, H. (2022). *STAN* (2.7).

CeramTec. (2022). *ROCAR® Silicon Carbide*.

Charles & Colvard. (2020). *Annual Report*. https://ir.charlesandcolvard.com/static-files/be5ff094-4d74-4926-844e-457c984fd7f6

de Bruyn, S., Jongsma, C., Kampman, B., Görlach, B., & Thie, J.-E. (2020). *Energy-intensive industries – Challenges and opportunities in energy transition*. study for the committee on Industry, Research and Energy (ITRE), Policy Department for Economic, Scientific and Quality of Life Policies, European Parliament, Luxembourg. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_190414_Energy_Intensive_Industries_DEF.pdf

Deutsche Feuerfest Industrie e. V. (2022). *Die Branche FEUERFEST*. https://www.dffi.de/feuerfest/ueberblick

Drent, M. (2021a, January 9). *Afgelopen jaar zes blazers bij ESD, minder dan gemiddeld*. https://www.rtvnoord.nl/nieuws/778247/afgelopen-jaar-zes-blazers-bij-esd-minder-dan-gemiddeld

Drent, M. (2021b, March 30). *ESD tegenover provincie: 'We zijn drie ton kwijt aan onzinnige procedures'*. https://www.rtvnoord.nl/nieuws/803670/esd-tegenover-provincie-we-zijn-drie-ton-kwijt-aan-onzinnige-procedures

Džubur, N., Sunanta, O., & Laner, D. (2017). A fuzzy set-based approach to data reconciliation in material flow modeling. *Applied Mathematical Modelling*, *43*, 464–480. https://doi.org/10.1016/j.apm.2016.11.020

ESD SIC bv. (2022). SiC Production. *SiC Production*. https://www.esd-sic.nl/process/sic-production/

European Commission. (2007). *Reference Document on Best Available Techniques for the Manufacture of Large Volume Inorganic Chemicals—Solids and Others industry*. European Commission. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/lvic-s_bref_0907.pdf

Fuchs, H. (1974). Siliciumcarbid. *Chemie Ingenieur Technik - CIT*, *46*(4), 139–142. https://doi.org/10.1002/cite.330460407

Goldman Sachs. (2019). *Goldman Sachs | Insights—Silicon Carbide's Meteoric Rise*. Goldman Sachs. https://www.goldmansachs.com/insights/pages/silicon-carbides-meteoric-rise.html

Graedel, T. E. (2019). Material Flow Analysis from Origin to Evolution. *Environmental Science & Technology*, *53*(21), 12188–12196. https://doi.org/10.1021/acs.est.9b03413

Grandview Research. (2019). *Silicon Carbide Market Size, Share & Trends Analysis Report By Product (Black & Green), By Application (Steel, Automotive, Aerospace, Military & Defense), By Region, And Segment Forecasts, 2020—2027*.

Hedbrant, J., & Sörme, L. (2001). Data Vagueness and Uncertainties in Urban Heavy-Metal Data Collection. *Water, Air and Soil Pollution: Focus*, *1*(3), 43–53. https://doi.org/10.1023/A:1017591718463

Hildingsson, R., Kronsell, A., & Khan, J. (2019). The green state and industrial decarbonisation. *Environmental Politics*, *28*(5), 909–928. https://doi.org/10.1080/09644016.2018.1488484

Karlsson, O., & Robertsson, S. (2022). *Securing supply of silicon carbide semiconductors—A case study at a large automotive OEM* [Master thesis]. Chalmers University of Technology.

Kennedy, K. (2005). *SiliconCarbide&More#10*. http://www.siliconcarbideandmore.com/index_files/SiC10final.pdf

Kim, Y.-W., & Malik, R. (2020). SiC Ceramics, Structure, Processing and Properties. In *Reference Module in Materials Science and Materials Engineering*. https://doi.org/10.1016/B978-0-12-818542-1.00022-9

Laner, D., Feketitsch, J., Rechberger, H., & Fellner, J. (2016). A Novel Approach to Characterize Data Uncertainty in Material Flow Analysis and its Application to Plastics Flows in Austria: Characterization of Uncertainty of MFA Input Data. *Journal of Industrial Ecology*, *20*(5), 1050–1063. https://doi.org/10.1111/jiec.12326

Laner, D., Rechberger, H., & Astrup, T. (2014). Systematic Evaluation of Uncertainty in Material Flow Analysis. *Journal of Industrial Ecology*, *18*(6), 859–870. https://doi.org/10.1111/jiec.12143

Laner, D., Rechberger, H., & Astrup, T. (2015). Applying Fuzzy and Probabilistic Uncertainty Concepts to the Material Flow Analysis of Palladium in Austria. *Journal of Industrial Ecology*, *19*(6), 1055–1069. https://doi.org/10.1111/jiec.12235

Liu, G., & Müller, D. B. (2013). Mapping the Global Journey of Anthropogenic Aluminum: A Trade-Linked Multilevel Material Flow Analysis. *Environmental Science & Technology*, *47*(20), 11873–11881. https://doi.org/10.1021/es4024404

Meerow, S., & Newell, J. P. (2015). Resilience and Complexity: A Bibliometric Review and Prospects for Industrial Ecology. *Journal of Industrial Ecology*, *19*(2), 236–251. https://doi.org/10.1111/jiec.12252

Movielinqs (Director). (2017, September 5). *Energy Enlightenmentz 2017—ESD-SIC en ENGIE*. https://www.youtube.com/watch?v=60V0JdJ0ebc

Quinlan, A. E., Berbés-Blázquez, M., Haider, L. J., & Peterson, G. D. (2016). Measuring and assessing resilience: Broadening understanding through multiple disciplinary perspectives. *Journal of Applied Ecology*, *53*(3), 677–687. https://doi.org/10.1111/1365-2664.12550

Resilience Alliance. (2010). *Assessing Resilience in Social-Ecological Systems: Workbook for Practitioners—Version 2.0*. https://www.resalliance.org/files/ResilienceAssessmentV2_2.pdf

She, X., Huang, A. Q., Lucia, O., & Ozpineci, B. (2017). Review of Silicon Carbide Power Devices and Their Applications. *IEEE Transactions on Industrial Electronics*, *64*(10), 8193–8205. https://doi.org/10.1109/TIE.2017.2652401

Sprecher, B., Daigo, I., Murakami, S., Kleijn, R., Vos, M., & Kramer, G. J. (2015). Framework for Resilience in Material Supply Chains, With a Case Study from the 2010 Rare Earth Crisis. *Environmental Science & Technology*, *49*(11), 6740–6750. https://doi.org/10.1021/acs.est.5b00206

Sprecher, B., Daigo, I., Spekkink, W., Vos, M., Kleijn, R., Murakami, S., & Kramer, G. J. (2017). Novel Indicators for the Quantification of Resilience in Critical Material Supply Chains, with a 2010 Rare Earth Crisis Case Study. *Environmental Science & Technology*, *51*(7), 3860–3870. https://doi.org/10.1021/acs.est.6b05751

Tanaka, H. (2011). Silicon carbide powder and sintered materials. *Journal of the Ceramic Society of Japan*, *119*(3), 218–233.

USGS. (2000). *Abrasives (Manufactured)—Mineral Commodities Summary*. https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/abrasives/040300.pdf

USGS. (2021). *Abrasives (Manufactured)—Mineral Commodities Summary*. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-abrasives.pdf

Warren, J. A., Riddle, M. E., Graziano, D. J., Das, S., Upadhyayula, V. K. K., Masanet, E., & Cresko, J. (2015). Energy Impacts of Wide Band Gap Semiconductors in U.S. Light-Duty Electric Vehicle Fleet. *Environmental Science & Technology*, *49*(17), 10294–10302. https://doi.org/10.1021/acs.est.5b01627

Wecht, E. H. P. (1977). *Feuerfest-Siliciumcarbid*. Springer-Verlag.

Weidema, B. P., & Wesnæs, M. S. (1996). Data quality management for life cycle inventories—An example of using data quality indicators. *Journal of Cleaner Production*, *4*(3–4), 167–174. https://doi.org/10.1016/S0959-6526(96)00043-1

Xavier, C., & Oliveira, C. (2021). *Decarbonisation options for the Dutch silicon carbide industry*. Netherlands Environmental Assessment Agency & TNO.

8 Appendix

8.1 Uncertainty Analysis

In the following, the steps of the uncertainty analysis are described in detail and the tables used for assessment are presented.

The flows in the system are divided into four different categories. Firstly there is a division between flows that are based on data and flows that are based on follow-up logic, such as that an outflows of a process without a stock must be the summation of the two inflows. The flows that are based on data are further divided into two categories, flows that are based on data from data sources such as national statistics or academic literature and data that is based on expert estimations. For the first the adjusted pedigree matrix by Laner et al. (2016) is used. The latter uses the expert estimation categorization, also be Laner et al. (2016). The two classifications, only rank the uncertainties on a scale from one to four. However, for both a fifth score is added for data that is randomly guessed.

Some of the flows cannot be awarded any quantities and are just included to show that there is a flow, but it is unclear how much. These flows are in grey.

Table 5 Expert estimate classification table (Laner et al., 2016)

Expert estimate	Score: 1	Score: 2	Score: 3	Score: 4
Evaluation criterion	Formal expert elicitation with (empirical) database – transparent procedure and fully informed experts on the subject	Structured expert estimate with some empirical data available or using transparent procedure with informed experts	Expert estimates with limited documentation and without empirical data available	Educated guess based on speculative or unverifiable assumptions

Table 6 Data quality indicators definition based on pedigree matrix by (Laner et al., 2016)

Indicator	Definition	Score: 1	Score: 2	Score: 3	Score: 4
Reliability	Focus on the data source: documentation of data generation, e.g., assessment of sampling method, verification methods, reviewing process.	Methodology of data generation well documented and consistent, peer-reviewed data.	Methodology of data generation is described, but not fully transparent; no verification.	Methodology not comprehensively described, but principle of data generation is clear; no verification.	Methodology of data generation unknown, no documentation available.
Completeness	Composition of the date of all relevant mass flows. Possible over- or underestimation is assessed.	Value includes all relevant processes/ flows in question.	Value includes quantitatively main processes/ flows in question.	Value includes partial important processes/ flows, certainty of data gaps.	Only fragmented data available; important processes/ mass flows are missing.
Temporal correlation	Congruence of the available date and the ideal date with respect to time reference.	Value relates to the right time period.	Deviation of value 1 to 5 years.	Deviation of value 5 to 10 years.	Deviation more than 10 years.
Geographical correlation	Congruence of the available date and the ideal date with respect to geographical reference.	Value relates to the studied region.	Value relates to similar socioeconomical region (GDP, consumption pattern).	Socioeconomically slightly different region.	Socioeconomically very different region.
Other correlation	Congruence of the available date and the ideal date with respect to technology, product, etc.	Value relates to the same products, the same technology, etc.	Values relate to similar technology, product, etc.	Values deviate from technology/ product of interest, but rough correlations can be established based on experience or data.	Values deviate strongly from technology/ product of interest, with correlations being vague and speculative.

8.2 Calculations of current SiC production share of world regions

In this thesis the world SiC production shares are used to give an overview of the different SiC markets and the global production structure and are also used as a basis to make assumptions in the MFA. In the following it is discussed how the shares are calculated, where the data for it comes from and what the uncertainties around it are that should be kept in mind. Two different ways of calculation are presented and discussed. The section concludes with describing how the two ways can be combined and the final shares are presented.

The first way is based mainly on data from Grandview Research (2019). The Grandview Research (2019) sample report lists the market volume of North America (107 kt) and Asia Pacific (553 kt) for 2012. The data for Europe and the RoW countries is missing in the sample version. From one of the companies contacted for an interview I received an overview of the European production shares per company. Summing these up I can get an estimate of the European production quantities, which is 327 kt. However, it needs to be noted that the year of these numbers as well as the original source of these information is unknown. Due to the unknown origin of this data, the overview is not provided here, but the researcher can provide it on request.

Adding the European numbers to the ones from North America and Asia Pacific already results in a total that is higher than the 955 k t given in the Grandview Research (2019) report. Though, this number also seems rather low as the USGS gives 1010 kt as the production capacity in 2012. For consistency reasons, 1 000 kt are chosen as the global production total as this is the number that is used throughout this thesis and in the MFA as the current production volume. For a discussion on this number see 8.3. The RoW is calculate as the difference between summing up the numbers for North America, Asia Pacific and Europe and the global production total assumed to be 1 000 kt. Table 7 shows the final shares of the calculations.

Table 7 Calculated global SiC production shares, based on Grandview Research (2019)

Region	Quantity in kt	Percent
North America	107	11%
Europe	327	33%
Asia Pacific	553	55%
Rest of World (RoW)	12	1%

The second way is based on USGS (2021) data. Figure 9 shows the mean yearly production capacity for the reported countries based on the USGS reports.

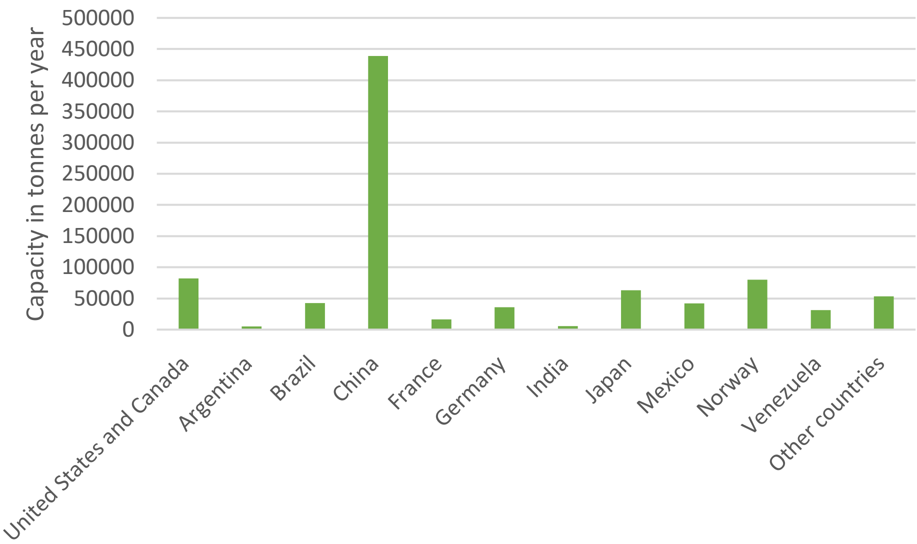

Figure 9 Mean yearly SiC production capacity (USGS)

When assigning the numbers from 2021 to the same categories as used before (North America, Europe, Asia Pacific and RoW), the shares look different from the ones above (seeTable 8 World Shares SiC calculated based on USGS (2021) data). The total global production capacity also in this case is assumed to be 1 000 kt per year, which is also reported by the USGS. A further discussion on this number can be found in 8.3.

Table 8 World Shares SiC calculated based on USGS (2021) data

Region	Quantitiy in kt	Percent
North America (United States)	40	4%
Europe (France, Germany and Norway)	135	14%
Asia Pacific (China, India and Japan)	515	52%
RoW (Argentina, Brazil, Mexico, Venezuela and other countries)	135	14%

Both ways of calculating have their flaws. Generally, it needs to be noted that some of the differences might also come from the fact that data is from different points in time. However, data by the USGS (2021) from the past two decades, shows that the market and production of SiC is rather stable (see Figure 10), which makes it appropriate to not take the specific years into account for the assumptions made here. Though the uncertainties surrounding this should be kept in mind.

The shares from the Grandview Research (2019) based calculations seem to massively overestimate the North American production. This is likely due to the fact that the North American numbers give the market volume and not the production itself. From the USGS (2021) it also can be seen that the US imports a lot of SiC which adds to the market volume but not to the production. The European production numbers are much higher in the first calculation of shares than they are in the USGS reported calculations. This is likely because the USGS only reports some countries individually. The countries they report are chosen in a way that they are both relevant for SiC as well as for fused aluminum oxide, which are both reported in the same fact sheet. This means some countries that are relevant for the European SiC production are left out, such as the Netherlands (65 kt (Xavier & Oliveira, 2021)) or Romania which on the overview sheet of European producers referred to before seems to produce 62 kt. These are significant production numbers which in the USGS case fall under “other countries” as only Germany and France are reported on. The numbers for the Asia Pacific region are comparably similar in both cases. Though the USGS data is slightly lower, which is probably again due to the fact that for the region only three countries (China, India, Japan) are reported but there might be other countries producing SiC that in the USGS reporting fall under “other countries”.

For this thesis a combination of the two calculations is used. For North America, the data from the USGS is used. For Europe the provided overview used in the first approach is used, as the USGS data misses out on some important European production. For the same reason for the Asia Pacific region the Grandview Research (2019) data is used. The difference between adding these three regions together and the 1 000 kt global production, give the RoW production numbers. Table 9 World SiC production shares used in thesis shows the final share used in this thesis based on this approach.

Table 9 World SiC production shares used in thesis

Region	share in kt	Percent
North America	40	4%
Europe	327	33%
Asia Pacific	553	55%
Rest of World (RoW)	79	8%

8.3 Global SiC production (capacity)

In this section a discussion is presented on the available data of the global SiC production. This is an important aspect for this thesis, as this number is the starting point of the MFA. In general, it also helps to get an impression of the actual size of the SiC market and can also help to make an estimate on the global energy needs of SiC production.

In this thesis global yearly SiC production is assumed to be 1 000 kt. The basis for this assumption is data reported by the USGS. The USGS (2021) states this number as the current global production capacity. The last word is important to note, it is the global capacity and not what is actually produced. What needs to be noted about the USGS data is that there is a remarkable difference between the reported production capacities per country and what is given as a total. Figure 10 shows the comparison between the world production capacity total and the total that is derived when summing up the production capacity numbers per country as also given by the USGS. The USGS notes for its total that it is rounded, though the difference seems rather large for rounding errors. While the reason for this divergence cannot be established, it is important to note this as an uncertainty factor.

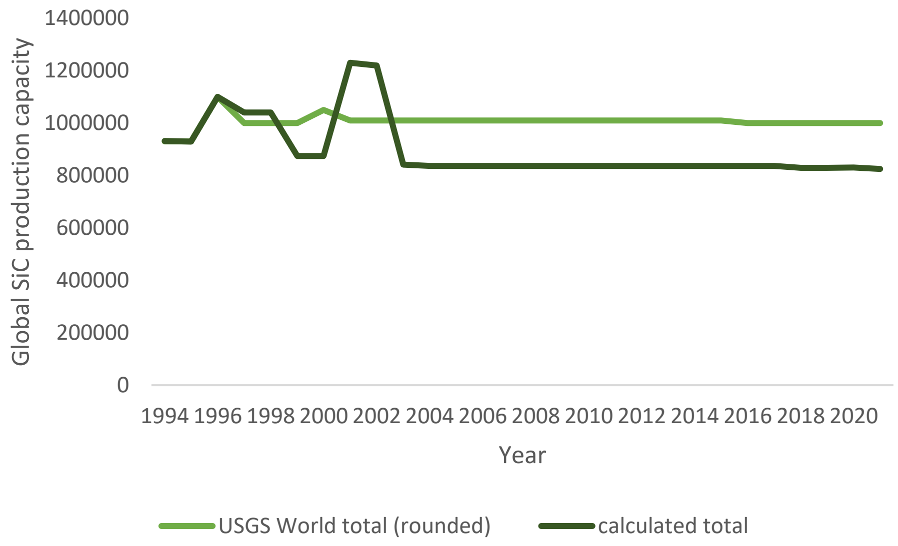

Figure 10 Comparison reported vs. calculated world total SiC production

Grandview Research (2019) gives 1060100 t as global SiC demand in 2013. Tanaka (2011) reports 800000 t of global SiC ingot production in years before 2011. In the Silicon Carbide & More Newsletter, in an edition from 2005, that global production is only at 80% (Kennedy, 2005).

Except for the Grandview Research (2019) data, it seems that actual global production is below 1000 kt per year. However, in this thesis 1000 kt is used as annual global production. This is mainly done for illustrative reasons. As discussed in the thesis, only little data could be found on SiC and the MFA generally contains a high level of uncertainty. This means that the MFA rather presents an overview in order to see the different orders of magnitude and to present the system’s structures. It is not about giving precise quantities, as those are not available. Using 1000 kt as the global production, makes it easier to show the different orders of magnitude, as it is a round number that makes it easy to get a feeling for percentages.

8.4 Supply Chain tables

<u>Semiconductor Industry</u>

Category	Data	Source
System Disturbance	After covid Restarting production takes around three months to get up and running again	[s]
	Growing boules taking a long time, a matter of weeks	[i], [e] and [h]
	only around 70% of the wafer can be used to make functioning chips à goal is to improve this to 90 or 95 %	[h]
	by around 2024 there should be a good balance between supply and demand, due to a lot of investment at the moment from suppliers in the production capacity	[h]
	Machines for epitaxy process	[g]
Stockpiling	Currently works on a principle of weeks	[h]
Diversity	work with one main supplier, maybe two. Now that more sources are emerging the goal is to qualify three or four	[h]
Substitution	annually less than 1% of all Si is being replaced	[h]
	transition from Si to SiC is easier than that from SiC to GaN which would be more expensive, takes more time and generally means bigger change	[h]
Use reduction	Around half of material is lost while sawing	[i]
	Cold-split process: losses can be reduced by a third	[g]
	the polishing of the wafers after epitaxy. During this process around half to two thirds of material is lost.	[g]
Recycling	Test wafers, less than 5%	[g]
	Recycling after use of chip extremely difficult	[i] and [h]
Closer Cooperation	more cooperation with wafer producers is needed to prevent defect material	[h]
Information		
Influence		
Laws and regulations	European RoHS (Restriction of hazardous substances) directive	[i]
	Ip Protection	[h]
	Only use for intended purpose	[h]
Driving forces	Price	[h]
	Moving to next wafer diameter would take around 5-7 years	[h]
	increasing energy prices only further the need for more efficiency and therefore increase demand for SiC	[h]
Competition with Si and GaN	SiC substrate for GaN chips in high frequency applications adds 10-15% more material use	

Other Industrial Applications

Category	Data	Source
Systems Disturbance	Emissions regulation, high electricity costs, transportation costs, the covid pandemic and the war in Ukraine	[l]
Stockpiling	Not seem to be a common thing	
	Physical stocks 14-30 days (contracts run over one quarter)	[f]
	Supplier has 50000t stocks per year in Europe	[f]
	3-6 months	[b]
	No stockpiles	[m]
Diversity	Around 20-30 competitors in SiC production market	[d]
	Two sources that can supply material with purity requirements	[f]
Substitution	Replacing ferro silicon	[f]
Use reduction	Highly sector dependent	
Recycling	Slurry recycling about 80-82% of SiC can be recycled	[p] & [o]
	Slurry recycling will no longer be relevant in the next 3-5 years	[p]
	Refractories in waste incineration have a lifetime of around five years, during use very little material losses	[n]
	Refractories for steel production lifetime 30 min to one week, during use 50% of material lost at the end of the lifetime not much material is left as it goes into the slag	[n]
	Refractories for cement production, lifetime three years and 50% material loss	[n]
Laws and Regulations	REACH EU legislation on chemical substances	[d] and [f]
	Military equipment export and supply chain restrictions	[b]
	EU Industrial Emissions Directive	[d]
	Occupational Safety and Health Administration	[m]
Starting a new plant	Take around one year	[d]
Driving forces	Energy – availability and price	[d]
	Potential of substituting SiC for ferrosilicon	[f] and (Grandview Research, 2019)