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RESEARCH ARTICLE

Integrating material flow analysis and supply chain resilience analysis to study silicon carbide

Catrin Böcher[1] | **Benjamin Sprecher**[2] | **Tomer Fishman**[1]

[1]Institute of Environmental Sciences (CML), Leiden University, Leiden, The Netherlands

[2]Industrial Design Engineering, TU Delft, Delft, The Netherlands

Correspondence
Catrin Böcher, CML Leiden University, P.O. Box 9518, 2300 RA Leiden, The Netherlands.
Email: c.bocher@cml.leidenuniv.nl

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Abstract

Silicon carbide (SiC) is a niche nonmetallic material that is essential in many industrial processes. Here, we integrate material flow analysis and supply chain resilience analysis to understand global SiC stocks and flows and to assess its supply chain. We use industry interviews to fill data gaps and collect information on the SiC system to overcome data scarcity. We find that globally around 1000 kt of SiC is produced each year. The biggest use of SiC is the abrasives industry (40%), followed by metallurgy (28%), refractories (20%), technical ceramics (0.7%), other uses (0.7%), and semiconductors (0.01%). As an energy-intensive material, the SiC supply chain is under pressure, increasing the relevance of resilience considerations. Besides typical supply chain risks such as low diversity of supply and geopolitical trade restrictions, SiC particularly faces risks due to its energy-intensive production process and associated emissions. In the SiC semiconductor supply chain, losses of nearly 75% are a particular issue. Due to high demand in the SiC market, stockpiles are negligible, and substitution is difficult in most sectors. We find that in the case of SiC, sustainability measures such as use reduction, recycling, or decreasing energy use or emissions would also positively contribute to supply chain resilience. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
abrasives, energy-intensive, industrial ecology, industrial materials, refractories, semiconductors

1 | INTRODUCTION

The COVID-19 pandemic and the war in Ukraine have caused major disruptions in international trade, exposing vulnerabilities in global supply chains. Chip supply chains were particularly affected by the COVID-19 pandemic (Aguilar-Hernandez et al., 2023). The Russian invasion of Ukraine, and the sanctions that followed, caused a rapid increase in energy prices, particularly in Europe. Increasing energy prices, which already started before the invasion, caused difficulties in energy-intensive industries, such as steel or fertilizer production (Sharafedin et al., 2021). Russia's war on

Ukraine not only disrupted global markets in terms of increasing energy prices but also caused concerns about the supply chains of many critical raw materials (CRMs), such as aluminum, nickel, palladium, and vanadium (OECD, 2022).

Besides economic damage in general, supply chain disruptions can slow down the development of industries needed for sustainability transitions. The energy transition is heavily dependent on a wide range of materials (Watari et al., 2019). To overcome vulnerabilities and prevent disruptions from slowing down sustainability transitions, researchers and practitioners have turned to investigating supply chain resilience (Brink et al., 2022). A well-known example is that of the rare earth element (REE) supply chains, which have been extensively studied in the wake of a well-publicized supply disruption in 2011 (e.g., van Nielen et al. (2023) or Sprecher et al. (2017)).

CRMs, of which REEs are also a part, have so far received the most attention when it comes to supply chain resilience research. These assessments have led policymakers as well as industry to act. The EU, for example, is keeping an eye on these materials by regularly assessing the criticality of various materials, to determine the materials that should receive special political attention (European Commission, 2023). Other materials do not receive similar attention from policymakers or industry. Examples of studies researching two of these CRM are the studies by Graedel and Miatto (2023) on vanadium and Padilla and Nassar (2023) on tantalum.

Silicon carbide (SiC) is not a very well-known material and is of less economic value than most of the CRMs. However, SiC is used extensively in the semiconductor industry, mainly to replace silicon (Si) as a semiconductor material in some chips. SiC is a highly popular semiconductor material as it can decrease energy losses and make more efficient chips (Goldman Sachs, 2019). This means that in the future, SiC will likely play an important role in the energy transition. Besides in the semiconductor industry, SiC is of importance for several other industrial processes. It is used as an abrasive, as a refractory, in technical ceramics and metallurgy (Xavier & Oliveira, 2021).

However, so far, SiC has not received much attention from a systems perspective. One exception is a report by the Dutch Environmental Assessment Agency on the decarbonization options of the Dutch SiC industry (Xavier & Oliveira, 2021). To our knowledge, no other comprehensive efforts exist that investigate SiC from a systems perspective.

Nevertheless, the SiC supply chain and material flows are interesting as an example of a material not used much in end-products, but that is important in industrial processes. Also, its production process is highly energy-intensive (Xavier & Oliveira, 2021). This can be a relevant factor impacting the supply chain and its vulnerabilities.

We set out to better understand the role of SiC in the economy as an example of a niche nonmetallic material. We investigate the following research questions:

How does SiC flow through the global economy?
How resilient is the SiC supply chain?

While we analyze the global material flows of the SiC supply chain, the resilience of the supply chain is viewed from a European perspective.

2 | METHODS

We use both material flow analysis (MFA) and supply chain resilience analysis.

Our MFA is static and follows Brunner and Rechberger (2016). We have a global system boundary, including all applications of SiC. The temporal boundary is a representative year in the period around 2018–2022, disregarding impacts from the pandemic. We use a representative year due to data limitations and a stable SiC market. For a more comprehensive discussion see supporting information S1.1. The MFA is carried out in STAN 2.7 (Cencic & Rechberger, 2022). Figure 1 shows the system definition. There is a lot of missing or low-quality data on SiC, leading to numerous modeling assumptions. These are reported in the supporting information (S2.1). We use an adjusted version of the pedigree matrix, based on Laner et al. (2016), to semi-quantify uncertainties (see supporting information S1.3 for more details).

To study the resilience of the SiC supply chain, we use the framework developed by Sprecher et al. (2017). Resilience of material supply chains is defined 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" (Sprecher et al., 2015). Resilience is actor-dependent. We take a European perspective on the supply chain resilience analysis. The framework includes seven variables. We split these variables into two parts. First, we investigate possible causes of disruption using the following variables: past supply disruptions, diversity of supply, and laws and regulations. Then, we examine the different resilience mechanisms to alleviate disruptions: stockpiling, substitution, use reduction, and recycling.

Findings from the MFA and the supply chain resilience analysis are integrated to enhance our understanding of the overall SiC supply chain. It is not simply that MFA results can be used to quantify whether the demands of society are met, and therefore, a system is resilient. Generally, as Sprecher et al. (2015) noted in their case study of NdFeB, a certain elasticity in supply and demand is needed so that disruptions can be absorbed by the system.

Our MFA results serve as input for the supply chain resilience analysis in several places. Figure 1 shows where the MFA results serve as input for the supply chain resilience analysis. The size of a stockpile that can cover a certain number of months is estimated using MFA output. The MFA also

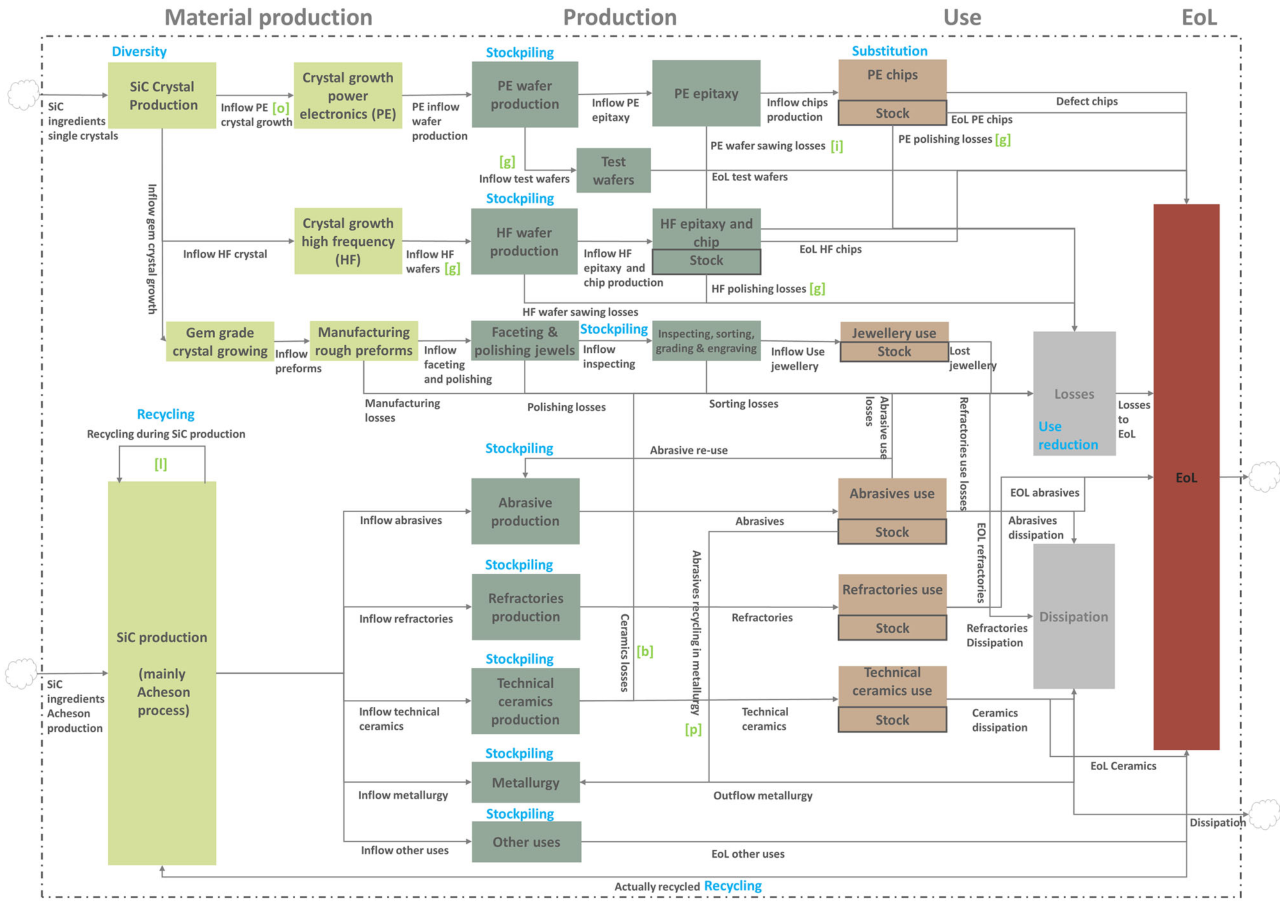

FIGURE 1 Material flow analysis (MFA) system diagram (global for one current year [2018–2022], annotated with resilience and interview connections).

indicates that stockpiling could be done in the production process. Regarding stockpiling, it is important to note that only stockpiles that last longer than a year are visible in the MFA due to the time frame of 1 year in the MFA. Use reduction can be in parts studied by looking at the losses identified through the MFA. The results of describing the different uses of SiC in the MFA can serve as the basis for uncovering its substitution potential. At the same time, the findings we obtained through the supply chain resilience framework also add valuable information to constructing our MFA. Figure 1 also shows where interview results serve as input for the MFA.

2.1 | Data

Primary data on SiC are sporadic. We therefore base our research on data triangulation, using interviews, academic literature, and gray literature.

We contacted around 90 companies and experts, 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 we approached companies from the semiconductor industry was by the participation of the first author in PCIM Europe, an industry fair for power electronics, intelligent motion, renewable energy, and energy management that took place in Nuremberg, Germany, between May 10 and 12, 2022. The interviews took place between April and July 2022.

We anonymize the names of the interviewees as well as the organizations they represent for reasons of confidentiality. Table 1 provides an overview of our interview partners, each of which is assigned a letter for identification. The order of letters corresponds to the order in which contact was made with interviewees. More information on the interviews can be provided upon request.

The interviews consisted of two parts. The first part included company- and sector-specific questions to gather data for the MFA and to understand the system. These questions varied per interview based on the background and expertise of the interviewee and emerged from the interview. The second part was semi-structured and focused on the supply chain resilience analysis, based on the questionnaire developed by Sprecher et al. (2017). The questionnaire covers the seven resilience concepts: system disturbances, stockpiling, diversity, substitution, use reduction, recycling,

TABLE 1 Interview partners overview.

Abrasives
Small German abrasives manufacturer **[a]**
Re-seller of SiC for abrasive products 1 **[j]**
Re-seller of SiC for abrasive products 2 **[k]**
German abrasives association **[q]**
Non-European abrasives association **[r]**
Refractories
German refractories producer **[n]**
Ceramics
Manufacturer of ceramics products in Europe **[b]**
German researcher on SiC in ceramics and SiC recycling **[o]**
Semiconductor industry
European researcher on SiC for the semiconductor industry **[c]**
European research project on SiC supply chain for semiconductor applications **[e]**
SiC semiconductor company 1 **[g]**
SiC semiconductor company 2 **[h]**
SiC semiconductor company 3 **[i]**
PCIM attendees **[s]**
Steel
Steel producer **[f]**
General
SiC association **[d]**
European SiC producer **[l]**
Geological survey **[m]**
German SiC recycling company for slurry recycling **[p]**

Abbreviation: SiC, silicon carbide. The letters in square brackets are used to refer back to the individual interviews both in the text as well as in Figure 1.

and feedback loops. These seven categories were also used to code the interviews. The coded interviews can be found in supporting information S2.3., S2.4., and S2.5.

3 | RESULTS

We first present the results of our global MFA and then the results of the resilience analysis.

3.1 | SiC uses and geographical distribution of SiC production

We find that the global SiC production capacity is about 1000 kt per year. With 553 kt (55%), the Asia Pacific region is currently the biggest producer, followed by Europe with 327 kt (32%), RoW with 79 kt (8%), and North America with 40 kt (4%).

The main areas of application of SiC are, in order of volume; abrasives, metallurgy, refractories, technical ceramics, other industrial uses, semiconductors, and jewelry (see Figure 2). These use SiC either in single crystal form (semiconductors, jewelry) or in forms, for example, material produced via the Acheson process (abrasives, refractories, technical ceramics, metallurgy, and others) (Xavier & Oliveira, 2021).

The production locations have changed over time. Fuchs (1974) notes that in 1960 the West-European production capacity was only 75 kt per year, with production capacity increasing to 160 kt per year in the 1970s. In the United States and Canada, however, a production capacity of 160 kt in the 1970s (Fuchs, 1974) was much above current North American production levels (40 kt). Overall, global production capacity increased from 600 kt in the 1970s (Fuchs, 1974) to around 1000 kt currently. The biggest growth of capacity can be observed in the Asia Pacific region, where production was negligible in the 1970s, but currently is the biggest producer with 553 kt yearly. Figure 3 aggregates some of these regions to make

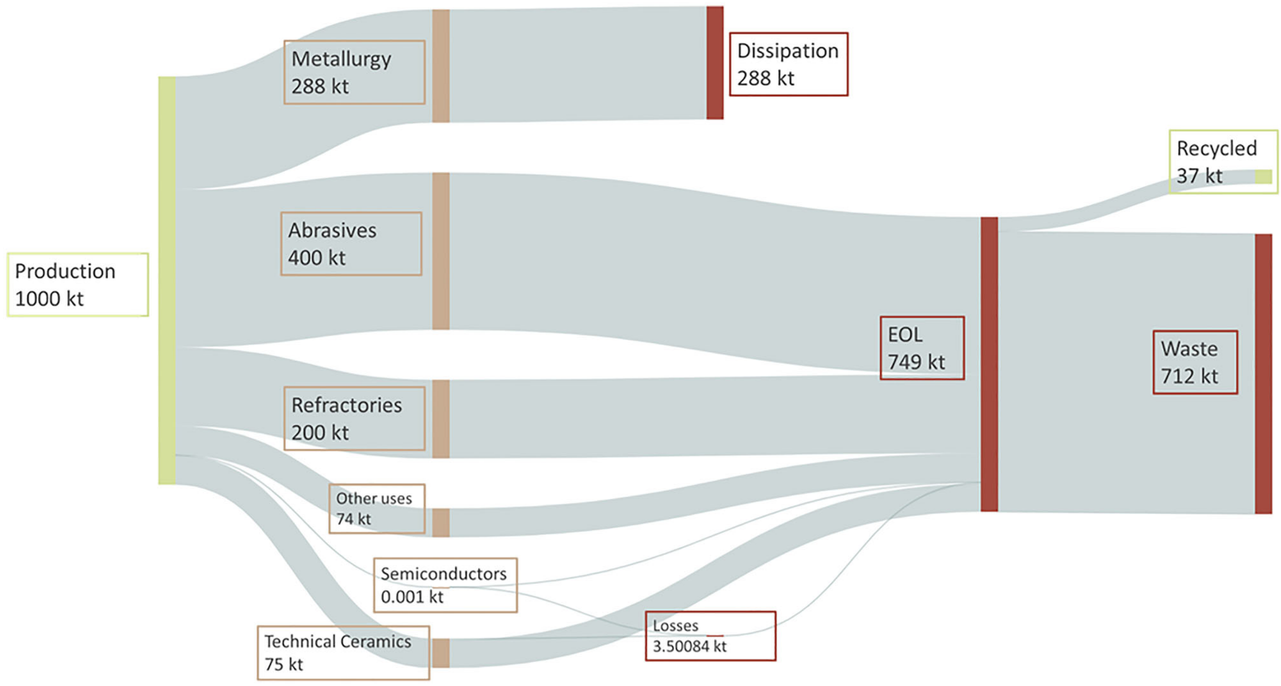

FIGURE 2 Current (2018–2022) global uses of silicon carbide (SiC) in kt (data can be found in S1.5).

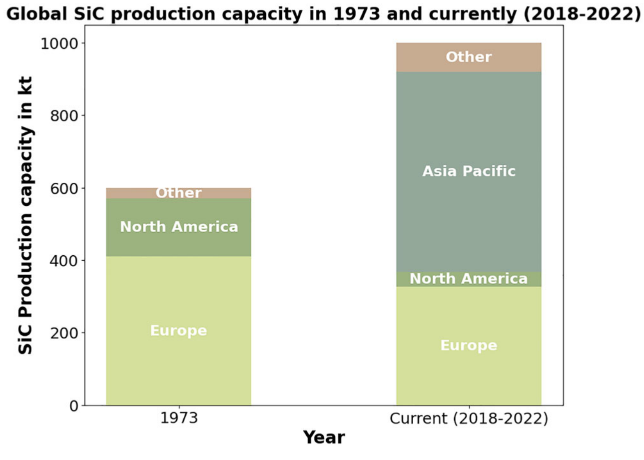

FIGURE 3 Global silicon carbide (SiC) production in 1973 (adapted from Fuchs, 1974) compared to 2018–2022 (for underlying data, see supporting information S1 Table S3, S1.4).

the capacities in 1973 and currently comparable. For 1973, Western Europe and the Comecon countries are aggregated to Europe and USA/Canada is labeled as North America. Some more background on the historical and current SiC production data can be found in the supporting information (S1.2).

3.2 | Diversity of supply

Our analysis finds that it is rather difficult for companies to establish a diversity of suppliers. Currently, there are only around 20–30 competitors in the global SiC production market (SiC association [d]). For the United States, the USGS (2021) reports that two companies produce SiC. However, 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, further limiting the choice of companies that wish to diversify. As a steel company noted, their choice of SiC is limited due to their strict requirements on the aluminum content in the material. This company was only able to identify two sources that could supply this particular grade of SiC (Steel producer [f]). Another interviewee noted that the purer the SiC you want, the more difficult it is to get (German refractories producer [n]).

As the supply chain for semiconductors looks different than that of the other industrial applications, we also find different potential disturbances. 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 (SiC semiconductor company 2 [h]). The same interviewee is optimistic that from 2024 onward there should be a better balance between supply and demand, due to a lot of recent investment from suppliers in the production capacity (SiC semiconductor company 2 [h]). However, 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. This 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 (European research project on SiC supply chain for semiconductor applications [e]).

The problem of increasing production capacity lies in the crystal boule growth process. This process takes a long time. Any disturbance during that process can have long-lasting effects, as illustrated by the effects of the COVID-19 pandemic on the supply chain. Growing the boules from which wafers are cut has high energy requirements and takes a relatively long time (a matter of weeks), longer than for Si (SiC semiconductor company 3 [i], European research project on SiC supply chain for semiconductor applications [e], and SiC semiconductor company 2 [h]). Restarting production after a disruption takes around 3 months (PCIM attendees [s]).

A low diversity of suppliers can form a supply risk, especially under geopolitically tense circumstances. Based on the above-discussed global market shares, we find an HHI of 4194 for the global SiC market, which indicates a high market concentration. Effects of geopolitical conflict could, for example, be observed in the recent past. The war in Ukraine caused some supply disruptions, particularly for the European market. 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 (Steel producer [f]). However, as the steel company only requires rather small quantities, this did not have a huge effect (Steel producer [f]). A big SiC producer is located in Russia. This means that currently, a big supplier is falling away (German refractories producer [n]). This causes supply issues for companies getting most of their supply from Russia as a re-seller of SiC reports (Re-seller of SiC for abrasive products 1 [j]).

As we show in Figure 3, the Asia Pacific region has a significant share in the supply of SiC. This is mainly due to the high production capacity in China. Two interviewees indicated concern about supply coming from China, mainly due to recent transportation issues, particularly after the pandemic (SiC association [d] and German refractories producer [n]). It is expected that the Chinese government will introduce policies to increase SiC production, in concert with export restrictions on SiC (Grandview Research, 2019).

3.3 | Supply risks

Problems with SiC supply are mainly due to environmental regulations on emissions, high electricity costs, transportation costs, the COVID-19 pandemic, and the war in Ukraine (European SiC producer [l]); German refractories producer [n]). We identify three related bottlenecks in the supply chain, namely, energy prices, green sources for energy and raw materials, and CO2 prices and emissions reduction (European SiC producer [l]). These bottlenecks lead to producers not being able to take on new customers and still having problems providing sufficient supply to their existing customers. At least in the refractories sector, the lack of raw materials limits the growth potential of companies (German refractories producer [n]).

Production of SiC is highly energy intensive, 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 most common process to produce SiC is the Acheson method, using silica sand and petroleum coke as its main ingredients. The semiconductor and jewelry industries do not use the Acheson method, as these industries require a material with much higher purities. However, due to secrecy in these industries, not much is publicly known about these processes.

The Acheson production process requires temperatures of around 2000°C, varying per plant and process details (Xavier & Oliveira, 2021). Traditional furnace installations consume 22–28 GJ of energy to produce 1 tonne of 100% pure SiC (European Commission, 2007; Xavier & Oliveira, 2021). Energy intensity did improve somewhat over the last decades, as in 1974 this was still 27–28.8 GJ per tonne of SiC (Fuchs, 1974).

Sufficient availability of affordable energy is a prerequisite to producing SiC. Production of SiC can put energy grids under pressure due to the high demand for energy. If electricity becomes more expensive than SiC itself, in the short term, some producers might start selling electricity instead, which has historically happened (SiC association [d]). This could mean that less SiC enters the market, which forms a potential supply risk for SiC. This highlights the need to find alternative routes of production besides the polluting and energy-intensive Acheson process (German researcher on SiC in ceramics and SiC recycling [o]).

High emissions are an unwanted side-effect of using high-temperature processes. Dust explosions, also known as blazer incidents, can be an issue during SiC production. For example, a local media outlet in the Netherlands reported six of these incidents in 2020 and an average of 40 per year in earlier years (Drent, 2021a). SiC production must also deal with SiC fibers, which are suspected to be carcinogenic. This led to a dispute between the local government and the Dutch SiC producer on how to include this risk in the production permit (Drent, 2021b).

3.4 | Resilience strategies

If supply is disrupted, there are several strategies that companies can apply to reduce the impact these risks have on their operations, we investigate stockpiling, substitution, use reduction, and recycling.

3.4.1 | Stockpiling

Stockpiling does not play an important role in any of the use categories in the SiC supply chain. Due to the low production capacity and growth of the industry, stockpiling is currently not possible beyond working inventories in the order of several weeks (SiC semiconductor company 2 [h]). However, building up a stockpile could be a goal for the future (SiC semiconductor company 2 [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 (SiC semiconductor company 2 [h]).

Similarly, for abrasives, while not entirely excluded at individual companies, stockpiling is unlikely due to high demand (European SiC producer [l]). On a country level, the United States has not kept stockpiles of SiC abrasive since 1999 (USGS, 2000). Stockpiles at foundries are difficult as stocks take up space (e.g., building warehouses), which costs money (Re-seller of SiC for abrasive products 2 [k]). Based on our MFA, this would, for example, mean that if the abrasives industry would like to build stockpiles that would last half a year, it would need to be able to store 200 kt of SiC (half of its yearly inflows).

3.4.2 | Substitution

Although highly dependent on the specific applications, for almost all applications we find that substitution of SiC is challenging (*Ceramics*: Manufacturer of ceramics products in Europe [b]; *Abrasives*: Re-seller of SiC for abrasive products 1 [j] and German abrasives association [q]; *Refractories*: German refractories producer [n]). The exception is the steel industry, for which substitution depends on the exact application. If SiC is used as a carbon source then one could instead use more recarburizer and FeSi or even SiMn and recarburizer, depending on the steel grade (Steel producer [f]).

However, SiC itself is currently considered a substitute for ferrosilicon in steel-making due to rising prices of ferrosilicon (Steel producer [f] and Re-seller of SiC for abrasive products 2 [k]). In the semiconductor industry, SiC also serves as a substitute for Si. Conversely, Si could also be a substitute for SiC, though at the cost of losing the efficiency advantages of SiC. It needs to be noted that in the case of semiconductors, one cannot just easily decide to substitute one for the other as the whole system needs to be re-designed depending on whether it uses a Si or a SiC chip (European researcher on SiC for the semiconductor industry [c], SiC semiconductor company 3 [i]). One interviewee stated that annually, less than 1% of all Si is being replaced by SiC (SiC semiconductor company 2 [h]). One could assume that the reverse could also hold if circumstances change. This, however, is not empirically verified.

Overall, this leads to the observation that the SiC supply/demand balance is as much at risk of being disrupted through increased demand for SiC because of it being used as a substitute, as that substitution of SiC can help alleviate supply/demand balance issues.

3.4.3 | Use reduction

In general, we find that SiC use is mostly already optimized, with little potential for further use reduction. Our MFA model was not able to quantify all losses. However, we identify significant losses in some of the industries. For example, for refractories, losses occur in the use phase for some of the applications. Refractories in steel and cement production have losses of around 50% during their use. However, due to a lack of data on the shares of different types of refractories, we could not quantify these losses for refractories in general. Also, it is questionable how much of the losses can realistically be prevented. Additionally, it is very application-specific whether the losses are dissipative or recoverable.

Reducing material use, thus making the product thinner, would lead to the need for earlier reparations (German refractories producer [n]). Making refractories thinner is risky, for example, in the steel industry where breaking refractories can lead to steel leakage (German refractories producer [n]).

There is a general lack of data to quantify losses during the use phase. This is particularly relevant in the abrasives industry where material is "lost" while used as an abrasive, which means that it is no longer available for recycling, as it is not collected.

The losses quantified in the MFA are mainly due to losses in the production of technical ceramics, where nearly 5% of the material is lost in our MFA model. One interviewee reported that for some types of SiC ceramics, losses can be 20% during production (Manufacturer of ceramics products in Europe [b]).

In the semiconductor industry, nearly 75% of material is lost during production. When cutting the boule into wafers, around 50% of the material is lost (SiC semiconductor company 3 [i]). In subsequent processing steps, only around 70% of the wafer can be used to make functioning chips (SiC semiconductor company 2 [h] and SiC semiconductor company 1 [g]).

Decreasing losses can positively contribute to reducing material use (Allwood et al., 2011). In the semiconductor industry, this is an ongoing effort. Regarding the sawing losses, a new method is currently under development that could reduce these losses by one-third (SiC semiconductor company 1 [g]). Concerning wafer usage, the ultimate goal is that 90% or 95% of the wafer could be used to make functioning chips (SiC semiconductor company 2 [h]).

3.4.4 | Recycling

We find recycling to be an important topic in the SiC industry, with many interview partners expressing strong interest in increasing recycling rates. For producers, recycling is interesting as it can help to save energy and emissions and potentially mitigate supply constraints. However, according to the literature, only around 5% of the material is currently recycled, and it is unknown where in the supply chain the recycling is taking place (USGS, 2021). Our MFA indicates some recycling taking place in the SiC production process, which is possible during the melting process in the Acheson process and through recycling off-grades from the processing plants (European SiC producer [l]). In general, the potential for recycling varies significantly for the different SiC uses.

In the semiconductor industry, recycling at the EOL level would be in the form of chips. However, recycling of chips is described as extremely difficult (SiC semiconductor company 3 [i] and SiC semiconductor company 2 [h]) because in a chip, the material is tightly mixed with other materials. 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€ (SiC semiconductor company 1 [g]). Currently, the chips are disposed of at the end of their lifetime (SiC semiconductor company 1 [g]). The only type of recycling already happening is during the production process and at the wafer level (as indicated by our MFA). 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 rather than in normal production (SiC semiconductor company 2 [h]). According to one interviewee, the test material represents less than 5% of the overall SiC used (SiC semiconductor company 1 [g]).

Regarding technical ceramics, the challenge is economical rather than technical. For example, mechanical seals in pumps in cars are not economically recyclable as their original price is only in the range of 10 cents per piece (German researcher on SiC in ceramics and SiC recycling [o]). The car and pump would need to be dismantled to take it out and collect it (German researcher on SiC in ceramics and SiC recycling [o]). However, some ceramics products, for example, kiln furniture, can be easily sorted at their end of life and could be collected on a larger scale, offering recycling potential (German researcher on SiC in ceramics and SiC recycling [o]).

In the refractories industry, we find that recycling depends on the contamination of the material, depending on what other material is attached to the refractory boards after usage. Furthermore, some refractory applications have high losses of material that goes into slags. Refractories in the steel industry are reported to have lifetimes between 30 min and 1 week, and during their use, around 50% of the material is lost (German refractories producer [n]). The material that is left is often grinded down and used as slag conditioner (German refractories producer [n]).

Abrasives are currently not being recycled on a large scale. However, the example of SiC recycling from slurry coming from Si wafer production for PV panels, where 80%–82% of SiC could be recycled, shows that there are possibilities (German SiC recycling company for slurry recycling [p] and German researcher on SiC in ceramics and SiC recycling [o]). Some of the material is directly re-used and some that does not fulfill the quality requirements anymore is used in metallurgy (189 tons). This specific recycling process is phasing out due to a change in sawing technology, but it shows that abrasives recycling can be possible with rather high recycling rates.

Based on the MFA, we can estimate the effects of recycling. Assuming that we would recycle 30% of SiC in technical ceramics and 20% of material in abrasives, we could save the production of about 102 kt primary SiC. Disregarding the quality of the material, this would suffice to cover all inflows for technical ceramics, or more than one-third of metallurgy SiC needs. This could also indirectly be a way for companies to build up a sort of stockpile of material; without having to bear the cost or space problems, the stocks would be within their industrial processes. Companies could exchange their used product at the end of life for new (recycled) material.

4 | DISCUSSION

SiC faces risks in many aspects, which can be mapped to the supply chain (see Figure 4). Some risks are similar to many other global supply chains such as those related to trade, geopolitics, or low diversity of suppliers. Others, like high-energy requirements and emissions, are more distinctive of the SiC supply chains.

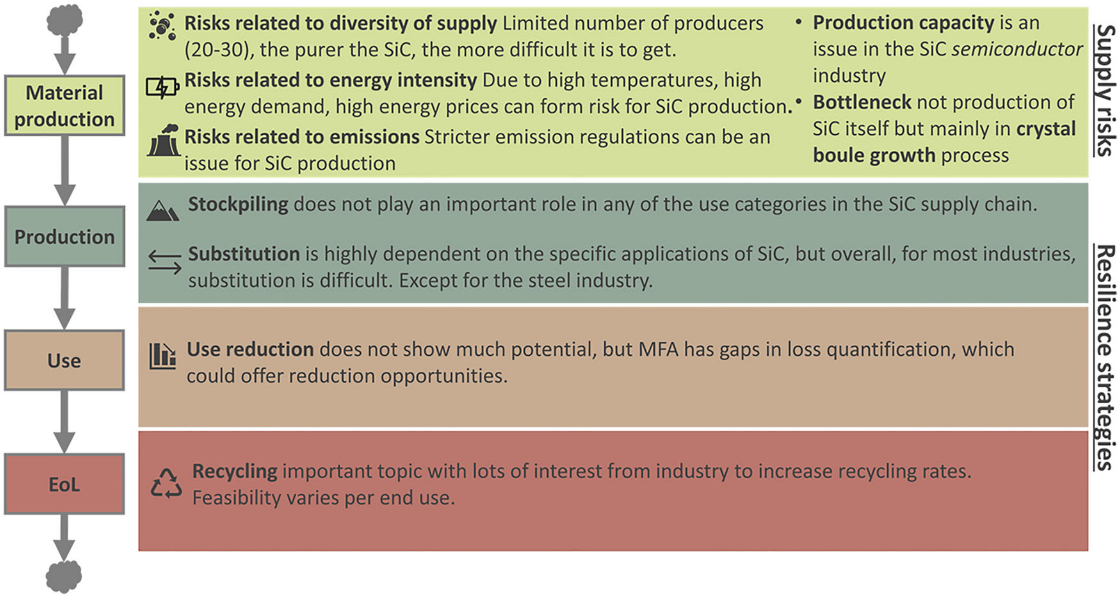

FIGURE 4 Synthesis of results.

4.1 | SiC resilience

Substitution will likely not contribute to making the SiC supply chain more resilient. For most industries, using SiC substitution is either impossible or only at the loss of significant product performance. Where substitution is possible, this might lead to problem-shifting; for example, in the steel industry, SiC and ferrosilicon can be substituted for each other. However, ferrosilicon production is also highly energy intensive and thus faces similar risks. This is opposite to findings from resilience analysis of the rare earth supply chain, where it was found that substitution was the main resilience mechanism (Sprecher et al., 2017).

Stockpiling also currently does not function as a mitigation strategy. The SiC supply chain illustrates the difficulty of building up strategic stockpiles for a material for which demand consistently exceeds supply. With our sample calculation for stockpiles in the abrasives sector, we show the quantity of material that would need to be stored, to form a useful stockpile, which would require much space and money to store. We therefore consider it a low potential supply risk mitigation strategy. If stockpiling were applied more widely in the SiC supply chain, it could only mitigate supply risks in the short term as interviewees pointed out that the space and money necessary to build up stocks is considerable.

To make the SiC supply chain more resilient in the long term and to address the SiC-specific risks of energy and emissions, more systematic implementation of resilience mechanisms in the supply chain is necessary. This could, for example, be done by reducing losses of SiC and increasing recycling. Regarding use reduction, our results suggest that in the case of SiC, it does not offer a lot of potential. However, reducing losses could play a relevant role. Recycling seems to have high potential but, as always, has the challenge of being similar in costs and energy use as primary production. Besides the technical challenges of recycling, the collection of end-of-life products is challenging.

4.2 | Tackling energy supply risks

To reduce the risks associated with energy demand, smart integration of SiC production facilities into energy grids could be a promising development. Leveraging their high energy consumption, SiC production plants could serve to balance the grid to deal with the intermittent supply of renewable electricity. This is already applied by the Dutch production facility, which is currently able to shut down the entire production process within 2 minutes when necessary (Xavier & Oliveira, 2021).

4.3 | Resilience and sustainability

Measures to make supply chains more sustainable (e.g., use reduction, recycling, or decreasing energy use or emissions) also positively contribute to supply chain resilience. This shows the synergies that can emerge from resilience research in sustainability-related fields. As Meerow and Newell already noted in 2015, more resilience research from an industrial ecology perspective would contribute to a better understanding of the relationship between resilience and sustainability, as resilience is often seen as a necessary part of a sustainable system. Future research could also investigate the trade-offs that might result from resilience for sustainability ambitions, such as lock-in effects (Sprecher et al., 2015). Such trade-offs highlight that sustainability issues need to be considered in any resilience efforts.

4.4 | Limitations and uncertainties

While all MFA and resilience studies rely on assumptions to a certain degree, the lack of data on the SiC industry means that the present work relies more than usual on assumptions and expert estimates. Uncertainty is particularly prevalent in the material inflow to the individual end-uses (as described in supporting information S1.3). For example, some products belong to multiple industries, which makes the classification of end uses difficult and introduces the risk of double accounting material flows or leaving out relevant products.

The decision to use a representative year of the period 2018–2022 rather than a specific year could be seen as adding uncertainty to the analysis. However, we argue that this is preferable over choosing a specific year in which the data are likely distorted, for example, through the impact of the COVID-19 pandemic.

All three data sources (interviews, academic literature, and gray literature) might have some inherent bias. For instance, gray 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 interviews are heavily Eurocentric with a particular focus on German companies. Since the MFA takes a global view, obtaining data from non-European interview partners would have been desirable, particularly from a Chinese perspective, as it is the biggest producer of SiC. On the other hand, more Europe-specific data on end-uses is unfortunately missing but would be an interesting addition for future research.

4.5 | MFA and supply chain resilience analysis

Combining MFA and supply chain resilience analysis can be a highly complementary combination of methods. MFA provides quantitative insights for the supply chain resilience analysis. For example, we use the results from the MFA to estimate theoretical stockpiling requirements as well as determine the diversity of supply. Future research could further explore the synergies of these two methods and how they can be applied in researching other industrial materials than SiC.

4.6 | SiC and the importance of researching process materials

We observe that limited knowledge of SiC stocks and flows can negatively influence its supply chain's resilience. Low awareness among stakeholders can cause less risk awareness. This means, for example, less attention to creating a diversity of supply or reducing losses.

Furthermore, the lack of information makes a comprehensive analysis of the SiC supply chain more difficult (supporting information S1.3.).

This research shows that relatively unknown specialty materials, such as SiC, should receive more research attention, to elucidate dependencies between industrial processes and materials used during processing (e.g., refractory, abrasive, or ceramics materials). These could lead to unexpected disruptions in our complex industrial systems. A better understanding of what these materials are, how we use them, and the resilience of their supply chains will be necessary to address the issue.

5 | CONCLUSION

While CRMs are currently the focus of attention, we should not neglect some of the process materials that have less obvious importance to our economies but can nevertheless cause significant havoc when their supply chains are not resilient enough to withstand disruptions. Quantity-wise, the majority of SiC is employed in industries other than the semiconductor industry (abrasives, refractories, technical ceramics, metallurgy, and others). In these industries, SiC is not high on the agenda, leading to a lack of data on SiC. For many users of SiC, the material is used in rather low quantities compared to other material inputs, which leads to a focus on other materials instead. Nevertheless, SiC can and has caused disruptions for these producers.

To understand the importance of a material for our economies, we need to be able to understand what we use it for and in which quantities. Our findings highlight that more data on materials like SiC is needed. This knowledge is crucial if we want to make our industries more sustainable and want to increasingly move toward a circular economy.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data, except for interviews, are available in the article's supporting information. Data regarding interviews are available on request due to privacy/ethical restrictions.

ORCID

Catrin Böcher https://orcid.org/0000-0002-1529-5740

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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