Securing supply of silicon carbide semiconductors

A case study at a large automotive OEM

Master's thesis in supply chain management

Oscar Karlsson
Stig Robertsson

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SUPPLY AND OPERATIONS MANAGEMENT

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Stig Robertsson

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Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1

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Oscar Karlsson
Stig Robertsson

Department of Technology Management and Economics
Chalmers University of Technology

SUMMARY
Due to the climate crisis increasing demand for sustainable transportation, the truck industry has started to develop and offer battery electric vehicles. To succeed in this endeavor, improving driving range and fast charging capabilities are key priorities for manufacturers. A technology that can improve both factors is silicon carbide semiconductors. Simultaneously, supply chain disruptions in the wake of the Covid-19 pandemic has shown that semiconductors are especially prone to disruptions and automotive actors have to be mindful of their sourcing strategies.

This thesis has aimed to investigate the silicon carbide market, possible supply network configurations for sourcing silicon carbide, as well as the most important factors the truck company should consider when forming a sourcing strategy for silicon carbide. To achieve this, interviews along with secondary data have been used together with a supply market analysis framework and a supply network configurations framework in order to perform a market analysis and form three supply network configurations. The market analysis and the supply chain configurations are then used to determine the most important factors to consider when forming a sourcing strategy.

It was found that a balanced network configuration where the truck company takes some, but not all control of the supply chain was deemed the most suitable for the company's current situation. The most important factors to consider when forming a sourcing strategy are the allocation of supply chain risk, choosing the right level of involvement and supplier selection.

Keywords: Silicon carbide, Semiconductors, Securing supply, Supply network configurations

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Glossary

OEM - Original Equipment Manufacturer

SiC - Silicon Carbide

AC - Alternating current

DC - Direct current

MOSFET - Metal-oxide-semiconductor field-effect transistor

IGBT - Insulated-gate bipolar transistor

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1. Introduction

This master thesis is a result of a collaboration between Chalmers university of technology and the electromobility purchasing department of a large truck manufacturer. Due to the sensitive nature of the thesis, this company will be anonymized and from hereafter be called "Company X". A focus area of the purchasing department of Company X is the future of power electronics where the semiconductor material silicon carbide is one part which the company wants to investigate.

1.1 Background

The truck industry is under pressure to transition towards more sustainable business models where manufacturing and product life cycle emissions need to be reduced to net zero. In the center of this transition lies the development of electrically propelled trucks powered by either batteries or hydrogen. The battery powered vehicle is the first to market with several models on sale today. However, limited driving range and slow charging are factors that do not allow customers to replace their diesel-powered trucks for other than short driving distances, testing or PR-purposes. To overcome this threshold battery electric truck manufacturers need to increase battery size, improve drivetrain efficiency and shorten charging times. One of the technologies enabling this development is the semiconductor material silicon carbide which can be used to improve the efficiency of electric drivetrains as well as enable faster charging.

1.1.1 Electrification at Company X

Company X is one of the automotive actors investigating whether to make the technology switch to silicon carbide. Marking the start of a major transition towards sustainable transportation, Company X started producing electric trucks some years ago and is now offering a full line of electric trucks ranging from light to heavy sizes. This is a step towards their goal of having net-zero emissions of greenhouse gasses before the EU climate plan.

To achieve these goals, the electromobility department within Company X plays a key role by working on the development of electric vehicles. Rapid sales growth of electric trucks is needed to achieve the net-zero goal, putting the department under heavy pressure to identify, develop and implement new technologies to ensure Company X's position as a leading actor on the market. To fulfill the needs of the customers longer driving range, and faster charging are primary objectives. They can be achieved by using more batteries and by increasing the efficiency of the truck's powertrain. The problem with using more batteries is that it increases weight and is also costly [1]. Company X is therefore looking to improve powertrain efficiency as one alternative to accelerate the transition towards electrically powered trucks.

1.1.2 Electric powertrains

Electric trucks work by using a battery to power an electric motor and auxiliary systems such as lights, heating and cooling. To achieve this different power electronic subsystems are used to convert or invert power, depending on the requirements posed by different components. These subsystems are the onboard charger, the DC/DC-converter and the traction inverter and are shown in *figure 1*.

Figure 1: Onboard charger, DC/DC-converter & Traction inverter [2]–[4].

The subsystems are now described and are based upon interviews and oral exchanges conducted with a Company X system chief engineer [5], [6].

The *Onboard charger* is the subsystem responsible for converting alternating current from an electrical outlet to direct current used to charge the battery. It works by using power semiconductors and inductors to convert an AC input to a DC output at the voltage needed to charge the batteries. The output power usually varies between 10-30 kW, making it a slow alternative compared to using an offboard charger that supplies DC directly, with power ratings above 500 kW.

A *DC/DC-converter* converts the output voltage from the vehicle's battery to match the input voltage required by the vehicle's auxiliary systems. To do this it uses power semiconductors to first transform DC to a square wave, or AC, and then filters it back to DC at the specified voltage using inductors and capacitors. On an electric truck, the output power ranges from 7-15 kW depending on the auxiliaries installed in the truck. While the output power of the DC/DC-converter is quite low, one has to take into account that it is almost always draining power from the battery, even when the truck is not being driven.

The *Traction inverter* is a subsystem which takes the output power of the battery and inverts it from DC to AC to power the vehicle's electric motor. It works in the same manner as the DC/DC converter, except the power is not filtered back into DC. The output power can range from 120-500 kW depending on vehicle size. Because this subsystem powers the actual motor in the drivetrain it is the most energy consuming subsystems in the vehicle.

These three subsystems share a commonality in that they all use power semiconductor devices which are prone to losses in the form of heat. The heat is then dissipated by a cooling system powered by the DC/DC converter. Because of this an improvement in power semiconductor technology could reduce both energy consumption and cooling requirements, resulting in longer driving range and a need for less cooling. An illustration of how the powertrain is interconnected, and the subsystems containing power semiconductors, is shown in *Figure 2.*

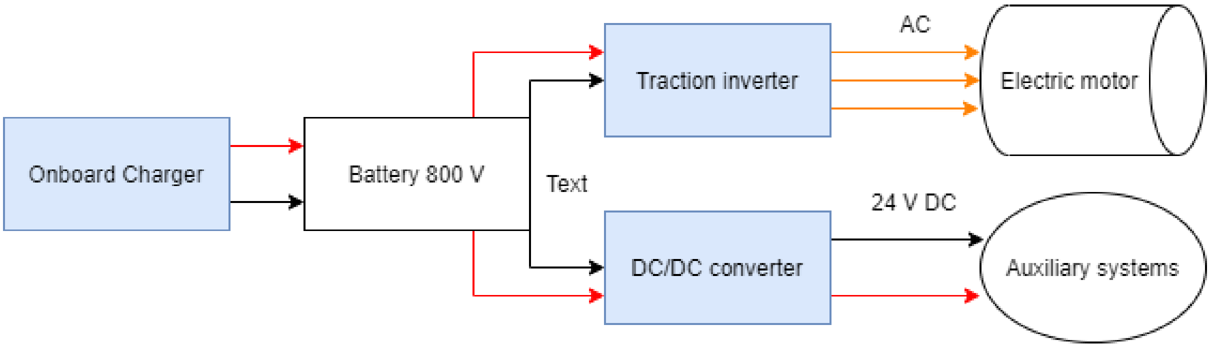

Figure 2: Powertrain of an electric truck with subsystems using power semiconductors marked in blue.

1.1.3 Power semiconductors

The power semiconductor devices residing within the three electric powertrain subsystems function as switches that have two different states, an ON state and an OFF state. The ideal ON state should allow for maximum current throughput, with minimum voltage dropped - meaning that the resistance should be minimal. The ideal OFF state on the other hand should be able to sustain as high voltage as possible without breaking down [7]. The ON-resistance and the breakdown voltage are dependent on the specific properties of the semiconductor material in such a way that if ON-resistance is minimized, so is the breakdown voltage. This means that devices that need to handle high voltages cannot have low resistance and vice versa. The result is a linear relationship between ON-resistance and breakdown voltage called the unipolar limit, upon which power semiconductor devices can be built [7]. This unipolar limit also introduces limitations to the switching frequencies of power semiconductors, where higher breakdown voltages and resistance limits the switching frequency. The unipolar limit is illustrated for the most commonly used semiconductor material Silicon in *Figure 3* below.

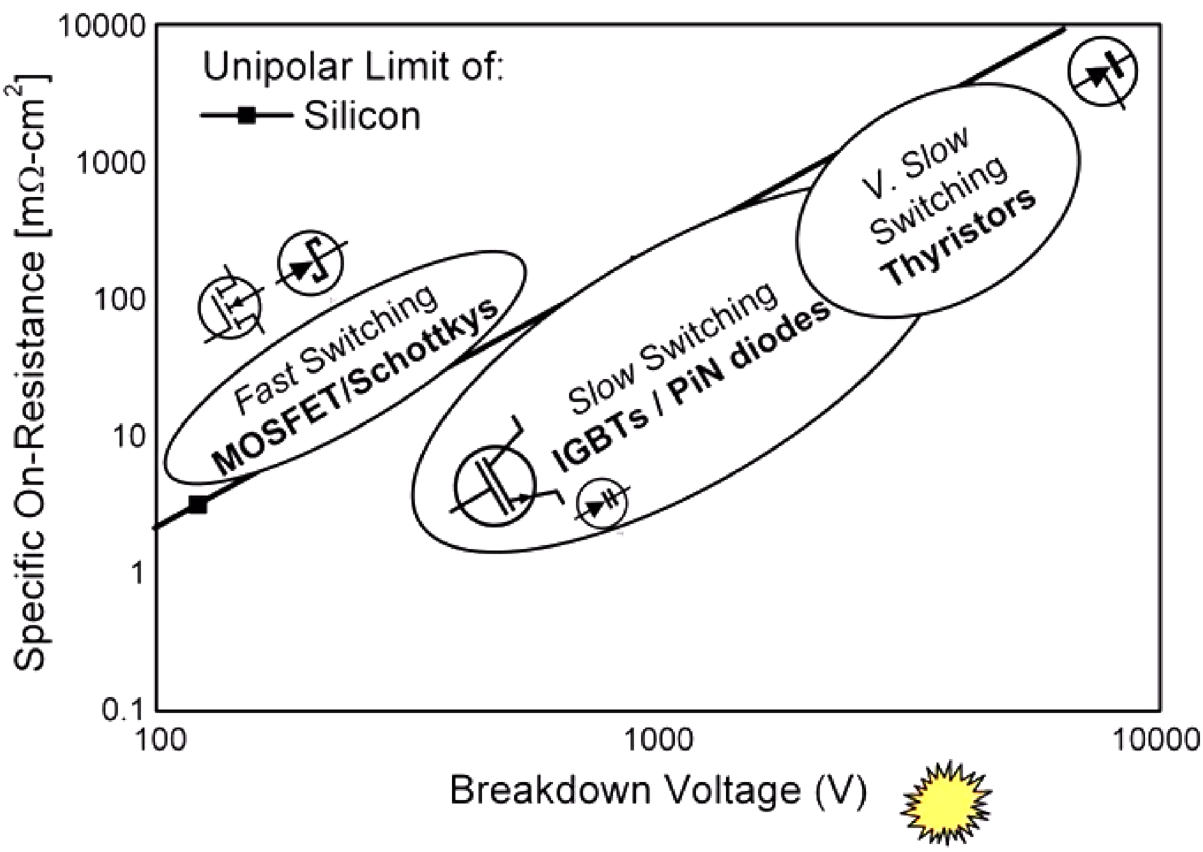

Figure 3: The unipolar limit of silicon [7].

While there are many different types of power semiconductors, there are three types that are commonly used within electric vehicles. These are described below according to descriptions from a Company X system chief engineer [5], [6]:

Power MOSFETs or metal-oxide-semiconductor field-effect transistors function as an ordinary transistor switching between an ON-state and an OFF-state depending on the applied drive voltage. It is the most common power device in the world and is frequently used within power supplies, DC-DC converters and low voltage motor controllers. The specific advantages of a MOSFET are fast switching speeds and high efficiency at variable loads. The disadvantage is that they cannot typically handle voltages higher than 100 V, only making them suitable for low power vehicles such as electric bicycles.

IGBTs are another form of transistors also functioning by switching between an ON-state and an OFF-state. It can handle fast switching, high voltages and high efficiency at specific loads. The main difference compared to the MOSFET is that the switching is not quite as fast, and that its high efficiency only exists under specific loads. The main advantage of the IGBT compared to a MOSFET is that it can handle much higher voltages and is thus suited for more high-power applications such as cars and trucks.

Power modules are customized devices that are made by using multiple of either IGBTs or MOSFETs, joined together in a single housing. It provides advantages of simplification of assembly and design where the specification of several power semiconductors in parallel or series in a single device is desired. Packaging multiple devices in one housing also allows them to be cooled together rather than separately, simplifying cooling system designs.

Figure 4 shows the different power semiconductor types.

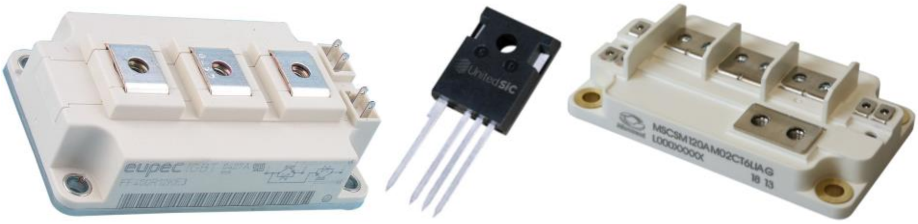

Figure 4: IGBT-module, MOSFET & power module [8]–[10].

For use in electric trucks the common choice has been silicon IGBTs or power modules containing silicon IGBTs because they can handle the high voltages used in truck batteries. However, if the material is changed from traditional silicon to a material with a different unipolar limit such as silicon carbide, losses could be minimized with lower resistances, higher voltages and faster switching.

1.1.4 Silicon Carbide

Silicon carbide is a semiconductor material that because of its material properties possesses a better suited unipolar limit for power semiconductors than silicon [7]. The key property that differentiates the two materials is the band gap, which is the least amount of energy required for an electron to jump from the valence band of a semiconductor to the conduction band. Silicon carbide has a wider band gap than silicon, meaning that more energy is required to make the material conductive. This wide band gap makes it possible to produce devices with higher breakdown voltages and lower ON resistance, ultimately resulting in lower losses. The result is a unipolar limit which is better suited for power semiconductors than the one of silicon; it is illustrated in *figure 5* below.

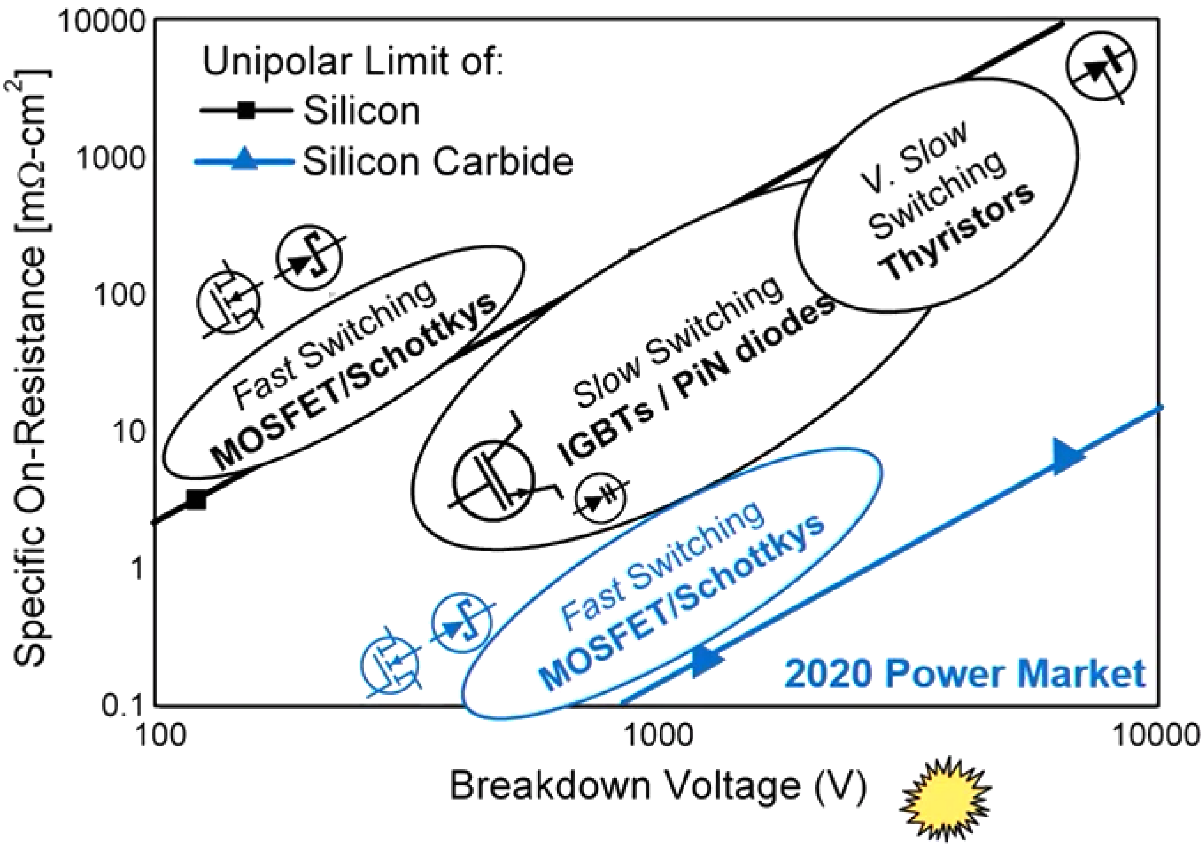

Figure 5: The unipolar limit of silicon carbide [7].

The unipolar limit of silicon carbide allows for more efficient MOSFET devices or MOSFET-based power modules to be made in a voltage range suitable for electric trucks. Silicon carbide can also withstand more heat than silicon before breaking down, further reducing the need for cooling [7].

Using power semiconductors made of silicon carbide is thus preferable to using power semiconductors made of Silicon for automotive applications. The technology has only recently become technologically and economically viable and was adopted in an electric car for the first time in 2018 [11]. Company X is now facing the issue on how to source this new material.

1.1.5 Semiconductor supply chains and Covid-19.

Typically, OEMs buy electronics systems from tier 1 suppliers who in turn manage the upstream tiers [12]. Upstream, the Tier 1 supplier has various options on how to acquire components containing semiconductors. A common case is that the Tier 1 suppliers source semiconductor devices from a distributor and handle assembly themselves. It is also common for the tier 1 supplier to design the products in-house but use electronics manufacturing services' companies (EMS) to handle assembly of some parts, such as the PCB (printed circuit board). *Figure 6* shows different types of supply chain setups.

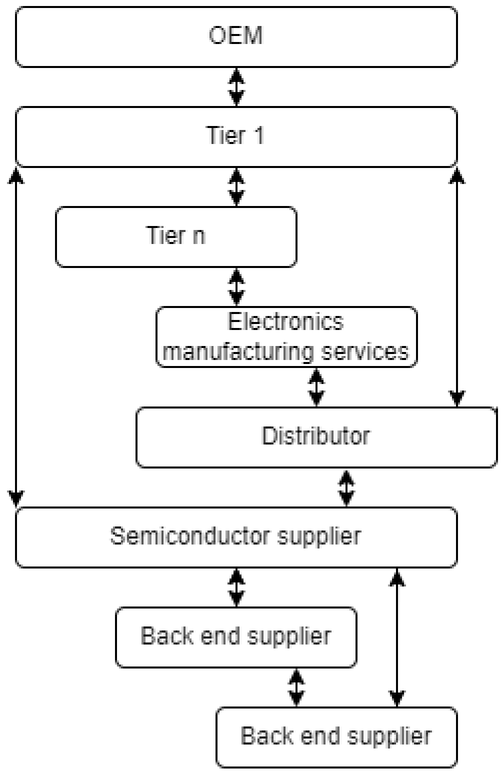

Figure 6: Typical electronics system supply chain [12].

Even though there are many different setups for sourcing semiconductors, the commonality between all of them is that up until 2020 the OEMs have rarely been directly involved. Instead, all of the responsibility and risk to manage the supply chain has been put on the tier 1 supplier [12].

In the wake of the Covid-19 pandemic, the world has experienced shortages and supply chain disruptions in many different areas, the most prominent example being the semiconductor shortages [13]. At the start of the pandemic, the automotive industry expected a downturn in demand and thus many orders of components including semiconductors were canceled. When demand quickly recouped and new orders were placed, a surge in demand for consumer electronics using the same semiconductor production capacity caused a shortage [13]. Due to the large investments, knowledge and time needed to build up semiconductor production facilities, the shortages were not easily fixed, and some are projecting it to last until 2023 [14]. This had a massive impact on the OEMs, with several actors having to stop production, including Company X.

Because of this OEMs are now starting to initiate direct relationships with semiconductor suppliers to try and solve the shortage problems. Discussions are also held over what potential future relationships might look like now that the vulnerability of these supply chains have become all too obvious.

Silicon carbide semiconductors are produced under roughly the same conditions as the silicon-based semiconductors of which there is currently a shortage. Company X now must face the challenge of determining how to source subsystems containing this new semiconductor material.

1.2 Aim

The aim of the thesis is to describe and analyze the silicon carbide power semiconductor market, identifying its actors, trends as well as other relevant factors influencing sourcing strategies. The aim is also to suggest the most important factors to consider when sourcing silicon carbide power semiconductors and lay the foundation for suggesting possible supply chain network configurations for procuring silicon carbide power semiconductors.

2. Framework

This chapter describes the theoretical concepts and models that are relevant used in this thesis, and then formulates the research questions.

2.1 Supply Market analysis

On the basis of the information available when the framework was developed, no supply market framework was found which were deemed to be suitable for the needs of the thesis as well as the characteristics of the silicon carbide market. Therefore, a framework for the supply market analysis has been created based on a combination of a variant of Porter's Five Forces developed by the State of Queensland [15] for purchasing activities, Lobermayer & Kotzabs [16] strategic sourcing process, and lastly inputs that were deemed to be necessary to capture the specific supply market that was to be described and analyzed.

The result is a supply market framework that can be viewed in *figure* 7 consisting of four sections: Production process, Market overview, Supply market relationships and External factors.

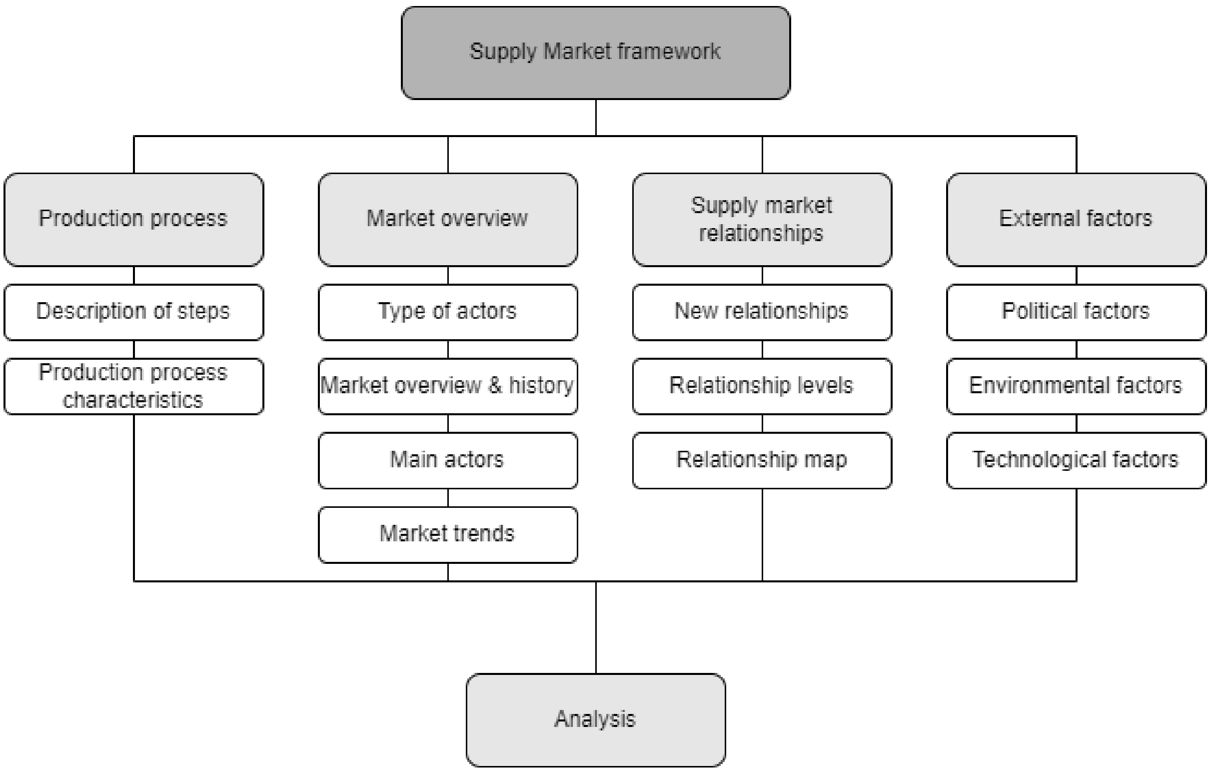

Figure 7: Supply market analysis framework

Following is a description of these sections and how they have been adapted to suit the aim of the thesis.

2.1.1 Production process

Describing and analyzing the production process of silicon carbide power devices is the first step of the overall supply market analysis. Here, the different steps of production are described, and the overall characteristics of the production processes are described.

2.1.2 Market structure and trends

The second step of the supply market analysis is to provide an overview of the silicon carbide market. It departs from the production process description to define the types of actors on the silicon carbide market, and the supply chain levels in which they exist. Thereafter, a description of the size and projected growth of the market and the market share of the different suppliers. It continues with a description of chosen key suppliers and ends with highlighting market trends.

2.1.3 Supply market relationships

The relationships between the different actors in the silicon carbide supply market are investigated. Viewpoints and considerations from interviewees on the type of relationships needed are described. Relationships between actors on the different levels within the supply chain are mapped.

2.2.4 External factors

This section investigates the relevant external factors that are affecting the silicon carbide market. These consist of the three of the six PESTEL (Political, Economic, Social, Technological, Environmental and Legal) factors, namely Political, Technological and Environmental factors.

2.2 Supply chain management

Cooper and Lambert [17] describes supply chain management in a conceptual framework consisting of three fundamental aspects. These aspects are the supply chain network structure, the supply chain business processes and the supply chain management components. The supply chain network structure consists of the focal company and the links between it and other members of the supply chain. Supply chain business processes refer to the specific activities conducted between supply chain members and the supply chain management components are the managerial variables that integrate and manage business processes across the supply chain. *Figure 8* illustrates these three fundamental aspects and corresponding key questions to successfully manage a supply chain.

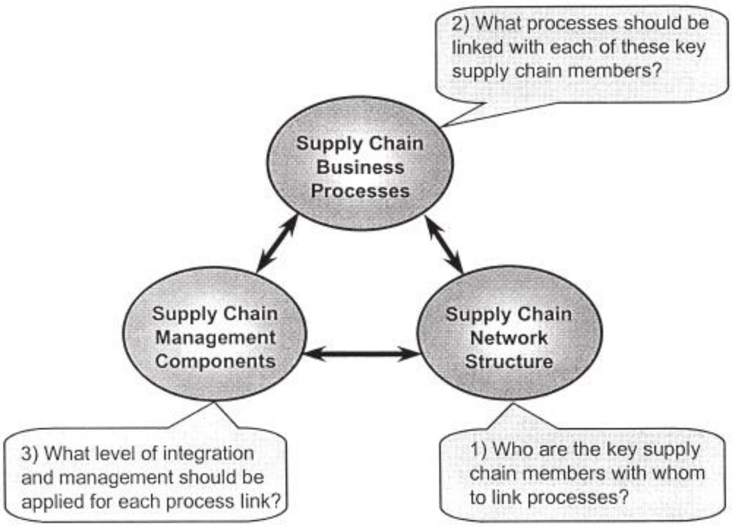

Figure 8: A conceptual framework of supply chain management [17].

These aspects in combination with a section on supply chain resilience make out the supply chain framework of this thesis and are described in further detail in the coming sections.

2.2.1 Supply chain network structure

Cooper and Lambert [17] describe three aspects to consider when determining a company's network structure. First, identify the critical supply chain members with whom to link processes. Second, determine the structural dimensions of the network including the number of tiers and the position of the focal company. Finally identify the different types of business process links that exist within the supply network. Each of these aspects are now further explained.

Critical supply chain members mean identifying the actors on the market, and then determining which of them are critical enough that allocating resources towards them is worthwhile. Cooper & Lambert [17] suggest starting this identification process by discarding the supporting actors, meaning actors who are solely providing services such as information flows, money transfers and logistics. The primary actors are in contrast, the ones who provide value-adding activities in the supply chain and it is among these the critical actors should be identified.

Structural dimensions of a supply network are the horizontal structure, the vertical structure and horizontal position of the focal company. The horizontal structure refers to the number of tiers within the network and the vertical structure represents the number of actors on each tier. A focal company can exist on any level of the horizontal structure, and this location is the last dimension of the supply network structure.

Business process links refer to the activities that connect supply chain members to each other. What these links can consist of are described in the next section.

2.2.2 Supply chain business processes

Supply chain business processes are according to Cooper and Lambert [17] activities that become integrated and managed in a supply chain process, rather than being managed as individual separate activities. The reason for integration is to ensure a continuous product flow which can only be achieved by also having a continuous information flow. Cooper and Lambert [17] identifies several key business processes but most of these are customer-oriented processes such as customer relationship management, customer service management and customer demand management. This thesis, being more focused on the supply side of the network, will only concern itself with the processes related to the supply side, which are:

- Procurement
- Manufacturing flow management
- Product development
- Demand management

These four processes are now described.
Procurement has traditionally operated as a bid-and-buy system but now gravitates more towards earlier supplier involvement and deeper relationships. In this way strategic plans can be made jointly between suppliers and purchasing organizations, increasing the support to the manufacturing flow process, product development and design. Combining these deep involvement relationships with high-speed information channels such as electronic data interchange (EDI) makes procurement a key business process to ensure a smooth and rapid flow in the supply chain [17].

Manufacturing flow management in the context of a supply network refers to the management and control of the manufacturing flow taking place between the focal company and its suppliers. It has to do with how and who initiates production, such as by customer demand and/or historical forecasts and can be based on either pull or push-based systems. Flexible manufacturing processes are required to quickly respond to changes in the market. In this process the level of involvement from the focal company will determine the degree of responsiveness from suppliers.

Product development as a business process in this case refers to the integration of development activities between the focal company and its suppliers. It is a key business process and integration of product development can reduce both time to market and cost [17].

Demand management is the process of balancing customer’s requirements with the supply side of the focal company. Demand from customers is a large source of variability and a part of demand management is about trying to determine what and when customers will purchase. Furthermore, forecasts need to be coordinated and aligned with the supply side of the company, both with regards to internal production but also the focal company’s suppliers.

Because a supplier and the focal company can have different business processes with different levels of involvement between them it can become difficult to illustrate the supply chain. To cope with this Cooper and Lambert [17] suggest four types of supply chain links that can be used to distinguish relationships within a supply network. The different types of links are meant to represent the amount of resources the focal company spends on relationships within the network. Note that these links are not necessarily direct between the focal company and other members but can also exist between other actors within the network. These links can represent any or all of the previously described business processes and are illustrated in *Figure 9* and explained below.

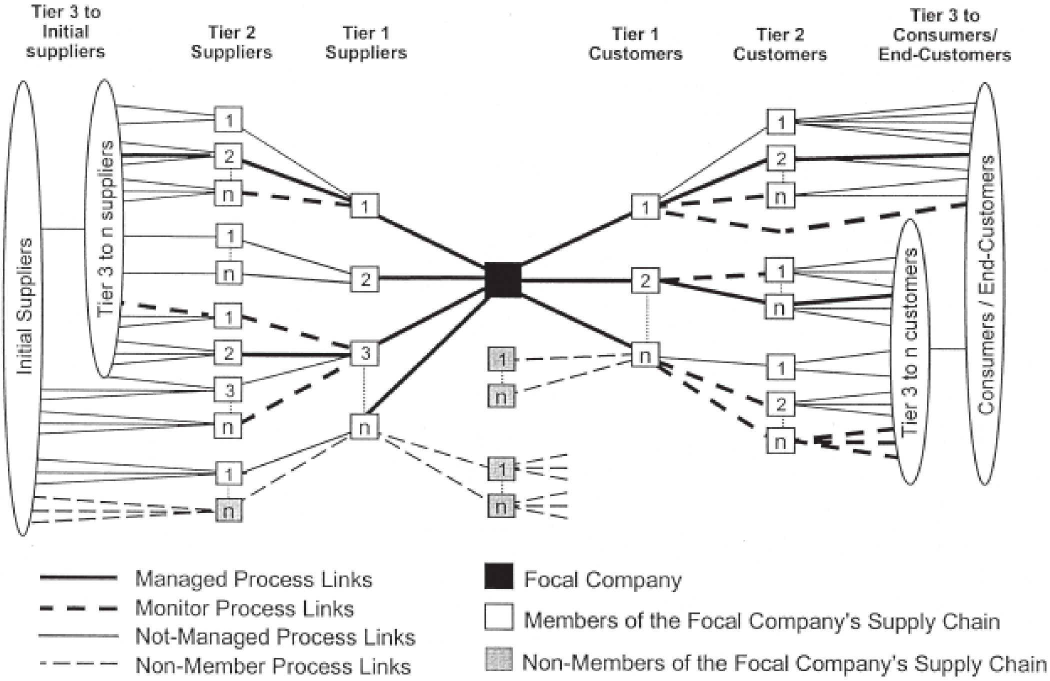

Figure 9: Types of process links [17].

Managed process links represent business processes which the focal company deems important enough to actively manage.
Monitored process links are business processes which are not conducted directly with the focal company, but important enough for the focal company to monitor.
Not managed process links are business processes with whom the focal company is not actively involved and are not critical enough to monitor.
Non-member process links are links between actors in the supply chain that are dealing with other actors outside of the supply chain, such as supplier's other customers.

2.2.3 Supply chain management and levels of involvement

Cooper & Lambert [17] describes the level of involvement in a business process link as the sum of its management components. As many of these components are of an operative or intra-organizational nature which will not be explored in this thesis, Gadde & Snehota [18]'s framework is more appropriate to determine the level of involvement between supply chain members.

The increasing importance of purchasing has naturally led to the increasing importance of how companies handle their supplier base [19]. In their article *"Making the Most of Supplier Relationships"* [18], Gadde and Snehota examine the reasoning behind different degrees of supplier involvement. In its most general form, level of involvement between two companies is determined by three aspects: monetary value, continuity of the relationship over time and sourcing policy (multiple or single). However, this simplification does not account for the fact that each business process is unique. High volumes, high levels of continuity combined with single sourcing does not necessarily mean that parties have a high involvement with each other, and vice versa.

To further nuance different levels of involvement Gadde & Snehota [18] suggests dividing involvement into three dimensions; coordination of activities, adaptations of resources; and interaction among individuals. Activities can be coordinated between the buyer and supplier to different degrees - an example of tight activity coordination being integrated logistics systems. Resources can also be adapted more or less specifically to the requirements of the counterpart. For example, through joint development special products or processes can be custom tailored to the wishes of the buyer. Lastly, individuals within the buying and supplying company might interact to different degrees. Different supplier relationships score differently on these dimensions, some high on all of them while others score less.

When developing a supply strategy and determining the intended level of involvement, companies must also understand the economic consequences of different types of relationships. Gadde and Snehota [18] divide these economic consequences into relationship costs and relationship benefits.

Relationship costs consist of direct procurement costs, direct transaction costs, relationship handling costs and supply handling costs. *Direct procurement costs* are the costs that are the most straightforward - the amount of money that a supplier invoices the buyer. *Direct transaction costs* are the costs that come with the purchase, such as transportation, logistics and ordering. *Relationship handling costs* are the relationship costs that are specific to supplier relationships and are dependent on the level of involvement. The cost comes from the continuous interaction and resource adaptation in high level of involvement relationships. *Supply handling costs* come from the overall costs of the purchasing function such as administration and warehousing operations.

Relationship benefits are more complex than relationship costs and are harder to assess and measure. They consist of cost benefits and revenue benefits. *Cost benefits* are the cost savings made possible by the collaboration with suppliers. For example, through better logistical coordination and joint efforts on product and process development. *Revenue benefits* are the increase in revenue that the buying company experiences because of a solution originating from a supplier relationship, such as increased sales due to technical innovation stemming from joint development with a supplier.

Lastly, it is important to note that the economic consequences of a supplier relationship is not only dependent on the content of that relationship alone, but also how it relates to the operations of customers as well as other relationships.

2.2.4 Supply Chain Resilience

Tukamuhabwa et al. [20] defines supply chain resilience as *"the adaptive capability of a supply chain to prepare for and/or respond to disruptions, to make a timely and cost effective recovery, and therefore progress to a post-disruption state of operations – ideally, a better state than prior to the disruption "*[20].

This definition captures the trade-off that exists between redundancy and efficiency when considering the resilience of a supply chain. One the one hand, companies want to be able to cope with supply chain disruptions when they occur. But on the other hand, they also wish to do so in a cost-effective and efficient manner. There is a balancing act in investing in redundancy, with companies having to judge the costs that the investment in redundancy would incur against the costs of a negative event [21].

The resilience of a supply chain can be judged by the four following elements: flexibility, velocity, visibility and collaboration [22]. Scholten and Schilder define them as follows [22]: *Flexibility* refers to the number of options and the degree of difference between these options in a supply chain in case of unforeseen events. *Velocity* refers to the reaction speed in case of said event occurs. *Visibility* refers to the extent to which actors within the supply chain share or have access to information that could be useful for the other actors' operations. Lastly, *Collaboration* refers to the extent that actors within the supply chain partake in collaborative activities. Furthermore, Scholten and Schilder find that collaboration, through activities such as information sharing and collaborative communication, increase the visibility of the supply chain. Visibility is in turn an antecedent for supply chain resilience by being an important enabler for both flexibility and velocity.

2.2.5 Mapping supply chain configurations

To have a clear view of the relationships and business processes taking place when mapping a supply chain Cooper & Lambert [17] suggests using the following approach. Each business process taking place between supply chain members is illustrated with its own managed link. Then monitored, not-managed and non-member links are added to give a more complete picture. *Figure 10* below shows an example of business process links between members in a supply chain.

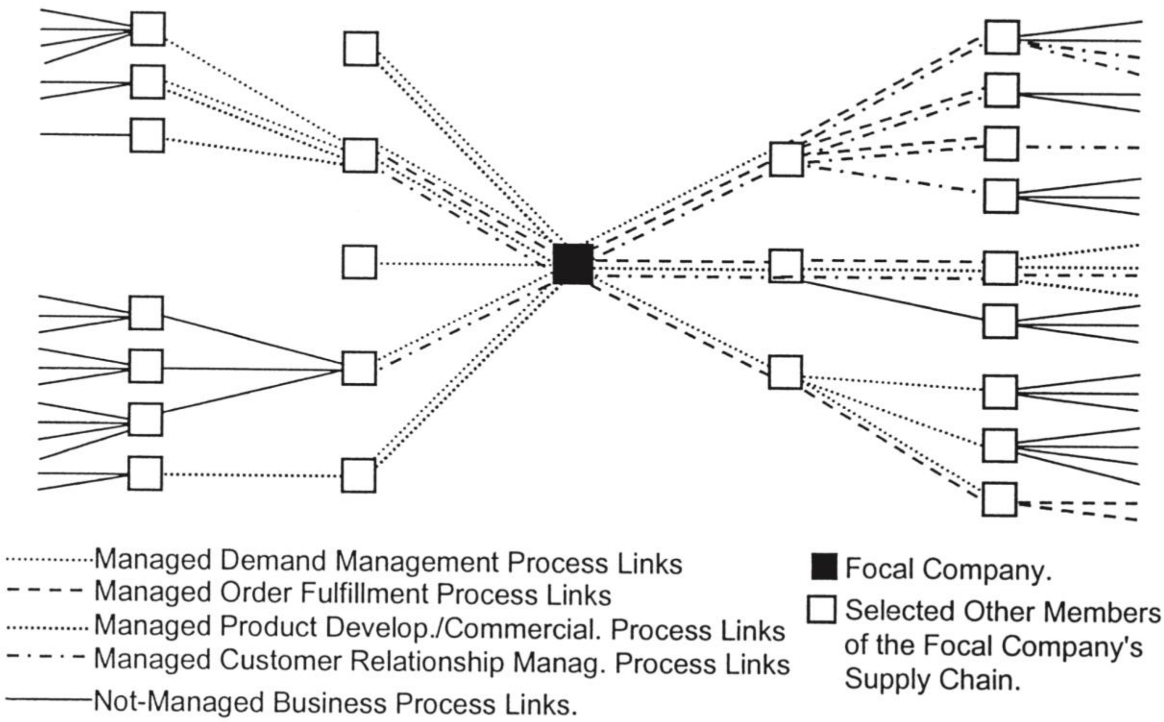

Figure 10: Business process links in a supply chain [17]

2.4 Research questions

The background in chapter 1 describes the current situation of Company X and their need to investigate silicon carbide. Combining the need of Company X with a market analysis and a supply chain management framework leads this thesis to the following research questions.

- *RQ1: What alternative supply chain network configurations can be created for subsystems using silicon carbide and what are their drawbacks and benefits?*
- *RQ2: What are the most important factors Company X should consider when forming a sourcing strategy for silicon carbide devices?*

3. Methodology

The thesis is of a mainly qualitative nature where data has been collected from interviews and secondary sources such as journals, news articles and presentations. As Bell et al. [23] points out, qualitative research tends to be inductive rather than deductive. This means that the relationship between theory and research is driven by the data collection and not the other way around. This inductive path has been chosen to avoid being limited by theoretical frameworks in the early stages of the data collection process. Instead, the thesis has continuously explored theoretical concepts during the data collection process. See *figure 11* for a workflow schematic by Bell et al. [23] that has been used.

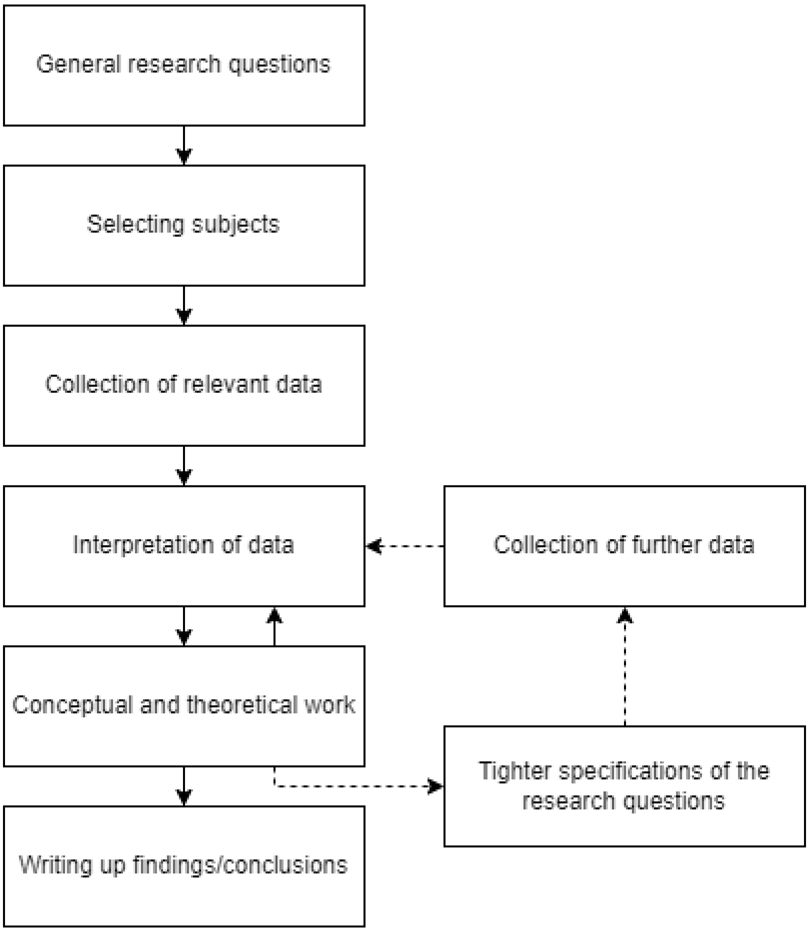

Figure 11: Workflow by Bell et al. [23].

There has been a back-and-forth process between the stage of interpreting the data, theoretical and conceptual work, reformulating research questions and collecting more data.

3.1 Research Design

The research design mainly resembles one of a case study, meaning that the study takes its departure from a specific organization's current situation - the organization in this case being the Company X Electromobility Purchasing department. However, it is not the organization itself that has been studied, but rather the situation that the specific organization has been facing.

To answer the research questions described in the previous chapter the thesis first analyzes the silicon carbide market. This analysis explores the production process of silicon carbide, the market for silicon carbide and its actors, the relationship dynamics of the market, and finally the external factors influencing the market. The thesis then identifies the specific needs of Company X with regard to silicon carbide, both from a technical perspective and a supply chain perspective. With the needs of Company X identified and the market analysis completed, alternative supply network configurations for sourcing silicon carbide subsystems have been created and the advantages and disadvantages of each configuration discussed. From this analysis follows an identification of the most important factors when forming a strategy for sourcing components housing silicon carbide devices. Finally, a recommendation on which sourcing strategy Company X should employ is made. An illustration of the research design can be viewed in *Figure 12* below.

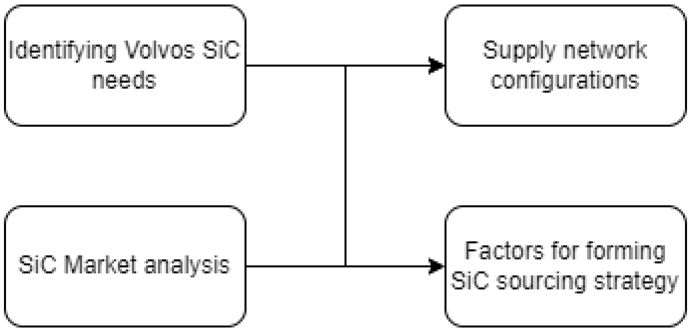

Figure 12: Research design.

The specifics of each step in the research design are described in further detail in the sections below.

3.1.1 Analyzing the silicon carbide power semiconductor market

For the analysis of the silicon carbide supply market, the Supply market framework described in chapter 2 is used. Data collection is done by conducting interviews with experts in the area as well as synthesizing data from other sources such as academic journals, industry reports and news articles.

3.1.2 The silicon carbide needs of Company X

To determine the needs of Company X regarding silicon carbide two categories of needs were first identified, technological needs and supply chain needs. The technological needs include determining the viability and feasibility of using silicon carbide semiconductors in Company X's electric trucks. It also includes investigating specific engineering requirements regarding material, components and implementation. The supply chain needs include determining the economic feasibility of using and sourcing silicon carbide. It furthermore investigates whether Company X plans to make or buy the three subsystems in the powertrain and determine the level of involvement required between different actors in the supply chain.

3.1.3 Formulating supply network configurations

By using the market analysis of the silicon carbide market together with the identified needs of Company X, three alternative supply network configurations for procuring silicon carbide devices were formulated. The framework by Cooper & Lambert [17] serves as the basis for these configurations. The configurations are then compared, and their corresponding advantages and disadvantages discussed.

3.1.4 Factors for forming a silicon carbide sourcing strategy

The market analysis and the needs of Company X complement each other and with the supply side on the one hand and the customer on the other, together forming an understanding of the entire supply network structure. Understanding both the needs of the supply side and the needs of Company X enables the formulation of key factors that should be considered when sourcing silicon carbide.

3.2 Data collection methods

This section explains the data collection methods used in this thesis for both primary and secondary data.

3.2.1 Primary data

Primary data was collected continuously over the span of two months with interviews conducted in a semi-structured fashion and transcribed via audio recordings in all cases where recording was allowed. The interview subjects received information regarding the topic, and some of the questions in advance to prepare them for the interviews.

The subjects that were interviewed are a combination of identifying the perspectives deemed necessary to cover for fulfilling the aim of the thesis, as well as the time constraints and the willingness of different actors to be interviewed. An important perspective that could have been covered more was that of the power subsystem suppliers. However, although the interviews made during the course of the thesis might not capture the whole spectrum, theoretical saturation is compensated by the extensive use of second hand sources covered below.

Tables 1 - 2 below categorizes the interviews along with their dates and topics according to the research design.

The silicon carbide needs of Company X			
Interviewee	**Organization**	**Topic**	**Date**
Manager of motor drive systems - design and hardware & System chief engineer - motor drive systems	Company X	Engineering needs	2021-10-26

Chief system engineer - electric distribution and charging	Company X	Engineering needs	2021-11-05
Sr buyer & Segment leader ECU	Company X	Securing semiconductor supply	2021-12-09
Senior commodity buyer Electric distribution & charging	Company X	Supply chain needs	2021-12-16

Table 1: The silicon carbide needs of Company X

Silicon carbide supply market			
Interviewee	**Organization**	**Topic**	**Date**
Engineering Director	Norstel	Silicon carbide Production chain	2021-10-18
Director of business development	Jabil	Securing supply of silicon carbide	2021-10-18

Table 2: Silicon carbide supply market

Besides specific interviews with thesis related questions as a main topic, information has also been gathered from participation in meetings with Company X suppliers. These meetings are excluded from the tables above due to confidentiality reasons and information gathered from them have only been used as a guide to track down already publicly available data.

3.2.2 Secondary data

Secondary data have been used to understand the technical perspective of silicon carbide as well as future market conditions and trends. Data has been gathered primarily by reading intelligence reports, lectures, industry journals and company websites. Furthermore, industry websites such as Powerelectronicnews.com and i-micronews.com have been frequently used to gather information regarding announcements of new relationships. The information from market research company Yolé Development that is publicly available have also been used to support the supply market analysis. To catalog all the different data sources, the reference management software Zotero has been used.

4 The silicon carbide Supply Market

This chapter presents the findings of the silicon carbide supply market study. It first describes the production process of silicon carbide power devices, the market actors and structure, the relationships as well as external factors affecting the supply market. It ends with an analysis of the supply market.

4.1 Production process

As with other semiconductor-based devices, silicon carbide power devices have a long and complex supply chain. It consists of several stages - described below in a simplified manner is the process of manufacturing a silicon carbide power device. Sources used for the description of the production process is an interview with a Director of a silicon carbide wafer production facility [24] and a technical report from the Clean Energy Manufacturing Analysis Center [25]. An overview of the production process can be viewed in figure 13 below.

Figure 13; The silicon carbide device production process

4.1.1 Raw materials

The two main raw materials used in silicon carbide wafers are Silicon (Si) and Carbon (C). They are earth-abundant and available globally. Thus, the raw materials in silicon carbide power devices themselves do not pose any major supply chain constraints.

4.1.2 Processed materials

The raw materials must go through several processing steps. Silicon carbide powder must hold a certain purity standard to form the boule that later on will be sliced to wafers. Also, Silane (SiH_4) is needed for the critical step of growing epitaxy on the silicon carbide wafers.

4.1.3 Silicon carbide ingots and substrates

The processed raw materials are made into ingots by first heating the silicon carbide powder to 2000-2300 degrees C in a furnace. The boule, a single crystalline ingot, is then created by dipping a so-called seed crystal into the molten silicon carbide. The crystal is then slowly extracted from the molten silicon carbide and crystallization and solidification occur, creating a large boule of cylindrical shape. The boule is machined and cut through multiple steps into thin circular polished silicon carbide substrates.

4.1.4 Epi-wafers

By the process of epitaxy, layers of silicon carbide are then grown on the finished polished substrates, creating so-called epi-wafers. It is by this stage that the main characteristics of the end products are decided [24]. Generally, the thicker the epitaxial layer is, the higher the breakdown voltage and the on-resistance is. The epitaxial stage again necessitates high temperatures (1550-1600 degrees C) and a very clean and controlled environment.

4.1.5 Chips/Bare Die

With the epitaxy grown on the wafers, the process now moves towards chip fabrication. The epi-wafers are sawed into individual chips that are put through several processes including depositing different layers, cleaning, baking and etching.

4.1.6 Device fabrication

The silicon carbide bare dies can either be put in a discreet device, with one die per final unit, or it can be fabricated together with others into a module. Either way, these final steps include amongst others wire-bonding, housing the device in packaging as well as rigorous testing.

4.1.7 Finished device

The finished devices can then be used for power electronic applications. For electric vehicle purposes, they can together with other components such as electronic components (capacitors, inductors), controllers, wiring harnesses, cooling systems and housing be manufactured into the power electronic subsystems used in the vehicles.

4.1.8 Production process characteristics

The inherent material properties of silicon carbide means that several stages of the production process differ from that of Si, especially within the wafer and epitaxy stage [26]. For example, silicon carbide requires higher temperatures to be processed compared to Si, and thus needs more advanced processes and machinery for those steps [24]. It is also a harder material, meaning that the machining process such as sawing and polishing also becomes more demanding. The wafers are transparent which means that conventional testing used with silicon wafers are not applicable. There are several other areas in the production process that are different compared to silicon production and that need further development. The machines needed for silicon carbide production are highly specialized and often suffer long lead times such as 1-2 years for some [24]. Furthermore, a high-capacity utilization of at least 80 percent is needed for most production facilities to break even [24].

To end up where it is today, the silicon carbide industry has overcome many obstacles in its production processes by incremental improvements over 30 years [27]. Thus, the know-how needed at several of the different production steps is significant. Compared to the mature and highly developed processes of the silicon production chain, difficult properties of silicon carbide means that the industry is still facing numerous challenges and areas of improvement within its production chain[26].

A key metric within the semiconductor industry is the wafer diameter. Larger wafers mean better economies of scale and more usable material for the actual devices, however, to increase the size of the wafers is challenging and has only been made possible by years of continual improvements[27]. The silicon industry has moved from 100 mm in 1980 to 300 mm today [28]. The silicon carbide industry is in comparison producing mainly in sizes of 150 mm, although several actors have recently announced successful production of 200 mm wafers [29]–[31]. Worth noting is that the move from 150 to 200 mm diameter would almost double the amount of usable substrate, making it an important step in improving the economies of scale within the industry.

4.2 The silicon carbide market

This section describes the supply chain actor types, overview and history, main actors and trends of the silicon carbide market.

4.2.1 Supply chain actor types

The semiconductor manufacturing process is as described above long and complex. All actors do not have the competencies, resources or the will to perform all stages. A specialization between stages in the production chain has emerged, even though there are actors that perform most of them. The natural split occurs between the finished silicon carbide wafers and the epitaxial stage. Whereas the finished silicon carbide wafers can be said to be somewhat standardized, it is at the epitaxial stages that many of the product characteristics of the end-product are determined. Therefore, it is common today that the actors that make the power devices also perform the epitaxy process[24].

The silicon carbide semiconductor industry can consequently be divided into three types of actors. Wafer manufacturers, device manufacturers and vertically integrated manufacturers. The wafer manufacturers usually start with the processed raw materials, silicon carbide in powder form, and finish with the polished sliced wafers. The device manufacturers purchase finished wafers or boules and end up with the power semiconductor devices. The vertically integrated manufacturers perform both processes.

4.2.2 Market overview and history

The silicon carbide power electronics device market is a part of the overall power electronics device market that also includes Si, GaN and other semiconductor materials. The power electronics device market is set to grow, with a CAGR (compound annual growth rate) of 6.9 percent, from 17.5 billion USD in 2020 to 26,5 billion USD in 2026 [32]. The power silicon carbide device market is predicted to grow rapidly. Until 2025, the market is predicted to see a CAGR of 30 percent, from 541 million USD in 2019 to 2,5 billion USD in 2025 [33].

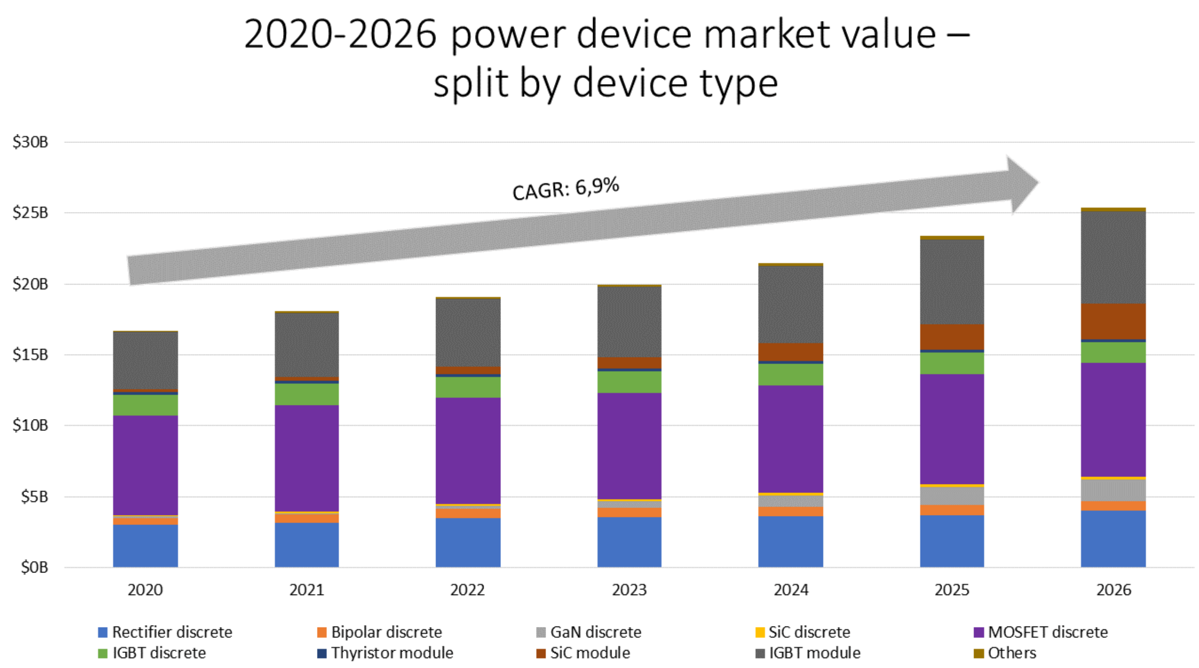

Figure 14; power device market value growth by device type, 2020 to 2026 [32]

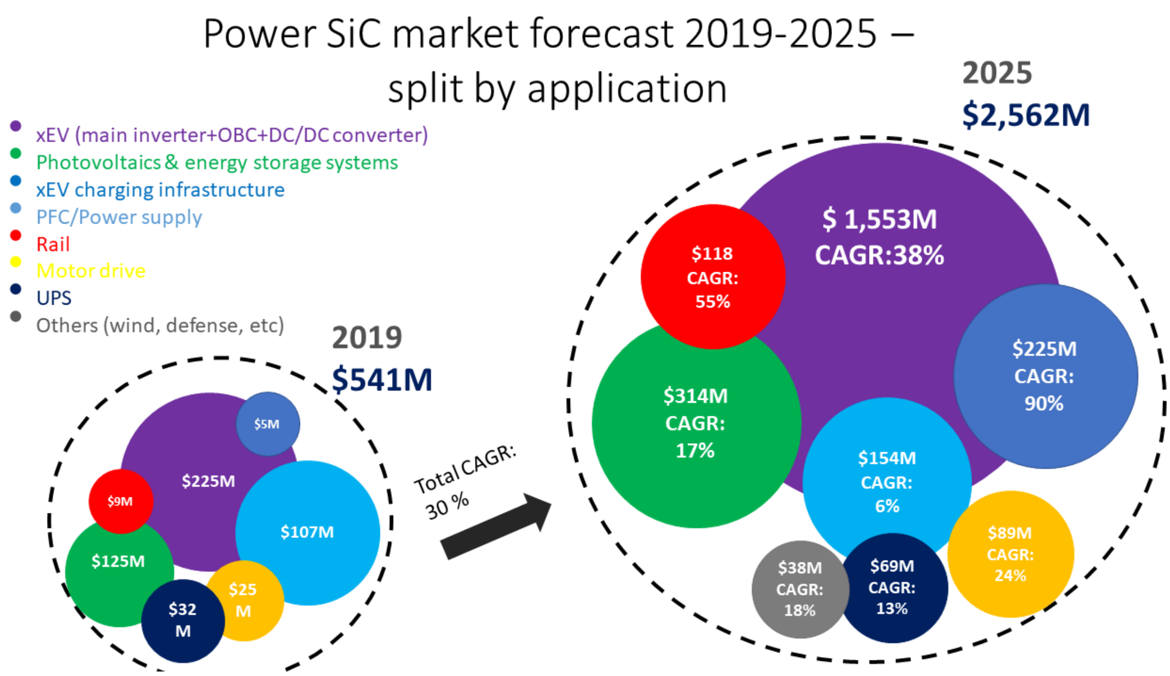

Figure 15; power silicon carbide market forecast split by application, 2019 to 2025 [32]

Many sectors are seeing increasing demand for silicon carbide power devices, such as renewable energy systems, energy storage systems and power supply units used in data centers [26]. However, the main driver for silicon carbide device demand is predicted to come from increased demand of automotive xEVs and charging infrastructure. silicon carbide power device use within automotive and charging infrastructure is set to grow at a CAGR of 38 percent and 90 percent respectively. Thus, it is the automotive sector that is seen as the main driver for silicon carbide power device growth today.

This is a new development within the silicon carbide power device industry. silicon carbide power devices have been available on the market for over twenty years. For a long time however, the main use was within industrial and energy applications, such as photo-voltaics and industrial applications [34], [35]. In 2018, Tesla was the first automotive OEM to use silicon carbide power MOSFETS within their traction inverter in their Model 3 [26]. This has spurred on the whole automotive sector's interest and demand for silicon carbide devices. Today, silicon carbide is used within Hyundai's and Porsche's newest EVs [36]. Many more automotive companies are now eyeing silicon carbide or are already in the process of implementing it.

Thus, the silicon carbide market is predicted to be dynamic. According to a semiconductor expert from a power electronic supplier: *"Don't think this market is going to be similar for 2 years. There's lots of things happening, this is very dynamic."*[37]. It's an essential technology for EVs, but silicon carbide technology also has a lot of growth potential in other sectors. *"There are many applications using IGBTs that could switch to silicon carbide but that just don't get priority from the manufacturers. The market is bigger than the automotive industry and it's going to change. You're going to see mergers and acquisitions, long term agreements with manufacturers buying capacity."* [37]

When looking at the actors within the silicon carbide industry and their respective market share, it is useful to look at the industry both at the wafer and device level.

Wafer market

Figure 17 is showing the market share of the silicon carbide device market in 2019.

Device market

Figure 18 is an estimation made based on Yolé Development market analysis figures for the year 2020 [32].

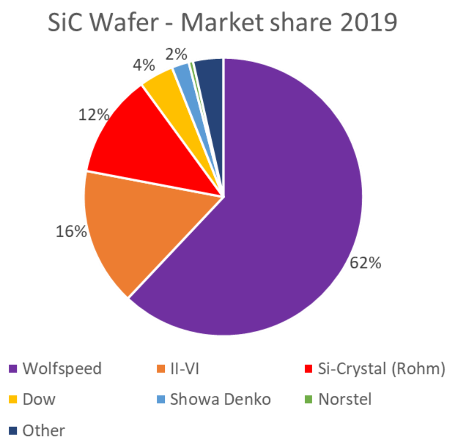

Figure 17; market share of SiC wafer supplier in 2019 [32]

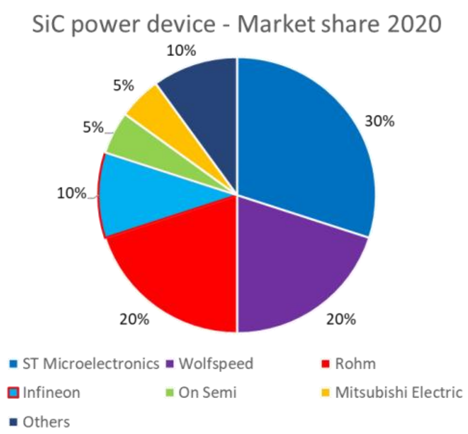

Figure 18; market share of SiC power devices in 2020 [32]

4.2.3 Main actors in the silicon carbide market

As can be seen when comparing the main actors within the overall power electronics device market with the actors present in at the wafer and device level within the silicon carbide industry, the silicon carbide industry is housing a mix of both established power electronics actors (Infineon, STMicroelectronics, On Semi and Rohm) and actors that are specialized within silicon carbide (Wolfspeed, II-VI). A type mapping of some of the different actors present within the industry is shown in *figure 19* below.

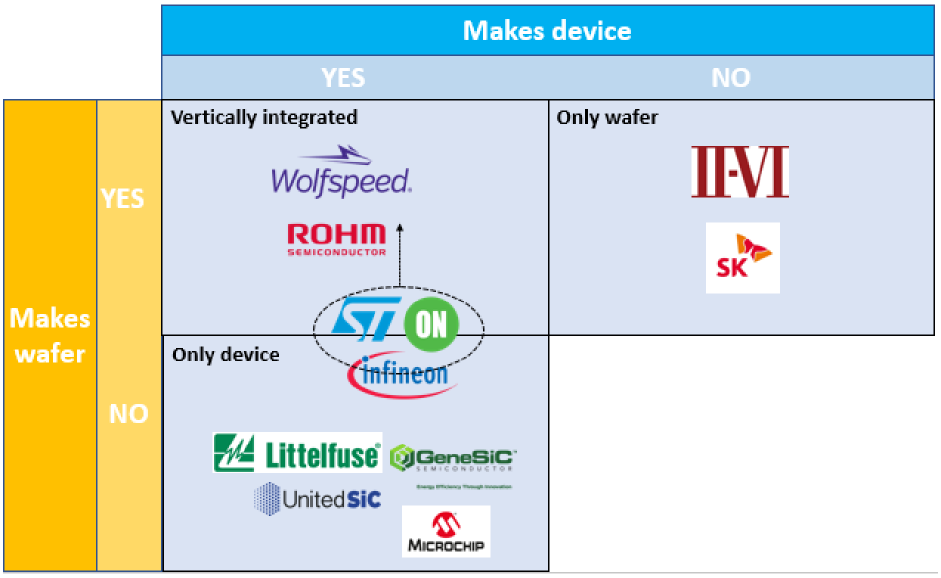

Figure 19; Mapping of the silicon carbide market actors and their type

Table 3 presents an overview of the main actors in the silicon carbide industry. Important to note is that several of these actors are not only involved with power semiconductor products and that their annual revenue and market cap is not only related to their silicon carbide related business. However, these figures give an estimation of the size of the companies.

Company name	**Headquarters**	**Annual Revenue (USD)**	**Market Cap (USD)**	**SiC actor type**
Infineon	Neubiberg, Germany	8.6 billion (2020)	54,82 billion (2021-12-07)	Device
ST Microelectronics	Geneva, Switzerland	10.2 billion (2020)	39,66 billion (2021-12-07)	Mainly device
Wolfspeed	North Carolina, US	525 million (2020)	13,46 billion (2021-12-07)	Vertically integrated
Rohm Semicondcutor	Kyoto, Japan	3,59 billion (2019)	9.5 billion (2021-12-17)	Vertically integrated
On Semiconductor	Arizona, US	6,30 billion (2020)	26,2 billion (2021-12-17)	Mainly device
II-VI	Pennsylvania, US	3,1 billion (2020)	7,23 billion (2021-12-20)	Wafer

Table 3: The main actors in the silicon carbide industry

Three of the actors present in the table, Wolfspeed, Infineon and ST Microelectronics are described in more detail below. This description includes the companies' history within silicon carbide, their current offering and position in the supply chain. The choice of these three companies is due to their position in the market and are thus deemed to be especially interesting.

Infineon

Infineon is one of the largest semiconductor companies based in Europe [38]. In addition to power electronics, they develop and manufacture a wide variety of semiconductor products such as microcontrollers, sensors and memory chips. With their biggest customer segment being the automotive sector, they are also judged to be the world's leading supplier of automotive semiconductors [39] .

Within the overall power electronics device market (including Si, silicon carbide and other materials), Infineon is the market leader in terms of revenue [32]. They have been involved in silicon carbide for over twenty years and have had silicon carbide power devices on the market for a long time [34]. These experiences and expertise are also what Infineon emphasizes in their product offering to potential customers.

With silicon power electronics, Infineon has had a sourcing strategy where they source their wafers from external sources, through both long-term contracts and multiple sourcing arrangements [34]. For silicon carbide, they have also utilized this strategy, striking long term agreements for wafer supply when necessary and pursuing multiple sourcing when possible [34]. They have struck long term agreements with Wolfspeed and Showa Denko for supply of silicon carbide wafers [40], [41]. Thus, they can be viewed as a device manufacturer type actor in the silicon carbide market.

STMicroelectronics

STMicroelectronics is a similar actor to Infineon in many ways. They are one of the largest semiconductor companies in Europe, producing a wide variety of semiconductor products [42]. They have been involved with silicon carbide technology for 25 years and introduced their first silicon carbide MOSFET in 2009 [43].

Within the silicon carbide device market, they hold the largest market share [32]. Together with Tesla they led the way of silicon carbide automotive implementation when Tesla used ST's silicon carbide MOSFET in their Model 3 traction inverter, the first use of silicon carbide in a mass-produced electric vehicle [26]. ST sources their wafers primarily from external sources, such as Wolfspeed. They have however an outspoken target of sourcing their wafers 40 percent internally by 2024. ST acquired Swedish silicon carbide wafer manufacturer Norstel in 2019, and are planning for new facilities in Catania, Italy and in Singapore [44]. ST can thus be said to be of the device manufacturer type actor, with an ambition to become more vertically integrated.

Wolfspeed

Wolfspeed is one of the few major companies in the silicon carbide industry that is referred to as "pure-play". This means that their whole business is centered around wide bandgap technology and especially silicon carbide. They have not been a big actor within silicon power electronics. Rather, Wolfspeed came from a company called Cree, which had for many years their main business areas within LEDs and lighting [45]. Recently, the company sold off its light and LED business to solely focus on their silicon carbide business and changed its name to Wolfspeed. Wolfspeed has a long history of research within silicon carbide technology and wafer manufacturing specifically. Together with another US company II-VI - second to Wolfspeed in the silicon carbide wafer market - they are both high-tech companies that have existed in the wide bandgap US ecosystem for more than thirty years [27]. They have incrementally improved the wafer manufacturing process, often via research funding by DARPA (Department of Defense) or AFRL (Air force research laboratory) [27], and now holds important expertise when it comes to manufacturing wafers from the unique and difficult properties of silicon carbide.

On the wafer level, Wolfspeed is the decidedly dominant actor. With a 62 percent market share of the overall wafer market [32], they can not only be self-sufficient on wafers, only producing power devices based on their own wafers, but also supply their device competitors with wafers. Wolfspeed is a vertically integrated type actor on the silicon carbide market.

4.2.4 Market trends

Acquisitions and investments for vertical integration

As described above, most of the actors in the silicon carbide device market are already established actors in the silicon power device market. However, they do not, apart from Rohm and Wolfspeed, have significant wafer manufacturing capabilities. Instead, they are dependent on other actors, most notably Wolfspeed for the supply of silicon carbide wafers. As Wolfspeed is also a competitor on the device level, this is seen as problematic by some of the device manufacturers [46]. American On Semi bought GT Advanced, a wafer manufacturer to increase their internal sourcing of wafers and to be less dependent on others. On Semi CEO Hassan El-Khoury said *"I don't want to be in that tug of war"*, on the topic of the strained supply of silicon carbide wafers and their dependency on Wolfspeed [46].

"Everybody is looking for production capacity, everybody knows that this is going to be a booming industry"[37] This situation has spurred investments and acquisitions by these actors aiming to increase their level of vertical integration. Wolfspeed themselves are investing 1 billion USD in their new manufacturing facility, enabling them to increase their production of both wafers and devices and further cement their position on the market [47]. As mentioned above, STMicroelectronics has bought Swedish Norstel, a silicon carbide manufacturer and will also invest in new production facilities in Catania, Italy and Singapore, with a ten-fold increase in production as a goal [44].

There are two main reasons for these efforts towards increased vertical integration [24] Firstly, device manufacturers want to be more self-sufficient and less dependent on others for the supply of silicon carbide wafers. Secondly, when controlling the whole chain, actors have more control over the end product's quality and development. In comparison to the mature silicon technology where one can expect excellent quality wafers from many different suppliers, that is still not the case for silicon carbide. The technology is still under development and is experiencing a high rate of yield losses and faults. When controlling the whole chain of production, it is easier to drive development forward [24]. It is therefore seen as advantageous to be able to control these aspects of production.

Supply assurance programs

As a reaction to the semiconductor crisis, some silicon carbide actors have started to offer supply assurance agreements as a new type of service offering. Wolfspeed is an example with their Assurance of supply program [48]. Citing the extensive manufacturing processes and the long time and large investments needed to increase production capacity, the agreements are based on commitments on volume from the customer 18 to 36 months before delivery. In this way, the silicon carbide actors can reserve production capacity early on in line with what the agreement has stipulated and then guarantee delivery. It also allows the actors to finance production capacity expansion in line with demand, reducing their own risk. Usually, the agreements include incentives such as two-way penalties and upfront part-payment to keep the volumes at the level that were promised at the start of the agreement.

4.3 Supply market relationships

Before the Covid-19 pandemic, direct relationships between OEMs and semiconductor companies were uncommon. Initial contact might have occured at the start of the engagement, but for the rest of the time direct contact with the semiconductor companies was seen as unnecessary by the OEMs' [12]. With the supply chain disturbances in the wake of the Covid-19 pandemic, the need for such relationships has been re-evaluated. Now, continuous contact and partnerships between OEM and semiconductor companies have started to develop. Different types of relationships are described further in the section below.

4.3.1 Types of relationships

When looking at the silicon carbide market, agreements are established between actors on several different levels in the supply chain. *Figure 20* shows a mapping of these agreements.

Firstly, silicon carbide device manufacturers are establishing long term contracts with wafer suppliers to secure supply of wafers. Wolfspeed has for example agreements with STMicroelectronics, On Semi and Infineon that have been made public [40], [49], [50].

Secondly, power electronics subsystems suppliers have also signed contracts and cooperate with silicon carbide device suppliers. An example is the large automotive supplier Borgwarner with a long time expertise in components used in vehicles built on the combustion powertrains, such as transmissions and turbochargers. To position themselves in the age of electric vehicles, Borgwarner acquired Delphi Technologies in 2020, who has specialized in electrical systems and software [51]. With the acquisition, they are able to offer the 800V silicon carbide inverter that Delphi has developed in partnership with Wolfspeed [52].

OEMs are also signing long term contracts directly with silicon carbide actors. One example in this case is GM and Wolfspeed. GM has signed a strategic supply assurance agreement with Wolfspeed for the delivery of silicon carbide power devices for their EV-Drivetrain [53]. The agreement comes when GM has an outspoken strategy of developing their drivetrain inhouse including the power electronics subsystems [54], eliminating the subsystem supplier and thus making GM source silicon carbide devices directly from the device manufacturers. Japanese Rohm has struck agreements with several Chinese actors, such as the OEM Geely.

Lastly, OEMs are forming relationships with subsystem manufacturers for silicon carbide power electronic systems, mainly for the traction inverter. BorgWarner, through the above-mentioned acquisition of Delphi, is supplying silicon carbide power electronic subsystems to multiple OEMs such as Porsche and unnamed US and German OEMs. Vitesco is supplying Hyundai Motor Group with an 800 V silicon carbide traction inverter.

The nature and actual content of these agreements and partnerships seems to vary and many don't explicitly state what the partnership will entail. However, it can be said that between actors on the device and wafer level the agreements are mainly focused on securement of supply of wafers, such as those between Wolfspeed and the other device manufacturers. The relationships further downstream between device manufacturers and OEMs or subsystem manufacturers are more oriented towards technological exchange and co-development.

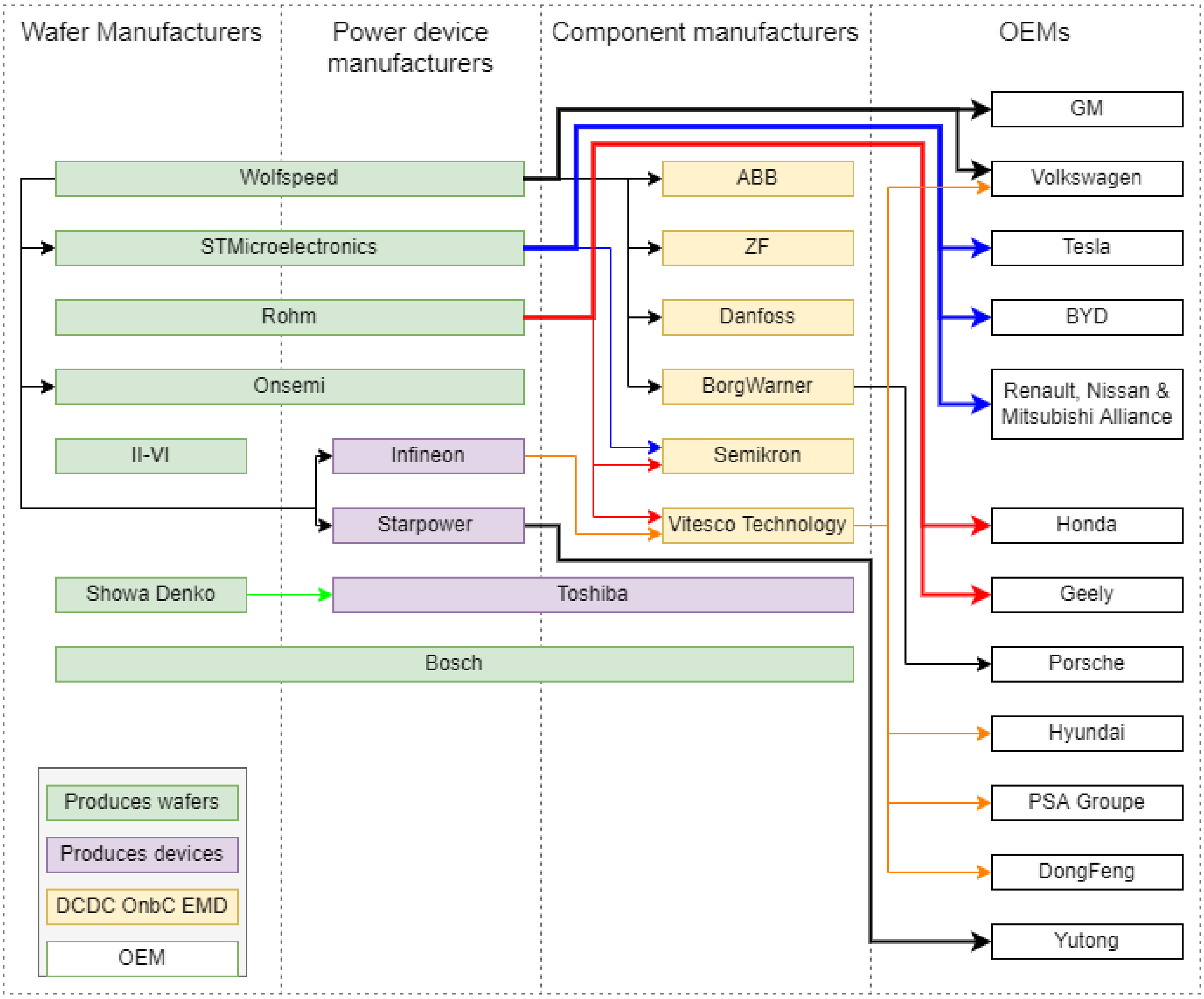

Figure 20: Supply map from wafers to OEMs. See appendix for further details

4.4 External factors

This section describes the political, environmental and technological factors that influence the silicon carbide market.

4.4.1 Political

The interest in silicon carbide is in many ways driven by the green shift of the transportation sector that society and industry is undertaking. This shift is in turn driven partly due to increased restrictions, regulations and incentives that governments around the world are implementing for a faster adoption of more sustainable transportation. Thus, the silicon carbide market is dependent on these political measures for continued growth.

Furthermore, the heightened geopolitical tension of the last decade is also a factor in the silicon carbide industry. The west has found itself in a situation where crucial technology and production in critical industries, such as the semiconductor industry, is developed and performed outside its borders. This has sparked initiatives from both the US and EU to catch up [55], [56]. Furthermore, this has also led the regions to be more protective of its existing industries, which has affected the silicon carbide market. In 2017, the US government stopped the purchase of Cree's silicon carbide business (Wolfspeed) by German Infineon citing national security concerns [57].

Europe is responding in its own way, by EU projects such as TRANSFORM (Trusted European silicon carbide value Chain for a greener Economy). The project is aimed at building *"a complete and competitive supply chain in Europe for Power electronics based on silicon carbide semiconductor technology"* [58]. By bringing together key silicon carbide actors, from the wafer-level to OEMs such as ST Microelectronics, Bosch and Daimler, they wish to *"maintain European sovereignty in the field of power electronics"*.

Although Europe, the US and Japan are still dominant within both silicon carbide production and development, Chinese actors are investing to catch up. With silicon carbide being included in their 14th five-year plan [59], China is viewing it as an important technology for the future. Currently, several Chinese actors have to import American and European power devices, such as Yutong sourcing power devices from Wolfspeed [60]. With the largest electric vehicle market in the world, Chinese actors are both investing in silicon carbide capacity and making alliances with established actors, such as the one between Rohm and Zhenghai group [61].

4.4.2 Environmental

The semiconductor industry is energy and water intensive. With silicon semiconductors demanding high temperatures during its production process, the case is even more so for silicon carbide [62]. This has an effect on the energy consumption of the production processes. However, life cycle studies have found that even though the material and energy impact of silicon carbide production is 2.5 times higher than that of Si, this increase is recouped by two orders of magnitude over its lifetime use [62].

4.4.3 Technological

In addition to silicon carbide, there are also other wide bandgap materials that are promising better efficiency within power electronics. The most prominent being GaN, gallium nitride. GaN power electronics has over the last couple of years started to penetrate the consumer goods market, being used in power adapters for consumer electronics such as mobile phones and computers. Apple's most recent power adapter uses GaN and is able to provide higher power and faster charging with a similar size footprint compared to a silicon counterpart [63]. So far GaN seems to be mostly suitable for lower voltage applications. However, being a few years behind silicon carbide in its development and widespread adoption, it is still unsure whether GaN will be widely used in xEV's and thus provide competition to silicon carbide [64].

4.5 Supply market analysis

Silicon carbide semiconductor technology is poised at becoming an important enabler for the automotive industry to fulfill key customer needs such as longer range and faster charging.

Although it is seeing an increasing use within many different industry sectors, it is the automotive industry that is driving the fast growth of the silicon carbide device market. Since its first-time adoption by Tesla in 2017, silicon carbide power devices are today seeing rapid adoption by many OEMs in the automotive industry.

The production chain of silicon carbide power devices is both long and complex. Furthermore, the production chain is different compared to the silicon production chain in several key steps, such as the wafer and epitaxial processes. This means that production capacity in the form of new machinery and facilities are needed, some of which takes a long time and is expensive to build up. At the same time, some silicon carbide actors are hesitant to invest in new production facilities unless they already have secured orders.

This combination of rapidly increasing demand, a complex production chain and the need for new production capacity and large investments points towards the need for increased coordination and communication among the actors at the different levels within the silicon carbide supply chain. And actors within the industry, both buyers and suppliers, are taking actions. With the ongoing supply chain disruptions of the overall semiconductor industry in mind, actors are now eager to avoid these issues for silicon carbide technology. There is today closer cooperation between OEMs and semiconductor companies, with several recent partnerships consisting of both long-term supply assurement and technological exchange. Also, long-term agreements are being struck directly between different actors on different levels in the silicon carbide supply chain.

Amongst silicon carbide device manufacturers, the level of vertical integration as well as the strategy that is connected to it differs significantly. Whereas some are completely self-sufficient on wafers, others purchase most of them from external sources. Furthermore, some actors are investing to decrease their dependence on external sources to different degrees. Today, it is clear that the level of vertical integration and supply chain resilience is not only important for the device manufacturers themselves but has also become an important part of their offering to potential customers.

5. Company X and silicon carbide

This chapter presents the findings related to Company X's expressed needs and requirements for silicon carbide and silicon carbide-related subsystems. It is divided into two sections; the engineering needs and the supply chain needs.

5.1 Engineering needs

The traction inverter, onboard charger and DC/DC converter have, according to a System chief engineer [6], similar needs when it comes to efficiency and power output. Company X wants more power, better efficiency and smaller size for all drivetrain subsystems, and sees silicon carbide as a viable material to achieve this. To accomplish these goals, they provide suppliers with high level specifications, such as efficiency numbers and physical dimensions [65]. It is then up to the supplier to reach the specifications in whatever way they choose. To use silicon carbide is not a part of the specifications, however, the system chief engineer claims that the efficiency requirements are so high that it would be difficult to achieve them without using silicon carbide devices [6].

Another important target for Company X is to reduce the size of the subsystems, which could also be achieved by switching to silicon carbide [6]. The smaller footprint of the subsystem means more output power per volume unit, paving the way for more powerful subsystems in the same amount of space.

Temperature specifications are also mentioned as an important requirement for Company X. Trucks need to be able to operate in all types of climates, potentially exposing the subsystems to severe heat or cold [6]. In this case silicon carbide would be advantageous compared to silicon because the material is able to both withstand and conduct more heat than Si.

According to the system chief engineer [6], implementing silicon carbide in the three subsystems is not without its design challenges given that the specifications are different from silicon semiconductors. However, it was stressed that the difficulty of these challenges was no cause for concern.

"Just do it, it's not rocket science anymore" - [6] regarding the implementation of silicon carbide.

5.1.1 Traction inverter

Implementing silicon carbide in the traction inverter is deemed the most urgent as this subsystem handles a large amount of power, and therefore has a considerable effect on range. The manager for the motor drive systems design and hardware [65] also emphasizes the possible reduction of enclosure size as an advantage of implementing silicon carbide.

5.1.2 DC/DC-converter

The DC/DC-converter is regarded as the second most important subsystem for the implementation of silicon carbide because it drains the battery even when the truck is not moving, consuming a lot of energy [6]. The power ratings are also set to increase while the size requirements of the enclosure remain the same, further emphasizing the need for a more efficient technology.

5.1.3 Onboard charger

For the onboard charger, silicon carbide devices do not provide the same benefits as with the other subsystems because it is not powered by the battery in the vehicle, meaning that the efficiency gains at this stage do not increase driving range. The size reduction, however, is beneficial as it would allow Company X to use the saved space for other components, such as batteries. A system chief engineer [6] also speculates that when a fast-charging infrastructure is available, the need for an onboard charger diminishes. The reason for this is that trucks are on the road to a much further extent than passenger cars, leaving little time for slow "overnight" charging.

5.2 Supply chain needs

This section presents the supply chain needs related to the three subsystems that could contain silicon carbide.

5.2.1 Price

The biggest reason for Company X not using silicon carbide today is that it has either not been available or has been considered too expensive [6]. One of the larger European suppliers [66] estimates that silicon carbide power modules account for 40 percent of the total cost for a traction inverter. Because it is approximately 2-3 times more expensive than Si, we can estimate a total price increase of 19 percent [7]. However, the battery savings gained from the increased efficiency would far outweigh this increased cost [67], signifying that silicon carbide is ready for implementation from a cost-performance perspective. The onboard charger, DC/DC-converter and the traction inverter all have different power ratings, which means that the same silicon carbide devices cannot be used in all three. However, Company X's system chief engineer [6] suggests sourcing from the same product family of silicon carbide power semiconductors could reduce relationship handling costs and direct transaction costs. Sourcing the three subsystems from the same suppliers is one way to decrease costs but Company X has employed a deliberate strategy not to do so. The reasoning is that buying everything together as one system reduces Company X's ability to adjust and create their own interfacing in the powertrain.

5.2.2 Make or buy

Company X does not currently possess the capacity nor the expertise to produce any of the three subsystems themselves. The traction inverter is however seen by the system chief engineer [6], as something which might be designed and assembled in-house in the future. The DC/DC-converter is viewed more as an off-the shelf product, and the onboard charger as a subsystem might disappear altogether or be sold as an option to the customer. Because of this Company X's need to produce chargers and DC/DC-converters in house is non-existent.

If the traction inverter were to be assembled in house, both the manager for the motor drive systems design and hardware, as well as the system chief engineer for motor drive systems [65] are open to the idea of sourcing directly from a silicon carbide device manufacturer. However, if the traction inverter is sourced from a supplier, neither of them see any reason for a direct relationship with a silicon carbide device manufacturer.

5.2.3 Supplier relations

From the engineering point of view silicon carbide power semiconductors are regarded as commodity components in the same manner as nuts and bolts. There is no expressed wish for customization of subsystems on the chip level, instead customization comes when designing the complete power electronic subsystems [6]. The system chief engineer for electric distribution and charging [6] does not consider it to be of much value to have engineering collaborations with the silicon carbide manufacturers because current purchasing volumes are too low and too uncertain to accomplish anything in terms of development and R&D. He does however consider it valuable to have good relationships with silicon carbide manufacturers on a management level to help with supply chain issues such as shortages.

A Senior buyer and segment leader [12] considers supply chain constraints as a big enough risk to make relationships with device manufacturers necessary. According to him, Company X's needs relationships with the device manufacturers to ensure a resilient and robust supply chain. He also emphasizes the fact that when the supply chain is managed by a Tier 1 supplier, the power device manufacturers will develop their product portfolio according to the needs of Tier 1 suppliers rather than the needs of the OEM. The senior buyer and segment leader therefore suggests sharing technological roadmaps and forecasts between the OEM and device manufacturers.

The same senior buyer and segment leader [12] stresses that the OEM should not take over any responsibility from Tier 1 suppliers when it comes to managing the supply chain. If they did, it would raise compliance and responsibility issues. Because of this he sees a situation where Company X forces a Tier 1 supplier to buy from a specific device manufacturer as problematic. On the other hand, he says that Company X should try to source silicon carbide from power device companies that can guarantee supply chain resilience, preferably by being vertically integrated. As Company X has limited control of how a supplier sources their components once a deal has been struck, the proposed sourcing strategy of the supplier should be an important selection criterion for Company X when evaluating whom to buy subsystems from.

A senior commodity buyer also brings up the fact that Company X do not usually commit to buying specific volumes, making it difficult to establish agreements with power device manufacturers directly as volume commitments are crucial for their capacity planning [67]. This is especially important in the case of the sale of electric trucks, where future demand to a large degree is uncertain.

At the same time, from interviews with suppliers in the silicon carbide industry, there is a strong sentiment that the OEMs such as Company X need to be involved both deep and early in the silicon carbide supply chain to secure supply [24], [37]. Against the backdrop of the semiconductor crisis, and with both growing demand for silicon carbide devices together with the need for a buildup of production capacity, there is a concern that there might be a risk of device shortages. *"You can't just expect the supplier to do everything. There needs to be a very collaborative way of working…you cannot expect silicon carbide devices to just be there, you have to get involved early on"*[37].

The type of involvement needed builds on an understanding of the processes in the supply chain: *"You have to know the processes of the supplier, and of the suppliers of the suppliers. To go two-three levels deep to understand what is going on, what is needed there and identify possible bottlenecks."*[37] Furthermore, the semiconductor crisis has shown a necessity for a new type of mindset by the OEMs, abandoning old paradigms: *"The JIT days are over. Everybody loves inventory these days, so make sure you have good agreements in place and think far in advance of your requirements and make sure you have it all laid out. Take control! "* [37]

6. Configurations & Sourcing strategy factors

This chapter presents three supply network configurations created utilizing the frameworks by Cooper & Lambert [17] and by Gadde & Snehota [18]. A traditional, controlled and a balanced configuration based on the finding of chapter 4 have been created to provide the full spectrum of possibilities for discussion. The type of actors present in the configurations are the power electronics subsystem supplier, the silicon carbide device manufacturer and the silicon carbide wafer manufacturer, due to them being identified as critical supply chain members. In reality there might be suppliers between these actors such as electronic manufacturing service-companies. These potential actors are left out of the configurations as they are deemed to be non-critical for the aim of the thesis.

For each configuration, the network structure and the links between the actors are described. The level of involvement in the supply chain is evaluated by all three involvement dimensions, and the economic consequences of the supplier relationships are discussed. In addition, a more general discussion on the advantages and disadvantages with regards to the supply market analysis and Company X's needs is presented.

The discussion of the three configurations will be used together with the learnings from chapter 4 and 5 to present the most important factors that affect the sourcing strategy of silicon carbide. Lastly, these factors will in turn provide guidance for a final recommendation on how Company X should approach the sourcing issue.

6.1 Traditional configuration

The first supply network configuration that is described and analyzed is inspired by how OEMs traditionally approached its silicon semiconductor supply chain before the Covid-19 pandemic. In this configuration Company X leaves virtually all responsibility to the subsystem suppliers, leaving them to source silicon carbide the way they deem to be best. Using this configuration Company X would not need to concern itself with upstream actors - neither managing nor monitoring links beyond the Tier 1 level - allowing them to make full use of their sourcing competence. The links present are managed process links between Company X and the Tier 1 suppliers, and not managed process links going from Tier 1 suppliers upstream, meaning all control and monitoring is left to the Tier 1s.

Within these managed links the business processes of procurement and product development are present, but not in relation to silicon carbide specifically but only in the relation to the subsystems. Furthermore, manufacturing flow management is also limited from the OEMs perspective to the activities performed by the Tier 1 supplier which could or could not include assembly of the subsystem. *Figure 21* illustrates this traditional configuration.

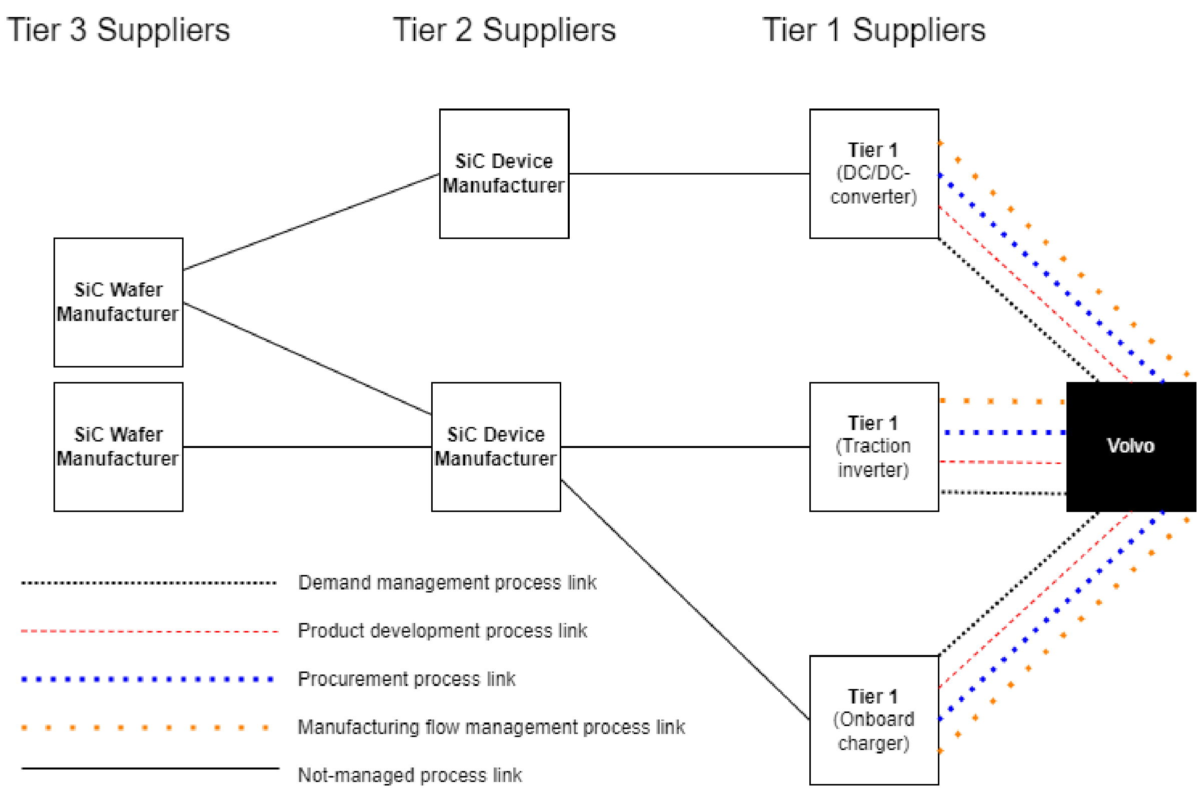

Figure 21: Example of a traditional configuration

With little contact between Company X and the silicon carbide actors, this configuration naturally scores low on all three dimensions of involvement. There is little coordination, adaptation or interaction between Company X and the supplier below Tier 1. With the low level of involvement this configuration is not resource intensive, meaning that relationship handling costs as well as supply handling costs should be low. On the other hand, the low involvement also means that cost and revenue benefits that can come from more tight collaboration with silicon carbide actors is omitted.

With such low levels of involvement, collaborative activities with members upstream in the supply chain are also low. Thus, the important antecedent of supply chain resilience, visibility, is low. This in turn makes it hard for Company X to act with both flexibility and velocity in case of unforeseen events within the supply chain.

There are several advantages with this approach. It gives a high level of authority to the tier 1 supplier to choose the best supplier according to their expertise. This could be advantageous with regards to the technological competency discrepancy between the OEM and the tier 1. The tier 1 who develops the subsystem should also have the right competency to take good sourcing decisions. This aligns well with what the Company X engineers are requesting, which is to give the subsystem suppliers high level specifications and let them solve the rest. As silicon carbide power devices are viewed as commodity components, from a strictly technical standpoint there is little need for direct contact between OEMs and device manufacturers. Furthermore, the responsibility boundaries between actors are clear in this configuration - the tier 1 takes care of its supply chain itself without involvement from the OEM. This way, liability and compliance issues that were voiced during interviews are avoided to a high degree. As the Tier 1 takes all the decisions with regards to its sourcing, it is also fully responsible for them. This configuration also aligns with the OEM practice of not committing to volumes early on.

In the context of sourcing semiconductor devices, the disadvantages of this configuration have already been proven. The supply chain disruptions in the wake of the Covid-19 pandemic has shown the vulnerabilities of this approach, with shortages of semiconductors leading to costly stops of production for the automotive industry. The lack of involvement and visibility into the silicon carbide supply chain hinders the OEM from acting preemptively in situations of crisis. Both the characteristics of the supply market described in chapter 4 as well as interviews with Company X personnel and industry experts points towards deeper involvement and better coordination between the actors in the silicon carbide supply network, including the OEM. Furthermore, this approach also omits the benefits that can come from closer relationships with the semiconductor manufacturers - such as both sharing and influencing technological roadmaps.

6.2 Controlled configuration

This supply network configuration is in many ways the opposite of the traditional configuration. The focus in this case is for Company X to take a dominant position and control important processes within its own supply chain. Like several other OEMs has already done, Company X would in this case partner directly with a device manufacturer through a supply assurance program. The device manufacturer then provides the power electronics subsystem suppliers with silicon carbide devices. The managed links between Company X and the tier 1 supplier would contain the same processes as in the traditional configuration. However, in this configuration, there are also managed links between the Tier 1 suppliers and device manufacturers. These managed links mean that Company X would have business processes between the Tier 1 and the device manufacturers that they manage. By committing on volumes as the supply assurance program stipulates, production volumes between the tier 1 and the device manufacturers are decided by derived demand. This way, Company X can steer the processes by actively taking leadership of the product and manufacturing flows. Furthermore, through its involvement within the manufacturing flows of the tier 1 and upstream suppliers, Company X can ensure buffers are in place at different levels of the supply chain, increasing its resilience.

The supply assurance partnership between Company X and the device manufacturer is symbolized by the procurement process that exists directly between them. Furthermore, this partnership also enables fruitful product development processes by the sharing of technological roadmaps. As Company X is closest to the end-customers, they are also best suited to understand how demand fluctuates. With tightknit connections to both the tier 1 and suppliers upstream, they can coordinate the supply chain via the demand management process.

This configuration also includes monitored links between device manufacturers and wafer manufacturers. With the supply assurance program, this would come somewhat automatically, as the production capacity of wafers needed for the committed volumes of silicon carbide devices have been booked.

Figure 22 illustrates the controlled supply network configuration.

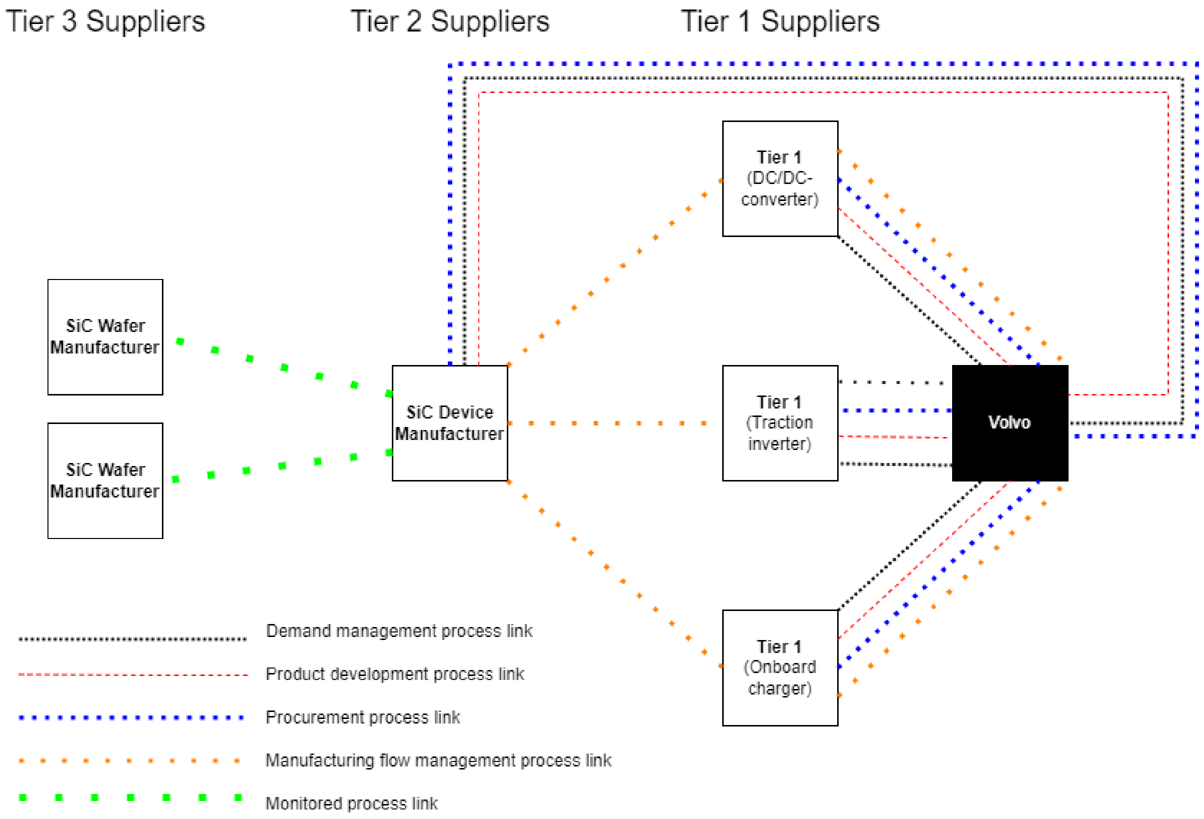

Figure 22: Controlled supply network configuration

The controlled configuration scores high on involvement dimensions for both the coordination of activities and interaction between individuals. Through the partnership between Company X and the device manufacturer, tight coordination is necessary for activities such as demand, material and capacity planning and limited joint exchange on product development. Furthermore, this tight coordination would necessitate intense interaction of individuals from different areas within both companies. As power devices are viewed as commodity components however, the need for resource adaption is limited. Thus, the resource adaption dimension is not scored as high.

In terms of economic consequences, the direct procurement costs should be lower than for the traditional configuration. By procuring the silicon carbide devices from the same manufacturer and doing so through a partnership might enable scale benefits that can affect the price. On the other hand, with a high level of involvement through intensive interaction and coordination, relationship handling, and supply handling costs could become considerable. However, through the higher level of involvement with silicon carbide actors, Company X could potentially reap other benefits such as lower supply handling costs.

Being part of the supply assurance program, supply chain resilience should be deemed to be high. By investing in production capacity of the device manufacturer, Company X is granted both a high level of security and high visibility for the securement of silicon carbide devices. But this comes at the cost of both flexibility and velocity. If the volumes committed by Company X would turn out to be inaccurate, and with little room to change them, Company X could be stuck with high costs. Thus, this raises the question of whether the supply assurance program model is the right redundancy action for Company X to take to increase supply chain resilience, and if there are other more cost-effective options available.

Advantages of this configuration is that it gives Company X control of the supply chain all the way up to the device manufacturer. Having this type of control would give Company X the ability to rapidly respond to supply chain disruptions which in the case of the silicon carbide market is crucial due to the long lead times and capacity limitations. Furthermore, the partnership and supply assurance would provide considerable resilience in the supply chain. Consolidating all silicon carbide devices to one manufacturer could also provide enough monetary volume to be prioritized if disruptions do occur. Another advantage with this configuration is that it gives Company X an opportunity to utilize the product development process to their advantage. By sharing technological roadmaps and technical discussions Company X could make sure that their input is taken into consideration when new products are developed.

A disadvantage of this configuration is that Company X would to a large degree disable the tier 1 supplier, who would otherwise utilize their sourcing and technology expertise within power electronics, which might be better than that of Company X. It could also result in compliance and liability issues between different actors in the supply chain. With Company X taking on more of the responsibility in many of the processes, they are also liable to a higher degree for the decisions they make. Furthermore, considering the highly dynamic nature of both silicon carbide technology and its market, it might be risky to be dependent on a single actor. Another risk is that even with consolidation, is that it might be difficult for a truck manufacturer to be among the most important customers for the device manufacturer at this time. This is because the passenger car industry is years ahead in terms of production volumes, making it likely for them to be prioritized when disruptions occur. The production volumes of Company X themselves are also at a level that might be too small to make full use of potential advantages with this configuration. Lastly, the risk that is averted by joining a supply assurance program can be transferred to the risk Company X takes on by committing to volumes early on. The electric truck business is still in many ways in its infancy, and it is hard to forecast future demand several years ahead.

6.3 Balanced configuration

This configuration attempts to strike a balance between the two previous configurations. In this case Company X would allow the Tier 1 suppliers to choose which device manufacturers to use and what products to buy, thus letting them manage their own supply chain. Company X would however establish relationships with the device manufacturers chosen by the Tier 1 suppliers and come to agreement to share forecasts and deal with sudden variability in demand. The device manufacturers would also have to allow Company X to monitor their relationships with wafer manufacturers to avoid surprise shortages. Thus, the links present are managed process links between Company X, tier 1 suppliers and device manufacturers as well as monitored links between device manufacturers and wafer manufacturers.

The business processes linked between Company X and the tier 1 suppliers are the same as in the traditional configuration. Between Company X and the device manufacturers the business process involved is the demand management process link. silicon carbide device manufacturers receiving both short- and long-term forecasts from the OEM helps them to better plan their production, lowering the risk for disruptions. An illustration of a balanced supply network configuration can be viewed in *Figure 23* below.

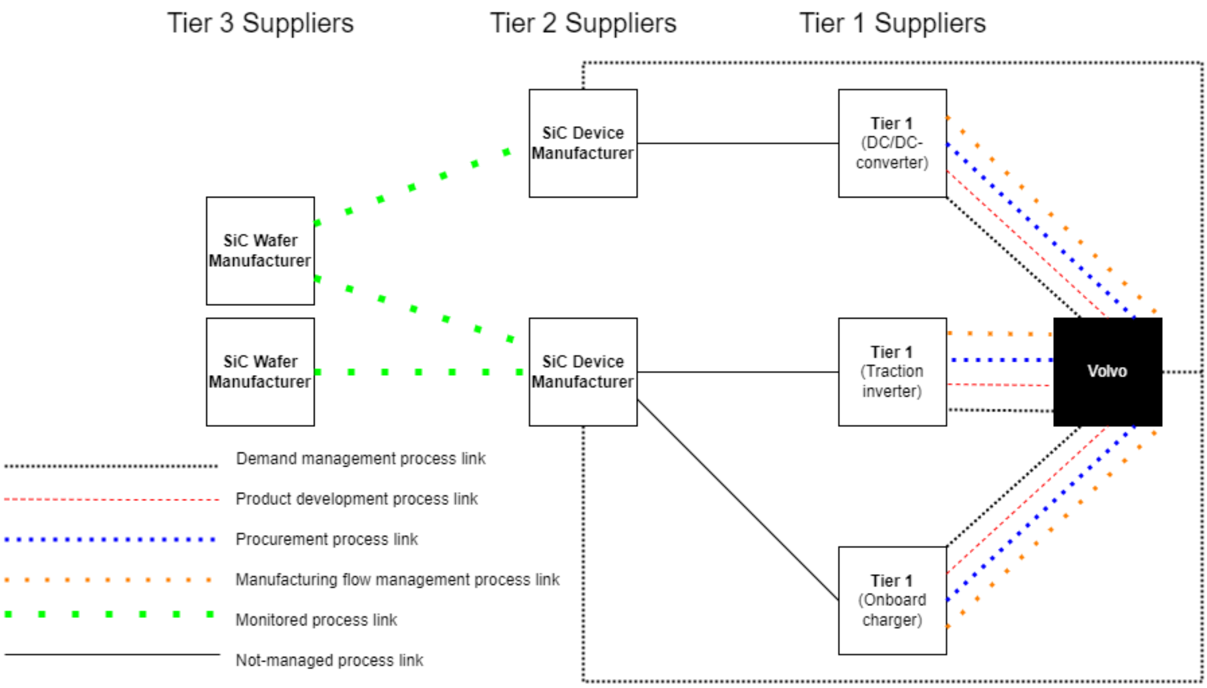

Figure 23: Balanced supply network configuration

In this configuration the level of involvement between Company X and the device manufacturer is considered to be on a medium level in the coordination of activities and interaction between individuals. This is because Company X has an open dialog with the device manufacturers regarding demand management related activities such as forecasts and disruption relief. Regarding the resource adaption dimension of involvement, the score is low for the same reason as in the other configurations.

With no influence over the actual procurement process of silicon carbide devices, in this configuration direct procurement costs would be on the same level as in the traditional configuration. However, supply handling costs would become lower due to the ability of Company X to receive faster response on demand variability because of the demand management process between the two parties. These lower supply handling costs come at the expense of a slightly increased relationships handling costs compared to the traditional configuration. The increased visibility and coordination between Company X and silicon carbide actors can prevent costly supply chain disturbances and thus contribute to cost benefits.

Thus, with a focus on visibility within the supply chain, and with collaborative activities in the form of business processes between different levels in the supply chain, the supply chain resilience can be strengthened. The increased visibility allows for both better flexibility and velocity. As Company X has direct connections with silicon carbide device manufacturers, and has knowledge of the wafer-level as well, it endows them with options for both swifter and a wider variety of actions in case unforeseen events occur.

The advantages of this configuration is that the level of involvement between Company X and device manufacturers could be kept at a relatively low level while simultaneously communicating and coordinating about key supply chain insights regarding variability and disruptions. Furthermore, Company X would be able to utilize the expertise of the Tier 1 supplier when it comes to the actual selection of suppliers and power devices and avoid compliance and liability issues that could easily occur with a higher level of involvement.

A disadvantage is that while Company X would quickly be aware of disruptions, they wouldn't necessarily have the authority or priority level to actually influence the outcome. Furthermore, depending on supplier selections made by the Tier 1 supplier, the total number of device manufacturers could become too many for Company X to be involved with, especially if the tier 1 suppliers decide to use multiple sourcing. This situation can become even more complex if the device manufacturers also use multiple sourcing on the wafer-level.

6.4 Sourcing strategy factors

When identifying the most important factors for Company X to consider when sourcing silicon carbide subsystems, both the silicon carbide market and the specific needs and context of Company X is taken into consideration. The most important factors are the allocation of supply chain risk, choosing the appropriate level of involvement and selecting resilient suppliers. The motivation for these factors being the most important are described in the subsections below.

6.4.1 Allocation of supply chain risk

The market analysis has shown that increasing the production capacity of silicon carbide devices requires large investments. At the same time, the silicon carbide actors themselves are unwilling to fully finance capacity expansion without knowing that they will be utilized to a certain degree. Thus, the securement of supply of silicon carbide devices is connected to assurances of future orders and volume commitments. Company X can either take a risk by committing on volumes that in large part are veiled in uncertainty or they can decide not to commit and hope that production capacity of the silicon carbide actors will be enough to cover their demand.

Since the whole transportation industry is moving to electric vehicles, and silicon carbide being an important enabling technology for this transition, other solutions for sharing the risk could be available. It could consist of new types of partnerships vertically between different levels of the supply chain, but also of sourcing partnerships between automotive actors, sharing the risk.

6.4.2 The right level of involvement

The second important factor to consider is the appropriate level of involvement towards device manufacturers. The semiconductor crisis has shown the necessity for Company X to initiate relationships with semiconductor suppliers for increased coordination to efficiently deal with disruptions. These relationships can increase the transparency between these actors and Company X has expressed the need for this type of transparency when it comes to silicon carbide as well. The question then becomes to which degree Company X should be involved with these device manufacturers, especially with the subsystem supplier in mind. On the one hand Company X wants to ensure a resilient supply chain, on the other hand Company X needs to tread a careful balance regarding how much control they can force upon a tier 1 supplier.

Current and future production volumes and production strategies also need to be considered when determining an appropriate level of involvement. The current production volumes are too low to make it worthwhile having any form of technological exchange, the low volumes also make it difficult to receive synergy effects from high levels of involvement. Future volumes can, however, make it risky not to establish deep relationships early as Company X might be left out if shortages arise.

The balancing act of involvement continues with regards to the right actions to take to increase supply chain resilience. Here, Company X has to consider the trade-offs between the costs of redundancy measures in the form of deeper and more committed involvement with silicon carbide actors and the costs that could occur if they would abstain.

6.4.3 Selecting resilient suppliers

The supply market analysis revealed that the level of vertical integration of the device manufacturers differs to a high degree. For example, Wolfspeed produces more than half of all wafers, not only for its own use but also supplying many of its competitors. This creates chains of potentially problematic dependencies that could have a negative effect on Company X if disruptions occur. This type of dependency is especially problematic if Company X is entirely reliant on the sourcing decisions of their subsystem's supplier.

With the differing degrees of vertical integration of the device manufacturers, Company X will have to adjust their level of involvement according to the suppliers that they have upstream.

For suppliers with low levels of internal wafer sourcing, Company X will have to make sure that their supply agreements and production capacity expansions are enough for their own consumption. Thus, Company X should take this in consideration when they choose their subsystem or silicon carbide device suppliers: what silicon carbide actors are they then matched up with? And how will that affect the level of involvement needed from Company X side?

Another issue affecting the choice of supplier is the initially low volumes. Ideally a supplier should regard Company X as an important customer that is to be prioritized which is a tough sell when volumes are low. To be prioritized as a low-volume customer Company X would have to bring other benefits to the silicon carbide manufacturers. These benefits could be in the form of publicly disclosing supply agreements with truck manufacturers, signaling that the silicon carbide manufacturer has a product portfolio ready for this market. Another benefit for the silicon carbide manufacturers could be in the form of technological insights from the truck industry.

6.5 Recommendation

The three configurations each have their own advantages and disadvantages and they are all prone to their own risks. The risks with the traditional configuration have already been proven with the semiconductor crisis, where the lack of control and visibility into the supply chain has proven to be costly for the automotive sector. On the other hand, the controlled configuration entails risk by having to commit on volumes early on, which can be difficult due to the variability in demand. The balanced configuration attempts to balance both configurations and the risks they would infer.

From Company X’s current situation the balanced approach is judged to be the most suitable because it aligns with the needs of Company X to not commit on volumes while simultaneously working towards minimizing supply chain disruptions issues. Steps towards a more controlled configuration could be made as volumes increase and if any of the subsystems starts being designed and built in-house. To counter the disadvantage of a potentially too complex supply chain when using the balanced configuration Company X could request that the tier 1 suppliers choose between a select few device manufacturers.

7. Conclusion

There are multiple ways to configure a supply network and successfully source subsystems containing silicon carbide devices and each configuration comes with its own benefits and drawbacks. To understand which one is best suited to the task an OEM must weigh many factors against each other to find a suitable balance between supply assurance and supply chain risk. In the case for Company X the balanced network configuration is deemed to be the most suitable as the controlled configuration requires higher production volumes and more easily forecasted demand, and the traditional configuration is not well suited to match the conditions of the silicon carbide market.

The most important factors for Company X to consider when forming a sourcing strategy for silicon carbide devices are the allocation of supply chain risk, supplier selection and the level of involvement necessary to secure supply. The supply chain risk allocation problem originates from the silicon carbide production capacity issue which demands that someone downstream from the device manufacturer must commit on volume. Selecting a device manufacturer who can guarantee wafer supply as demand increases is crucial and difficult due to the different levels of vertical integration between the suppliers. Finally, the necessary level of involvement must be selected to suit current needs of Company X while also allowing for increases of demand.

While these conclusions are derived from a specific case at Company X, the results are also applicable for other situations where silicon carbide semiconductors are sourced. In particular, the most important factors to consider when forming a sourcing strategy are applicable for other automotive actors, an industry where volume commitments are unusual. Furthermore, the discussion around the different supply network configurations includes many aspects that are relevant when sourcing silicon-based semiconductors.

8. Further research

This thesis has analyzed the conditions of the silicon carbide market and presented alternative supply network configurations and important factors to consider when sourcing silicon carbide, during which several questions regarding implementations of factors and configurations can be raised.

One of them is regarding what types of contracts that can be constructed in a situation where OEMs cannot commit on volumes and silicon carbide manufacturers are demanding it. The controlled and balanced configuration both suggest the involvement of three parties in agreement, raising compliance issues between them. The design of such agreements is therefore suggested as a possible area for future research.

Another area of interest is how non-member supply chain links affect OEMs when sourcing silicon carbide. A key question on this topic is to investigate how priorities are made for customers participating in supply assurance programs, and how non-members of the network with higher volumes influence the supply chain resilience of the OEM.

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Appendix

Table of silicon carbide market relationships

Silicon carbide partner	Other partner	Type of partner	Date of agreement	Focus of agreement	Short descripton	Link
Wolfspeed	GM	OEM	2021-10-04	Supply assurance	GM to participate in Wolfspeed Assurance of supply program - secure long term supply of silicon carbide devices	Link
Wolfspeed	Volkswagen	OEM	2019-05-19	General	Wolfspeed selected as key partner for Volkswagen. Will work together with system suppliers and module manufactuerers	Link
Wolfspeed	ABB	Module supplier	2019-11-18	General	ABB will use Wolfspeeds silicon carbide devices for their power modules	Link
Wolfspeed	ZF	System supplier	2019-11-05	General	Wolfspeed and ZF has formed strategic partnership for electric drivelines	Link
Wolfspeed	Delphi/BorgWarner	System supplier	2019-09-15	General	Wolfspeed formed a partnership with Delphi which BorgWarner has acquisitioned. The partnership still stands.	Link
Wolfspeed	ST Microelectronics	Device/Module supplier	2021-08-17	Supply	Continuation of long-term supply agreement of silicon carbide wafers	Link

Wolfspeed	Infineon	Device/Module supplier	2018-02-26	Supply	Wolfspeed and Infineon announce supply parnership for silicon carbide wafers	Link
Wolfspeed	On Semi	Device/Module supplier	2019-08-06	Supply	Wolfspeed and On Semi announce supply partnership of silicon carbide wafers	Link
ST Microelectronics	Tesla	OEM	2017	Unknown	Tesla uses STM devices in their inhouse developed traction inverter for the Model 3	Link
ST Microelectronics	Renault-Nissan-Mitsubishi	OEM	2019-09-19	Design and Development	ST Microelectronics was chosen to supply silicon carbide devices for the OBC for the Renault-Nissan-Mitsubishi alliance	Link
Rohm	ST Microelectronics	Device/Module supplier	2020-01-15	Supply	Rohm and their subsidiary silicon carbiderystal has entered an agreement for supply of silicon carbide wafers to ST Microelectronics	Link
Rohm	Semikron	Module supplier	2017-03-13	General	Rohm and Semikron collaborate by the use of Rohms silicon carbide power devices within Semikrons power modules	Link

Rohm	Geely	OEM	2021-09-17	General	Rohm and Geely have formed a strategic partnership focused on silicon carbide power devices.	Link
Vitesco	Hyundai	OEM	2021-03-24	General	Vitesco will supply 800 V silicon carbide traction inverters for Hyundai	Link
BorgWarner	Unnamed German OEM	OEM	2021-11-03	General	BorgWarner will supply a large unnamed german OEM with 800 V silicon carbide traction inverters	Link
BorgWarner	Unnamed US OEM	OEM	2021-11-03	General	BorgWarner will supply a large unnamed US OEM with 800 V silicon carbide traction inverters	Link
Vitesco	NEV	OEM	2021-09-13	General	Vitesco will supply 800 V silicon carbide traction inverters for a large unnamed chinese OEM	Link
Rohm	Vitesco	System supplier	2021-05-04	General	Rohm will provide silicon carbide devices and technology for Vitesco's 800 V traction inverter	Link
Rohm	UAES	System supplier	2021-11-18	General	Rohm has been selected by the Chinese system supplier UAES as a prefered partner for silicon carbide technology	Link

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SUPPLY AND OPERATIONS MANAGEMENT
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2022
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