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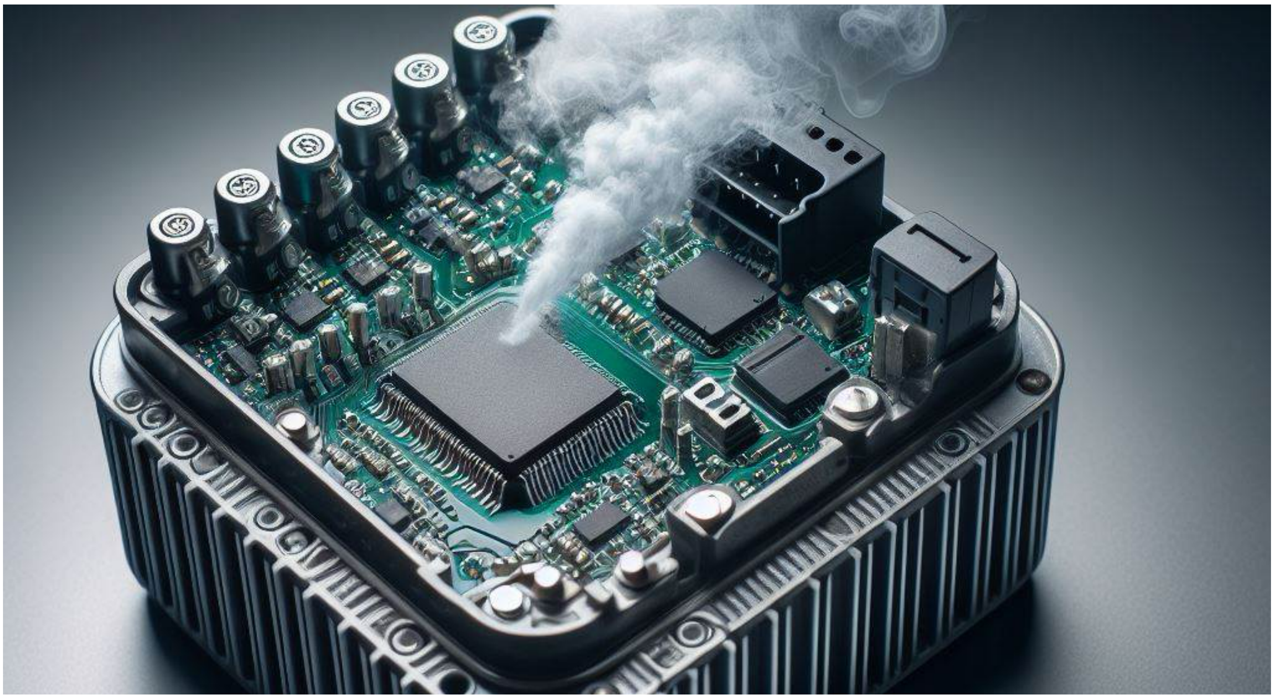

Decarbonizing the Automotive Electronics Supply Chain: A Maturity Assessment Framework of Suppliers

Master's thesis in Management and Economics of Innovation

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Cover:
Smoke emitting from electronic component (ECU)

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Abstract

This research aims to enhance knowledge of how electronics component suppliers in automotive supply chains are progressing towards decarbonization. A qualitative approach was employed, utilizing interviews with Tier 1 and Tier 2 suppliers, alongside a literature review and analysis of company sustainability reports. To ensure the validity of the research instrument, a pilot study was conducted to assess the feasibility of a draft maturity model. This model incorporates four key dimensions, each element of which influences a supplier's decarbonization journey. The resulting maturity model is designed to be simple and universally applicable, enabling the assessment of various suppliers and their progress towards decarbonization.

Keywords: *OEM, Maturity Model, Multi-tier supply chain, Sustainable supply chain, ECU, Decarbonization*

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List of Acronyms

Below is a list of acronyms that have been used in the thesis.

CBAM:	Carbon Border Adjustment Mechanism
CDP:	Carbon Disclosure Project
CoCSR:	Code of Corporate Social Responsibility
CSR:	Corporate Social Responsibility
ECU:	Electronic Control Units
EIME:	Environmental Impact Made Easy
EMS:	Energy Management System
ESG:	Environmental, Social, and Governance
ETS:	Emission Trading System
EU:	European Union
EuP:	Energy-using Products
GHG:	Greenhouse Gas
GRI:	Global Reporting Initiative
HFCs:	Hydrofluorocarbons
ISO:	International Organization for Standardization
IT:	Information Technology
LCA:	Life Cycle Assessment
MNC:	Multinational corporations
N_2O:	Nitrous Oxide
OEM:	Original equipment manufacturer
PCB:	Printed circuit boards
PCF:	Product Carbon Footprint
PFCs:	Perfluorocarbons
PIE:	Public Interest Entity
PV:	Photovoltaic

REC: Renewable Energy Certificates

RO: Reverse-Osmosis

RoHS: Restriction of Hazardous Substances

SBTi: The Science Based Targets Initiative

SC: Supply Chain

SF_6: Sulfur Hexafluoride

SME: Small and Medium Enterprises

SSCM: Sustainable supply chain management

VAP: Validated Assessment Program

VOCs: Volatile organic compounds

WEEE: Waste Electrical and Electronic Equipment

1 Introduction

The master thesis is done in collaboration with the electronics and purchasing department of a large-scale commercial vehicle original equipment manufacturer (OEM). The electronics department handles the design and purchase of the various Electronic Control Units (ECUs) that go into their vehicles. The focus of this thesis will be on the decarbonization of electronic components of an ECU like printed circuit boards (PCBs) and semiconductors, in the initial stages of the supply chain.

1.1 Background

Climate change, a pressing environmental issue, is causing a rise in global temperatures, leading to more frequent and severe heat waves. Extreme weather events, a direct consequence of climate change, damage the environment, leading to habitat loss and biodiversity decline. Climate change also intensifies social and economic inequalities, disproportionately affecting communities that depend heavily on natural resources. Therefore, the environmental impacts of climate change are extensive, affecting all aspects of the planet's ecosystems.

Manufacturing industries within the European Union (EU) represent a significant source of greenhouse gas (GHG) emissions (Panagiotopoulou et al., 2021). They rank as the second-highest contributor, following the energy sector, to the EU's overall GHG footprint (Miceikienė et al., 2021). Several factors influence the carbon footprint of the manufacturing sector, including electrical energy consumption and material production processes (Álvarez-Martínez & Mainar-Causapé, 2021). Estimates suggest that industrial activities in Europe contribute between 30% and 40% of total GHG emissions, with electricity consumption within the manufacturing sector itself accounting for approximately 37% of its emissions (Pirouz et al., 2020).

In the case of automotive and commercial vehicle manufacturers, these emissions occur all along the life cycle of vehicles, from raw material extraction and processing to manufacture and ultimately usage/ disposal at the end of life (Hirz & Nguyen, 2022). Research underscores the crucial role of comprehensive evaluations in understanding the life-cycle carbon footprints of vehicles across different propulsion technologies which includes a thorough examination of combustion engines, hybrid powertrains, and battery-electric systems (Jing et al., 2020). Furthermore, analyses of GHG emissions disclosures within sustainability reports highlight inconsistencies in transparency between automotive corporations' headquarters and subsidiaries (Rogowska & Wyrwa, 2021). These findings illuminate the importance of standardized emissions reporting methodologies across international borders.

The Paris Agreement brings together countries against global warming but also helps them adapt themselves to climate change impacts to prevent temperature rise beyond pre-industrial levels by more than two degrees Celsius. The Science Based Targets Initiative (SBTi) helps corporations align their climate ambitions with scientific data so that they can contribute towards achieving objectives set under the Paris Agreement. Such efforts provide a framework for reducing greenhouse gas emissions, highlighting collective action by nations and businesses.

As per the GHG protocol (Russell, 2019), carbon emissions are divided into 3 major scopes. Scope 1 emissions are considered direct emissions which are from own sources like company vehicles or facilities, while Scope 2 emissions are considered indirect, resulting from purchased energy like electricity for manufacturing. However, most emissions in the automotive industry, known as Scope 3, are indirect emissions not covered in Scope 2, occurring in the value chain. This comprises of the release of GHG from the procurement and manufacturing of acquired substances and energy sources, activities related to transportation in conveyances not owned or operated by the reporting organization, and the use of products and services that have been sold. As the world moves towards a more sustainable future, these industries face the challenge of significantly reducing their GHG emissions across all scopes.

Considering this, a crucial aspect of a company's carbon footprint is Scope 3 emissions, which includes indirect emissions in every part of the value chain, from both suppliers (upstream activities) and customers (downstream activities) (Reavis et al., 2022). Often the largest contributor to a company's footprint (Downie & Stubbs, 2012), these emissions require careful consideration. When analyzing a company's carbon footprint, focusing on cradle-to-gate emissions, rather than the entire life cycle (cradle-to-grave), is a common practice (Wells et al., 2012). This approach offers a more manageable scope for analysis, particularly within life cycle assessments. Additionally, focusing on cradle-to-gate emissions aligns with established carbon footprint guidelines, ensuring consistency and allowing for easier comparison between different assessments (Wells et al., 2012).

Over the years, electronic components have evolved in automobiles, replacing mechanical parts as automotive technologies progress (Hua et al., 2023). Modern vehicles are no longer purely mechanical; instead, they are extensively controlled and monitored by digital computers connected through internal vehicular networks (Koscher et al., 2010). This shift reflects the ongoing evolution of the automotive industry, with electronic components playing a crucial role (Gowda & Thatkur, 2023). Additionally, integrating electronic components into vehicle operation has been found to reduce emissions compared to one without them (Šarkan et al., 2022). Among the numerous parts in an automobile, electronics includes the ECU which houses an assembly of small electronic components that play a significant role in the vehicle's operation. Though ECUs as a product do not emit greenhouse gasses directly, they contain PCBs and semiconductors, that go through a resource-intensive production and energy use, which can contribute to high carbon footprint (Wolff et al., 2020). Hence it could be interpreted that an ECU is a significant contributor to emissions during the cradle-to-gate life cycle of these vehicles.

While considering the supply chain of an ECU, different suppliers are involved, each contributing components and materials. Large organizations increasingly recognize the importance of multi-tier supply chains for achieving sustainability goals (Kusi-Sarpong et al., 2023). These complex networks, however, rely on effective information sharing across all tiers to optimize costs, improve planning, and ultimately enhance competitiveness (Kembro, 2015). The recent global pandemic further underscored the need for transparency within these structures as understanding the location characteristics of firms throughout the supply chain became critical in managing disruptions and ensuring overall performance (Lavassani et al., 2022). This thesis will concentrate on the decarbonization efforts of the focal company's ECU and semiconductor suppliers across multiple tiers of the supply chain.

1.2 Purpose

The purpose of this research is to enhance the knowledge on by exploring the decarbonization journey of electronics component suppliers, such as Semiconductor, in automotive supply chains from a maturity perspective. In the direction of purpose, research questions are created to answer master thesis objectives.

I. What steps are electronic component suppliers taking to decarbonize the ECU supply chain, and what are their future plans?
II. What challenges are these actors facing during their decarbonization journey and how are they addressing them?
III. What factors contribute to the higher maturity level using maturity assessment within a supply chain?

1.3 Limitation and Scope

This research is subject to several limitations stemming from the focus area of analysis and the selection of information sources. Firstly, the study is restricted to ECUs and/or related to it as the primary focus within the sector of electronics, thereby excluding other areas. Secondly, suppliers participating in the research are chosen based on their willingness to share information, which may introduce bias or restrict the representativeness of the sample. Thirdly, interviews are conducted with individuals selected internally by the suppliers, limiting the researcher's control over the selection process, and potentially resulting in unanswered questions due to the scope of respondents' job responsibilities.

To enhance our understanding of the research scope, Figure 1.1 (below) illustrates the interrelationships within the supply chain, though this illustration is a simplified version of the actual process. OEMs are pivotal manufacturing entities responsible for producing end products. These products rely on various components supplied by external sources. Tier 1 suppliers specialize in manufacturing ECUs and maintain direct contact with OEMs. Conversely, Tier 2 suppliers focus on producing semiconductors, which serve as integral components for Tier 1 suppliers in this case.

Since the products from Tier 2 suppliers are integral components for Tier 1 suppliers, there is direct interaction between them. It's important to note that OEMs selectively choose Tier 1 and Tier 2 suppliers, limiting the applicability of research findings to the selected suppliers. Moreover, representatives from each supplier self-select, and research outcomes may vary based on individual knowledge and perspectives.

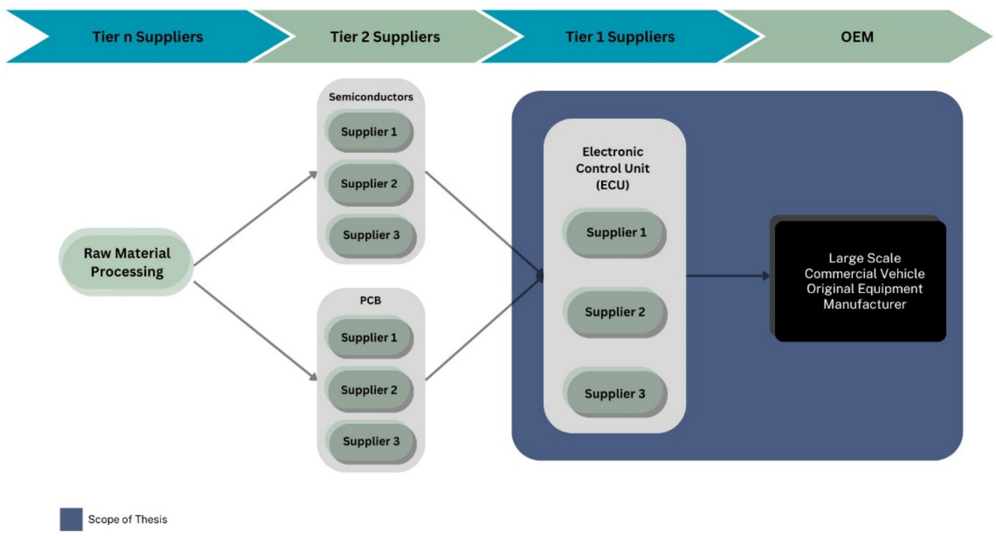

Figure 1.1: Scope of Thesis

2 Frame of Reference

The ‘Frame of Reference’ chapter is the theoretical pillar of this study. It offers a thorough review of the existing literature and theories that are appropriate to the research topic. The aim is to build a strong foundation for examining the research topics by understanding various viewpoints and models. The chapter begins with an exploration of the decarbonization of electronics and the current measures being implemented in the electronics industry. This is followed by a discussion on the emissions produced by the industry and the numerous regulations and policies within the EU. The subsequent section highlights the significant challenges encountered by these manufacturers. The chapter then investigates the theory of multi-tier supplier management for sustainability. It examines articles on maturity models, including their dimensions, indicators, and levels. This chapter not only assists in understanding the current knowledge in the field but also discover the gaps that this research seeks to address. Finally, the findings from this research will be discussed in the context of these references to draw insightful conclusions.

2.1. Decarbonization of electronics

The manufacturing industry, particularly the electronics sector, plays a pivotal role in the global economy, influencing various sectors such as transportation, retail, and construction (Dwivedi et al., 2023). The incorporation of decarbonization technologies into high-energy industrial operations significantly diminishes the carbon footprint and enhances energy efficiency, as evidenced by Cormoş et al. (2020) and this integration represents a pivotal strategy in the pursuit of sustainable industrial practices. The transition towards sustainable practices in the automotive industry necessitates the decarbonization of electronics, a critical component of this shift and the process of decarbonization in this sector is intricate, as it involves supply chains that demand specific raw materials (Trovao, 2022). The introduction of intelligent manufacturing systems can facilitate decarbonization by enhancing productivity, promoting sustainability, and contributing to social advancements. This is particularly relevant in the automotive industry, which is characterized by organizational complexities and a variety of plant contexts (Petavratzi & Gunn, 2022).

A particular concern within the electronics manufacturing sector is the release of volatile organic compounds (VOCs) (Babar & Shareefdeen, 2013). The transportation industry, particularly the automotive sector, stands on the verge of substantial decarbonization in the near future and this approaching shift is driven by many factors, especially the growing importance of sustainable energy sources like solar and wind power (Arges, 2024). Development in the fields of electrochemical energy storage and vehicle electrification further reinforce this trajectory. Additionally, the implementation of rigorous environmental regulations within the automotive industry can provide a competitive edge and as per the research conducted by Poelhekke and Ploeg (2014), such policies have the potential to draw foreign direct investment and enhance the industry's standing in terms of sustainable practices.

As part of the worldwide effort to keep the rise in temperature to 1.5°C above pre-industrial times, numerous countries have established goals to reach net zero greenhouse gas emissions by the year 2050 (Nagapurkar et al., 2023). Due to the complexity of its supply chain and the numerous components in electronic products, the electronics manufacturing industry faces unique challenges, and a significant portion of its carbon footprint is attributed to indirect supply chain activities (Huang et al., 2009). Despite strides in reducing normalized emission rates, the emissions of Fluorinated compounds from electronic device manufacturing have been on a steady rise, increasing at a rate of 3.4% annually from 1995 to 2020 (Raoux, 2023). This trend emphasizes the ongoing challenges and the need for continued efforts in emission reduction within the industry.

Vehicle electronic systems are governed by ECUs, specialized modules that oversee a multitude of functions. The intricacy of automotive wire harnesses has escalated due to the proliferation of electronic components and ECUs in vehicles (D'Aniello et al., 2022). As indicated by Siegel et al. (2018), contemporary vehicles are outfitted with as many as 70 ECUs, which capture signals from a variety of components including the chassis, powertrain, user interfaces, and safety networks. ECUs are extensively employed in modern vehicles to manage operations, augment driving comfort, and ensure safety (Bari et al., 2023). Consequently, as progress is made into the future, the quantity of ECUs is anticipated to rise in tandem with the integration of additional technologies into vehicles.

Semiconductors and printed circuit boards, integral components of ECUs, depend on intricate manufacturing procedures that can result in substantial environmental impacts (Jess et al., 2020). The decarbonization of ECU production requires a comprehensive strategy. This might include utilizing recycled materials to make parts, adopting manufacturing processes that conserve energy, and supporting the use of renewable energy in the electronics supply chain. (Hisserich et al., 2023). By giving precedence to these tactics, the automotive industry can realize a notable decrease in the embodied carbon footprint of vehicles, thereby facilitating a transition towards a more sustainable transportation environment (Robinson & Cole, 2021). The subsequent section delves into the current practices within the industry.

2.1.1. Decarbonization measures

The urgency to decrease carbon emissions and improve environmental consequences has amplified the importance of decarbonization initiatives in manufacturing sectors.

The role of sustainable manufacturing practices in supporting sustainability performance within manufacturing operations is increasingly significant (Abdul-Rashid et al., 2017). These practices incorporate the integration of processes and systems that employ sustainable resources, minimize waste production, and mitigate environmental and social impacts throughout the product lifecycle (Machado et al., 2019). By incorporating sustainable manufacturing practices and principles of the circular economy, manufacturing industries can effectively reduce energy consumption, carbon emissions, and adverse societal and environmental impacts (Moktadir et al., 2018).

For the electronics industry to reduce its GHG emissions and achieve sustainability goals, it requires a multi-pronged approach, encompassing material selection, energy sources, and product life cycle considerations. A cornerstone of decarbonization efforts lies in adopting low-carbon materials and processes. Research by Lau et al. (2021) highlights the importance of this strategy, emphasizing the potential of a circular economy to minimize emissions. Additionally, Deng et al. (2023) explore alternative raw materials that could support a more sustainable electronics industry. Transitioning to a low-carbon electricity grid is another crucial step. Yang et al. (2022) emphasizes this point, recognizing the need to address emissions not just in electronics production but also in related sectors like metals and chemicals.

Afif et al. (2022) further emphasize the importance of readily available and affordable renewable energy sources. By harnessing renewable energy and capturing process emissions, the electronics industry can significantly reduce its carbon footprint. Reducing emissions also requires a holistic approach that considers the complete product life cycle. Wang et al. (2019) highlight the effectiveness of optimizing product design and incorporating remanufactured components. Furthermore, efforts are underway to optimize semiconductor manufacturing processes that traditionally emit potent GHG (Yang et al., 2022). The forthcoming section delves into the diverse categories of emissions prevalent in the electronics industry.

The sustainability outcomes of the supply chain can be influenced by the degree of collaboration and communication between customers and suppliers. Research has underscored the importance of collaboration capital and supplier communication in fostering upstream supplier capabilities for downstream customization (Madhavaram, 2023). This indicates that customers, through active engagement in open communication and collaboration with suppliers, can stimulate the development of capabilities that endorse eco-friendly practices. Furthermore, the performance of suppliers can be affected by the bargaining power of customers as mentioned by Chang et al. (2022) and the negative impacts of customers' bargaining power on supplier performance can be alleviated when customers and suppliers strategically align on aspects such as innovation and efficiency. This suggests that customers who champion sustainable practices can collaborate with suppliers to align objectives and strategies towards efforts of decarbonization.

The decarbonization of first tier suppliers is pivotal in managing sustainable supply chains. As supply chains become more global and intricate, first tier suppliers, who serve as intermediaries, are instrumental in propelling sustainability efforts and ensuring the propagation of sustainability standards to lower tier suppliers (Wilhelm et al., 2015). However, the sustainability impact of second- and third-tier suppliers is becoming a matter of concern due to the pressures of globalization and stakeholder demands for transparency and accountability (Miemczyk et al, 2012). To tackle sustainability issues in multi-tier supply chains, it is crucial for multinational corporations (MNCs) to involve their primary suppliers in sustainability endeavors (Villena & Gioia, 2018). Some MNCs have already started to mandate primary suppliers to adhere to sustainability norms and propagate these norms to lower-tier suppliers (Villena, 2019). The sustainability performance of suppliers has become a topic of significant importance in both corporate operations and academic research (Naffin et al., 2023).

The process of decarbonizing suppliers of electronic components is a key strategy in mitigating the environmental footprint of the electronics sector. The creation and disposal of electronic components significantly contribute to electronic waste (e-waste), which presents substantial environmental challenges (Wang et al., 2019). The practice of remanufacturing and reusing electronic components can mitigate environmental pollution and foster a more sustainable methodology for managing electronic waste (Xiong et al., 2013). Moreover, the decarbonization of suppliers is in line with worldwide initiatives to curtail carbon emissions and tackle climate change (Ju et al., 2021). The journey towards decarbonization in the electronics sector involves many stakeholders, including suppliers of components, manufacturers, and policy makers. Prominent suppliers, such as those furnishing visual displays and integrated circuits, are instrumental in spearheading innovation and sustainability in the sector (Shin et al., 2012). Manufacturers are progressively being subjected to regulations and objectives related to product reuse and environmental impact, propelling them towards more environmentally friendly product designs and supply chain operations (Wang et al., 2019).

2.1.1.1. Emission in the electronic industry (SBTi Scope 1, 2 and 3)

The electronics industry faces a significant challenge in reducing its GHG emissions. The SBTi outlines a framework for addressing these emissions, categorized into Scopes 1, 2, and 3.

- Scope 1: These are direct emissions from the industry's own operations, such as those generated by on-site combustion activities.

- Scope 2: These are indirect emissions associated with the electricity and steam consumed by the industry.
- Scope 3: These are indirect emissions, especially upstream activities, spanning the entire supply chain, are the most significant contributor to the industry's GHG footprint (Yang et al., 2022; Park et al., 2022; Huang et al., 2009).

Within these scopes, specific gases like the potent greenhouse gas nitrous oxide (N_2O) are a particular concern. Lee et al. (2012) emphasizes the need for technologies that target N_2O reductions in electronics manufacturing processes to address Scope 1 emissions. Additionally, semiconductor manufacturing traditionally emits powerful GHGs like hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6). Researchers are actively optimizing these processes to minimize emissions of these harmful gases (Yang et al., 2022).

While progress has been made in lowering Scope 1 and 2 emissions, tackling Scope 3 presents a greater challenge due to the complex and variable nature of emissions across different suppliers and supply chains (Reavis et al., 2022; Booth et al., 2023). Research by Huang et al. (2009) highlights that a significant portion of the electronics industry's emissions falls not under direct operations (Scope 1) but under embodied emissions (Scope 3) associated with materials, parts, chemicals, and components throughout the supply chain. Unfortunately, the reliability of data from primary suppliers can be inconsistent and untrustworthy and transparency tends to diminish across various tiers in the supply chain, particularly with smaller suppliers (Villena & Gioia,2018).

Additionally, a study by Lee (2011) found that Scope 3 emissions, which include contributions from Tier 1 and Tier 2 suppliers, account for 80% of emissions within a typical OEM supply chain. This emphasizes the critical role of these suppliers in achieving decarbonization goals. Semiconductor Tier 2 suppliers are particularly significant, as research by Higgs et al. (2009) indicates that semiconductor manufacturing generates around 80% of its emissions from electricity and water consumption. Lee (2011) further suggests that focusing on Scope 3 emission reduction can be more cost-effective compared to Scope 1 and 2 reductions. Increased transparency in decarbonization efforts could potentially accelerate collaboration towards shared objectives.

This underscores the critical importance of considering the entire value chain when assessing emissions within the electronics industry. Effective decarbonization strategies must encompass not just the industry's direct operations but also its extensive network of suppliers and partners.

2.1.1.2 Regulations and Policy

Numerous research efforts are underway to tackle climate change and drive green innovation within the manufacturing industry. The EU manufacturing sector is adopting a broad spectrum of decarbonization measures, encompassing the modification of business models, product substitution, and the offsetting of GHG emissions (Schneider et al., 2023). The implementation of intelligent manufacturing systems is being pursued to enhance productivity, promote sustainability, and effect social improvements, which are particularly relevant in sectors such as automotive, where meeting decarbonization objectives is a priority (Succar et al., 2023). The EU has made considerable strides in this regard by instituting the Emission Trading System (ETS) and proposing a Carbon Border Adjustment Mechanism (CBAM), both aimed at reducing GHG emissions and ensuring compliance with the Paris Agreement (Galiffa & Bercero, 2022).

The EU has instituted two principal mechanisms to mitigate GHG emissions: the ETS and the CBAM. The ETS functions as a cap-and-trade scheme, controlling carbon emissions from designated industrial facilities and serving as the EU's primary instrument for achieving the emissions reduction targets stipulated in the Kyoto Protocol (David, 2022). Despite its importance, the EU ETS has encountered obstacles, including instances of reported fraud that have compromised its efficacy (Zimakov, 2021). Conversely, the CBAM is designed to avert carbon leakage by imposing charges on imports according to their carbon content, thereby ensuring the reduction of global GHG emissions within its purview (Sato, 2022). While the EU ETS is concentrated on regulating emissions within the EU, the CBAM broadens its scope to tackle emissions linked to imported goods, with the aim of mitigating carbon leakage risks and preserving industrial competitiveness (Sato, 2022). The EU has set ambitious goals to curtail GHG emissions by 55% by 2030 and attain carbon neutrality by 2050, with the CBAM expected to play a pivotal role in this initiative (Urazgaliev et al., 2021).

Furthermore, the EU has enacted Directive 2014/95/EU, a novel regulation that compels large entities of public interest entity (PIEs) within the EU to incorporate yearly non-financial disclosures on sustainability and diversity into their management report or as an independent document (Monteiro et al., 2022). This directive obliges corporations to disclose their carbon emissions, inclusive of Scope 3 emissions. These are indirect emissions originating from the supply chain of the companies (Hertwich & Wood, 2018). While there is a relative consistency in the data concerning direct emissions, the data on indirect emissions, especially those under Scope 3, exhibit considerable discrepancies (Busch et al., 2020). The breadth and completeness of companies' voluntary disclosures of GHG emissions can be influenced by external stakeholder pressure (Liesen et al., 2015). Despite the potential of Scope 3 emissions to make up a substantial part of a company's carbon emission, their reporting remains optional under international regulatory frameworks (Blanco et al., 2016). This voluntary aspect, coupled with the absence of explicit guidelines, leads to inconsistent reporting of Scope 3 emissions (Huang et al., 2009).

To rectify this, there is a growing demand for increased evaluation in Scope 3 reporting to assure data accuracy and foster improved environmental management practices (Huidobro et al., 2023). The importance of reporting Scope 3 emissions cannot be overstated as these emissions, which encompass supply chain or cradle-to-gate emissions tracing back to resource extraction, form a significant part of a company's inventory (Hoyer, 2020). Consequently, it is imperative for companies to monitor and report their Scope 3 emissions to enhance reporting consistency, increase accountability towards targets, and foster collaboration on innovative solutions to mitigate environmental impact (Booth et al., 2023).

2.1.2 Challenges during the decarbonization journey

Decarbonizing the manufacturing industry presents significant challenges due to the intricate nature of industrial processes. The sector faces constant obstacles between economic growth drivers and sustainability issues, making it particularly challenging to implement measures to reduce carbon dioxide emissions (Dolge & Blumberga, 2021). The decarbonization process in sectors that are particularly challenging to mitigate, such as the electronics industry, requires addressing emissions derived from manufacturing and industrial processes, a task that presents substantial technical obstacles (Rumayor et al., 2020). The role of technological solutions in surmounting these challenges is pivotal. Electrification and clean hydrogen have been recognized as potential strategies for decarbonizing industrial process heat, a critical component in reducing emissions across sectors (Schoeneberger, 2024). Furthermore, the pursuit of deep decarbonization in heavy industry is a daunting task, with the pressure to remain competitive driving the imperative to decrease energy consumption and GHG emissions (Bataille et al., 2018). The shift towards Industry 4.0 is perceived as a strategic blueprint that manufacturers must follow, underscoring the significance of adopting technological innovations in the journey towards decarbonization (Ghobakhloo, 2018).

The electronics industry is currently at a crucial crossroads in its journey towards sustainability. Decarbonization efforts require a multidimensional approach, presenting both challenges and opportunities. A crucial hurdle lies in rapidly expanding commercially viable renewable energy sources like wind and solar power (Tugores et al., 2021). According to the study by Partridge, (2013), a prominent hurdle in India is the elevated cost of electricity generation through renewable technologies in comparison to traditional methods. While the cost is anticipated to decline with the accumulation of expertise in renewable energy practices, the upfront investment can pose a significant obstacle for firms in the electronics industry. Furthermore, the integration of renewable energy systems into the current power infrastructures of manufacturing industries presents a considerable challenge (Materi et al., 2021). While progress has been made, further commercialization of new technologies is necessary.

Likewise, Iweh et al. (2021) emphasizes the importance of carbon capture, zero-carbon fuels, advanced nuclear power, and firm renewables for maintaining grid reliability and affordability alongside the transition to cleaner energy sources. This clean energy shift is not just for the energy sector itself; electronics manufacturing (and other industries) must also decarbonize. Decarbonization within the electronics industry is further complicated by a complex web of environmental regulations. Chiang (2009) identifies the significant impact of regulations like Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS), Energy-using Products (EuP), and carbon footprint directives on the industry. While these regulations are crucial for preserving the environment, they pose difficulties for manufacturers as they are required to factor in waste management during the design and production stages of their products, which ultimately contributes to protecting the environment (Chiang et al., 2009).

The electronics industry's journey towards a circular economy also faces hurdles beyond navigating complex environmental regulations. Transparency and information flow throughout the supply chain are critical challenges identified by Mukherjee et al. (2022). This lack of traceability and communication can significantly impede the implementation of sustainable practices like a circular economy. Furthermore, a lack of awareness about the benefits of sustainability and a resistant mindset towards change can create additional obstacles (Menon & Ravi, 2021). Small and medium-sized enterprises (SMEs) within the industry face particular challenges due to a lack of support from supply chain partners and uncertainty regarding the return on investment in sustainable practices. These issues all stem partly, from insufficient information and transparency (Khiewnavawongsa & Schmidt, 2013). To achieve sustainability within a supply chain requires a clear visibility into upstream operations and this visibility can be fostered through enhanced connectivity and information sharing among stakeholders (Dubey et al., 2017). The subsequent section will explore into the management strategies for multiple tiers of suppliers to foster a more sustainable supply chain.

2.2 Multi-tier Supplier Management for Sustainability

Supply chain management is the core of relationship management, link by link, connecting numerous links across multiple tiers (Lambert and Enz, 2017; Jabbour et al, 2019). To maintain competitive advantage and address global environmental challenges, focal companies within supply chains must engage in green management practices for their suppliers (Zhu et al., 2013). Sustainability concerns are deeply rooted in today's global supply chains, characterized by intricate multi-tier structures that span vast networks (Sarkis et al., 2019). However, implementing these practices necessitates radical changes in how organizations approach management throughout their supply chains (Soderstrom and Weber, 2019). The advancement of sustainability throughout the supply chain demands ongoing evolution, innovation, and practical implementation (Jadhav et al., 2019).

Established companies are increasingly aware that focusing solely on first-tier supplier sustainability is insufficient (Hartmann and Moeller, 2014). While focal companies may have limited direct authority over the sustainability practices of lower-tier suppliers, they ultimately hold the responsibility for the overall sustainability performance of their supply chains in the eyes of customers (Hartmann and Moeller, 2014). Incorporating and coordinating sustainability efforts across all supply chain tiers plays a crucial responsibility in mitigating and diminishing sustainability risks (Zissis et al., 2018). The lack of direct relationship between focal companies and lower-tier suppliers can significantly increase the risk of sustainability challenges arising (Wilhelm et al., 2016), ultimately leading to decreased risk management performance within the multi-tier supply chain (Wang-Mlynek and Foerstl, 2020).

Effective management of sustainability risks across multi-tier supply chains necessitates both direct and indirect coordination efforts, encompassing all tiers from first-tier suppliers to lower-tier suppliers (Kähkönen et al., 2023). Given their crucial role in sustainability and risk management, first-tier suppliers play a critical intermediary role in advocating for sustainable practices to be adopted throughout the supply chain, including lower tiers (Kähkönen et al., 2023). Some focal companies have successfully mitigated risks by strategically integrating multi-tier suppliers into their environmental product development processes. This approach not only reduces time and cost but also enhances competitive advantage through environmental considerations (Kuei et al., 2015).

Many of the most critical environmental and social challenges within the supply chain manifest in the second tier or extend to lower-tier suppliers upstream (Ernst and Kim, 2016). However, managing lower-tier suppliers presents distinct challenges due to limited visibility into their operations, as companies often lack direct recognition of these suppliers (Tse and Tan, 2011; Wilhelm et al., 2016). Typically situated in regions with lax sustainability regulations, lower-tier suppliers contribute up to 90% of GHG emissions (Tachizawa and Wong, 2014; Plambeck, 2012). This is often attributable to their status as SMEs, which tend to be less prominent and have unstable relationships within the supply chain (Lee et al., 2012; Ponce and Prida, 2004).

In multi-tier supply chains, two distinct approaches are categorized based on collaboration practices: direct and indirect approaches. The direct approach, as outlined by Tachizawa and Wong (2014), involves focal companies having direct access to lower-tier suppliers, enabling activities such as monitoring and collaboration. This direct engagement can lead to more effective coordination (Pilbeam et al., 2012) and minimize misinformation (Simpson, 2010). However, the increased managerial effort required to meet the demands of focal companies can present a disadvantage (Mena et al., 2013). On the other hand, Tachizawa and Wong (2014) describe an indirect approach where contact with lower-tier suppliers is facilitated through another supplier. Given the challenge of supervising the whole supply chain, cross-tier collaboration becomes fundamental (Mueller et al., 2009; Koh et al., 2012). Furthermore, research suggests that SMEs can be effective intermediaries, cascading sustainability requirements from focal companies down to their own suppliers (Ayuso et al., 2013).

2.3 Maturity model

The maturity model was originally introduced in 1973 for IT organizations by Nolan (1973) and has since become recognized as a valuable development tool for various types of organizations (Van Looy et al. 2013). For instance, insights from the model have been adapted for software factories and integrated into the sustainable operations domain (Machado et al, 2017). This evolution reflects the enhancement of organizational capabilities over time, as observed in industry developments (Hynds et al, 2014). Adoption of maturity model has increased (Scott, 2007), including maturity model in academic research (Becker et al, 2010).

The maturity model primarily illustrates how organizational competences evolve over phases (Gottschalk, 2009), enabling organizations to improve their performance and adapt to change (J. Becker et al, 2009). Additionally, the maturity model serves as an instrument to conceptualize processes for specific targets (Schumacher et al, 2016). Maturity can be achieved through both qualitative and quantitative means (M. Kohlegger et al, 2009). Becker (2009) mentions steps for the maturity model development process that are strongly linked to Hevner's (2004) design science approach.

Becker (2009) suggests methods for developing maturity models to test a new model, such as literature research and review, expert interviews, and conceptual modeling. These methods begin with expert interviews conducted in a semi-structured manner, focusing on problem identification and research problem validation. Theoretical foundation is supported by existing literature research and review, which offers suggestions for a design strategy, serving as a benchmark for designing a new model (Schumacher et al, 2016). Through benchmarking model design characteristics, the present maturity model is evaluated to identify similarities with the new model. Once all processes are completed, maturity model assessment can be used to validate actual application in the industry (Schumacher et al, 2016). It is essential to note that maturity models tend to fail if they are too complicated, with excessive details in dimensions or characteristics. Thus, adjustments based on representing industry practical needs are necessary. Simplifying complicated models to enhance understanding and usability could be one solution (Schumacher et al, 2016).

There are three types of maturity models, ranging from the simplest to the most complex. The first type, being the simplest, comprises descriptions for each level. The second type involves a Likert scale questionnaire with statements but lacks explanations, requiring respondents to rank their answers based on the maturity level's numeric position. The third and most comprehensive type establishes both broad and specific goals for every characteristic (Fraser et al., 2003). Maturity levels play a pivotal role in delineating the maturity path, which involves distinct levels of maturity characterized by varying degrees of detail in maturation processes (de Bruin et al., 2005; Fraser et al., 2003).

The assessment model will encompass maturity levels characterized by specific attributes as outlined in the reference model (Ofner et al., 2009). This model is structured across multiple layers, including maturity level, competency objectives, and descriptions of activities tailored to different stages of maturity (de Bruin et al., 2005; Ahlemann et al., 2005; Fraser et al., 2003). Recognizing the potential for alternative paths to maturity (Teo and King, 1997), this model provides flexibility by offering a range of activities at each level. This allows organizations to select approaches that best suit their specific context and internal characteristics, fostering organic evolution and change (Mettler and Rohner, 2009; King and Kraemer, 1984).

2.3.1 Sustainable Supply Chain Maturity Model

Performance assessment has developed from measurement to management (Bititci et al, 2014). Not only academics but also entrepreneurs have to design a maturity model because it helps to analyze and monitor companies' improvement (Vásquez et al., 2021; Seidel-Sterzik et al., 2018). Therefore, performance and maturity model support to establish and extend mature governance also environmental demand (Salvador et al, 2021; Salvador et al, 2023).

Recently, companies believed sustainability sooner or later becomes the main function to the success of business (Haaneas et al. 2011). It is essential for companies to implement a model for sustainability that could help to classify actions to meet sustainability requirements for stakeholders, customers and employees (Hynds et al, 2014). Sustainability as a global trend like 'quality' demands companies to create, innovate, adapt and integrate as business priority (Elkington, 2004; Lubin and Esty, 2010).

In the era of globalization, business connections and supply chain relationships are expanding across different countries. Consequently, there is a growing demand from regulators and non-governmental organizations for companies to demonstrate compliance with sustainability standards for products sourced from overseas (Okongwu et al., 2013). Companies that provide sustainability reports demonstrate their dedication through a transparent process, which includes engagement with stakeholders related to sustainability. Transparency not only helps to attract more customers and stakeholders but also serves as a competitive advantage (Okongwu et al., 2013). The connection between supply chain and sustainability has given rise to a new concept known as sustainable supply chain (de Almeida Santos et al., 2020).

The maturity model serves as a valuable approach for sustainable supply chain management (SSCM) by providing a well-established framework to map the inherent stages of a system's progress, from inception to maturity (Cuenca et al., 2013). Implementing a Sustainability Maturity Model across a supply chain can yield significant benefits. Maturity models enable companies to assess their efforts towards sustainability, identify their position in the sustainability journey, and navigate paths for continuous improvement (Correia et al., 2017). According to Machado et al. (2017), maturity models help audit sustainability processes, navigate strategies, and create specifications to achieve more effective sustainable performance. Another advantage of the Sustainable Supply Chain Maturity Model is its ability to uncover unsustainable sectors, develop strategies, implement sustainable processes, and effectively monitor and report sustainability performance (Ahmed and Sundaram, 2009).

2.3.1.1 Dimensions and Indicators of Maturity Model

Sustainability maturity model play a crucial role in gauging an organization's progress towards achieving environmental and social responsibility goals (Elariane & Salem, 2023). These maturity model involve evaluating a range of dimensions and indicators that provide a all-inclusive picture of an organization's sustainability performance. However, as highlighted by Olde et al. (2016), selecting the right indicators is critical. Transparent and well-defined procedures are essential to ensure the chosen indicators are not only appropriate to the specific context but also possess sound validity, meaning they accurately measure what they are intended to assess. This balance between transparency and relevance is fundamental to the effectiveness of any sustainability maturity assessment.

The concept of sustainability includes a broad range of environmental and social factors, making assessing an organization's progress complex. Different sources prioritize distinct dimensions and indicators within sustainability assessments. Baumgartner et al. (2010) emphasized the crucial role of resources and knowledge. Whereas, Srai et al. (2012) discussed the concepts of carbon footprint, waste minimization, and renewable energy. The relevance of a circular strategy was underscored by Golinska et al. (2014), a concept that remains pertinent today. Furthermore, Hynds et al. (2014) highlighted the importance of Life Cycle Assessments (LCA) and design for sustainability within a sustainability maturity model.

Maturity Level

The idea of maturity involves a progression through various stages of development as it involves comparing the organizations or the process's current state with the desired state in terms of maturity and this comparison is achieved by conceptualizing and quantifying these maturity levels (Schumacher et al., 2016). Babin and Nicholson (2012) propose a method for determining an organization's maturity levels, which is based on sustainability scores and an evaluation of the organization's sustainability capabilities. They recommend a point system for ranking suppliers. In this system, organizations are scored based on their compliance with specific standards such as the

Global Reporting Initiative (GRI), Carbon Disclosure Project (CDP), or International Organization for Standardization (ISO).

In Figure 2.1, the various levels of maturity can be seen to understand how a generic maturity framework looks like. Generally, the maturity model's framework has four to five levels of maturity with each higher level showing a higher grade of capability than the lower one (Hynds et al., 2014). As per the research by Sehnem et al., (2019) the importance of achieving higher maturity levels to streamline processes, guarantee predictability, enable in-depth analysis, and promote ongoing enhancement. Also, by elevating these maturity levels, businesses can improve their operational effectiveness and better align with sustainability principles.

To understand the use and implications of different levels of maturity different articles were reviewed and a generic maturity framework would look like the Figure 2.1. As per Julkovski et al., (2022), the significance of having a maturity from Level 0 is to show that there are organizations with process' that have not been implemented or fail to fulfill their desired purposes. Initially, the maturity assessment tool drew upon the work of Reefke et al. (2014) and used only a two-level framework based on the six-level maturity shared in the article.

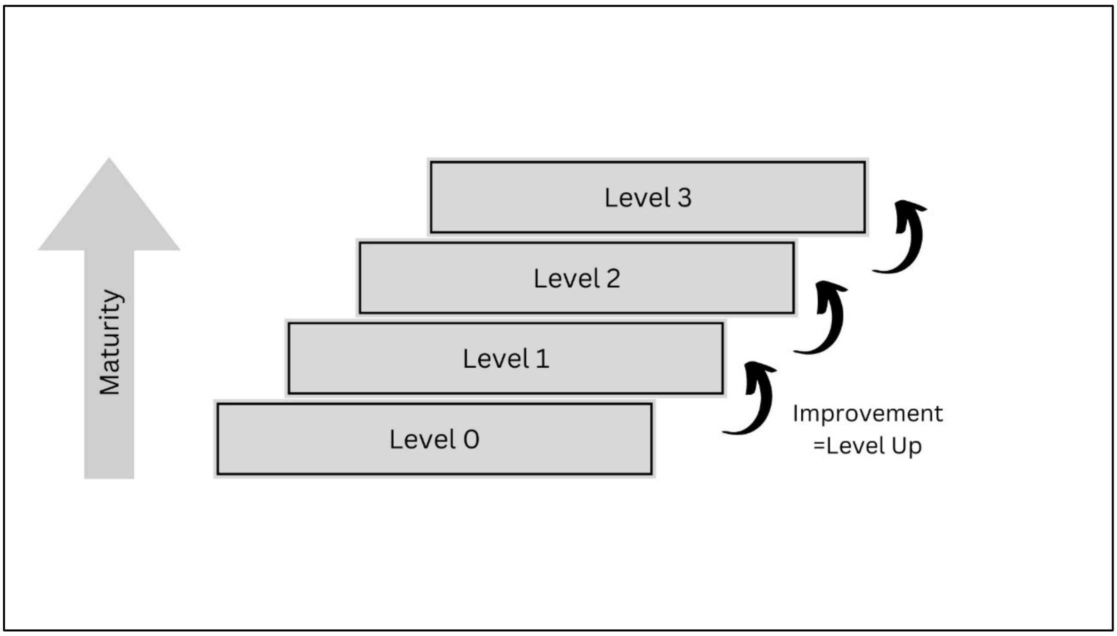

Figure 2.1: Generic Maturity Framework.

3 Methodology

This chapter presents related research activities and methodology employed in this study. The research activities commenced with the selection of an appropriate sampling method, followed by the specification of data collection methods. Following that, all methods were finalized, leading to the beginning of the data collection process, which was further followed by data analysis.

This research offers valuable insights to enhance the knowledge and explore the decarbonization journey among suppliers, focusing on the maturity level of suppliers that influences the development of a sustainable supply chain for electronics in vehicles. To fulfill that research purpose, qualitative research is used because of its flexibility and adaptability to gather phenomena (Yates and Orlikowski, 2002). Qualitative methods provide a systematic and subjective approach, facilitating a deeper understanding of life experiences (Delgado-Hito and Romero-Garcia, 2021). It also emphasizes precision and authenticity (Cypress, 2017), ensuring the credibility and reliability of the findings (Dodgson, 2019). Furthermore, qualitative methods offer the advantage of flexibility and adaptability, enabling researchers to respond to unanticipated changes in their research process (Köhler, 2024).

Literature argues that qualitative data can be complex, leading to the utilization of both inductive and deductive approaches in data analysis (Azungah, 2018). In this chapter, the focus will be on discussing the inductive approach. Thomas (2006) argues that qualitative research enables researchers to uncover patterns or themes in raw data without being constrained by frameworks or methodologies, thus allowing for greater flexibility and exploration.

Håkansson (2013) asserted that research methods not only provide procedures to fulfill research tasks but also serve as a framework for conducting research. Empirical research, one such method, yields general findings by exploring the probability of establishing various relationships among different variables. It emphasized gaining knowledge through actual experience and observation of situations and people (Håkansson, 2013). Exploratory research is suitable for qualitative data collection, aiding in better understanding of people's experiences (Håkansson, 2013; Delgado-Hito & Romero-Garcia, 2021), which is the objective of this study to enhance comprehension of the decarbonization journey for electronics.

3.1 Sampling and Data Collection

This section will detail the sampling methods and data collection process, including the rationale for selecting specific sampling methods and how data collection was conducted to address the research questions.

3.1.1 Sampling Method

According to Turner (2020), '*sampling is the selection of a subset of the population of interest in a research study.*' Precise sampling methods are crucial for minimizing errors and enhancing representativeness (Berndt, 2020). Sampling offers the advantage of being suitable for studies with limited resources and helps in providing more reliable results (Bhardwaj, 2019). Sampling methods are typically divided into probability and non-probability sampling techniques (Tyrer and Heyman, 2016). Non-probability sampling involves selecting samples where the probability of selection is unknown (Turner, 2020), making it particularly useful for qualitative and exploratory research (Berndt, 2020; Turner, 2020). In this study, non-probability sampling will be employed, as the sampling is chosen by the OEMs. Furthermore, this research will utilize an explanatory research design aimed at exploring information within the decarbonization journey for electronics, primarily through interviews with suppliers.

Non-probability sampling divided into several with one of the two samplings are purposive sampling and snowball sampling. Snowball sampling, according to Bhardwaj (2019) will *depend on referral* because certain members will choose directly the sample from the population (Turner, 2020). As mentioned earlier, OEMs directly select ECU suppliers and, for most semiconductors, indirectly select semiconductor suppliers based on their relationships with them. Given the sensitivity of information in the electronics industry related to sustainability, these close relationships are crucial. They are expected to foster transparency, encouraging suppliers to share their experiences more openly. Moreover, snowball sampling would advance the data collection process (Bhardwaj, 2019).

According to Turner (2020), purposive sampling is used when researchers select specific individuals or samples with particular traits. This approach helps researchers face fewer challenges in data collection and ensures direct access to the data needed from the individuals (Bhardwaj, 2019). In this study, the research concentrates on the broader topic of electronics in vehicles, with a specific focus on sustainability. Given that electronics encompass ECU and semiconductor suppliers, sustainability considerations will primarily involve sustainable supply chain practices within these suppliers' companies. By targeting these specific participants, the research aims to achieve an in-depth analysis and understanding of the subject matter. Participant selection will be internally determined by the actors or suppliers, based on their expertise and qualifications in the field.

3.1.2 Sample Size

Determining the right sample size is crucial for guaranteeing the credibility and accuracy of research results. The importance of sample size is underscored by its influence on the quality and applicability of research findings, as noted by Vasileiou et al. (2018). The initial research methodology of this research suggested a wide inclusion of Tier 1 and Tier 2 suppliers. However, due to time limitations and inconsistent response rates to our meeting invitations, the sample size was adjusted to include a specific group of key suppliers.

It is worth noting that both underestimation and overestimation of the sample size can significantly impact the project outcomes (Gupta et al., 2016). This is particularly relevant in our case, where the response rate from Tier 2 suppliers was significantly lower than that from Tier 1 suppliers.

To rectify this imbalance and to ensure thorough data collection from both tiers, a questionnaire was formulated. Despite the constraints in the sample size, this approach ensured that our study was inclusive and exhaustive, yielding valuable insights from both supplier tiers. The sample size, although smaller than initially anticipated, was adequate to fulfill the research objectives and provided a representative sample of the supplier tiers. This pragmatic approach to sample selection guaranteed the study's feasibility within the stipulated time frame while preserving the integrity and depth of the research data.

3.1.3 Data collection

The following section highlights how the data was gathered for this research. This research categorizes data collection into primary and secondary because both these would complement each other during data analysis (Smith et al., 2011). To outline the project's scope and objectives, preliminary dialogues and informal discussions were conducted with OEM's personnel associated with the subject matter. This process enabled the refinement of the project's focus to solely encompass suppliers of ECU (Tier 1) and Semiconductors (Tier 2). This was a deviation from the original plan, which had also intended to incorporate PCB (Tier 2) suppliers. A clear representation of the OEM's supply chain and various actors is illustrated in Figure 1.

The primary data collection for this thesis involved the utilization of semi-structured interviews, which provided rich qualitative insights. The subsequent section explains the characteristics of the interviewees, offering contextual information pertinent to the study. Afterwards, a comprehensive account of the methodology employed in gathering secondary data is outlined, providing a clear understanding of the research process.

3.1.3.1 Primary Data

Within the framework of research methodology, primary data is defined as the information specifically collected to address the research question or hypothesis under investigation (Hox & Boeije, 2005). Interviews, recognized as the most effective and widely employed method for primary data collection (Hox & Boeije, 2005), enable participants to express their viewpoints and experiences in their own language, primarily due to the use of open-ended questions (Doody & Noonan, 2013).

According to Easterby-Smith et al. (2018), interviews predominantly fall into three categories: highly structured, semi-structured, and unstructured and these represent the most prevalent methodologies employed in the conduct of interviews. Structured interviews are characterized by a meticulously designed interview schedule, which ensures standardized questioning and promotes comparability of data across participants (Baker, 2006). Semi-structured interviews, on the other hand, occupy an intermediate position, employing a thematic framework that enables researchers to delve into predetermined areas of interest while also accommodating unexpected insights that may arise during the conversation (Flick, 2014). This adaptable approach facilitates a deeper comprehension of participants' viewpoints. In contrast, unstructured interviews resemble informal discussions, lacking a predetermined schedule. Although this method allows for a thorough exploration of emerging themes, it may pose challenges in ensuring consistency of data across interviews (Flick, 2014).

Likewise, questionnaires occupy a valuable position within the qualitative researcher's toolkit for gathering primary data. While Bryman (2006) associates structured questionnaires with quantitative research, qualitative studies can also leverage this tool strategically. By incorporating open-ended questions, researchers can encourage in-depth responses that capture rich qualitative data. However, the utility of questionnaires is not without limitations. Murphy (2023) underscores the importance of meticulous design to mitigate potential biases and inaccuracies in the collected data. Similarly, Umar et al. (2020) emphasizes the crucial role of systematic interpretation and analysis to ensure the reliability and validity of findings derived from questionnaires.

In this research, qualitative methods are employed for data collection, utilizing both semi-structured interviews with a group of people and survey-based techniques with a question form comprising of open-ended questions to gather primary data. Open-ended questions in interviews are valuable for data collection as they draw out thorough and in-depth responses from participants, enabling them to freely convey their thoughts, emotions, and experiences, thereby yielding abundant qualitative data (Khuzaiyah et al., 2022). While open-ended questions offer valuable advantages for qualitative data collection, a well-recognized drawback lies in the potential burden they place on respondents (Dillman (2007). Extant literature indicates that open-ended questions exhibit substantially higher instances of unresponsiveness compared to alternative survey items (Millar and Dillman, 2012).

The aim of this study is to identify the decarbonization journey of various Tier 1 and Tier 2 suppliers in the OEM's upstream supply chain. The set of interview questions used in this research were designed to be adaptable, allowing for modifications based on the tier of the supplier, thereby ensuring their relevance to the specific industry and products of each supplier. The interview questions were designed to address the initial two research questions, thereby facilitating the exploration of the third research question, which is integral to the formulation of dimensions for the maturity assessment of suppliers. Subsequently, interview invitations were forwarded, resulting in discussions with three ECU suppliers and one semiconductor supplier. The details of various interviewees are mentioned in below table 3.1. The questions asked to the interviewees are attached in Appendix A.

Table 3.1: Interview Details. Keys: ECU = Electronic Control Unit, OEM = Original Equipment Manufacturer, SMC = Semiconductor.

Details of suppliers interviewed in the study						
Interviewee code	**Tier of Supplier**	**Roles**	**Duration**	**Date**	**Mode**	**Industry**
Supplier A	Tier 1	Senior Project Manager Sustainability	00:50	20-02-2024	Online	ECU
Supplier B	Tier 1	Deputy General Manager	01:16	04-03-2024	Online	ECU
Supplier C	Tier 1	Environment and Sustainability Expert	00:56	05-04-2024	Online	ECU
Supplier D	Tier 2	Head of ESG	01:36	11-04-2024	Online	SMC

During the interviews, the researchers introduced themselves and described the purpose of the research to the group of interviewees, so they had an idea of what was to be expected out of it. The interviews were scheduled with the help and authorization of the supervisors at the OEM.

Table 3.2: Question form details. Keys: ECU = Electronic Control Unit, OEM = Original Equipment Manufacturer.

Details of suppliers who filled in the question form					
Surveyor code	**Tier of Supplier**	**Roles**	**Date**	**Actor type**	**Industry**
Supplier E	Tier 1	Director of Sustainability	07-05-2024	OEM	ECU
Supplier F	Tier 1	Sales Manager	02-05-2024	OEM	ECU
Supplier G	Tier 1	Key Account Manager	06-05-2024	OEM	ECU
Supplier H	Tier 1	Head of Sustainability	08-05-2024	OEM	ECU

The question form was shared with suppliers as part of pilot testing to ensure the validity of the dimensions in the maturity assessment tool and their results were recorded for the research. The outcome was that four ECU suppliers and one semiconductor supplier shared their views on their decarbonization journey and the challenges they faced during that journey. The question form is attached in Appendix B.

3.1.3.2 Secondary Data

Secondary data analysis represents a foundation of research methodology across a wide range of academic disciplines (Omari, 2021). This approach leverages existing data sets, originally collected for purposes distinct from the current research question. In this research, secondary data was gathered from scientific literature, companies' sustainability reports, and other internal reports related to decarbonization. Secondary data analysis can serve as a springboard for further investigation or provide valuable context for new primary data collection efforts. An extensive literature review was carried out to understand the assembly and manufacturing processes of ECU's and semiconductors respectively. The industry wide decarbonization measures were understood from the respective suppliers' sustainability reports. Secondary data analysis offers several advantages in the research domain. It permits the validation of research assertions, improves data preservation practices, enhances the capacity for meta-analytical endeavors, and enables subsequent analyses (McAlister & Harvey, 2016).

3.1.4 Pilot testing

Pilot studies function as exploratory investigations conducted before embarking on a larger research project (Polit & Beck, 2017). Their primary objective is to assess the feasibility and effectiveness of various methodological components, including study designs, measurement instruments, research procedures, recruitment strategies, and operational plans (Creswell & Creswell, 2018). The outcome of this research would be a maturity assessment tool that could be implemented to understand the decarbonization goals, journey, and challenges of existing and new suppliers of the OEM.

Pilot testing serves as an essential primary step before implementing a maturity assessment tool across a supply chain (Blome et al., 2019). This initial phase offers a valuable opportunity for researchers and practitioners to evaluate the tool's effectiveness, identify potential weaknesses, and refine it for optimal performance (Jahre et al., 2020). Scientific literature emphasizes the importance of conducting pilot tests with a representative sample from the target population (Blome et al., 2019). This ensures the assessment addresses the specific complexities and challenges relevant to the industry or sector it aims to evaluate. Through pilot testing, researchers can assess the tool's clarity, user-friendliness, and ability to accurately capture data points that reflect maturity levels (Jahre et al., 2020). In essence, pilot testing serves as a crucial quality assurance measure, paving the way for a more robust and reliable maturity assessment tool upon full-scale implementation.

Pilot testing, a maturity assessment tool offers a multifaceted evaluation mechanism. Research by Lobbezoo et al. (2023) highlights its effectiveness in assessing the clarity of explanations, question structures, and response options. This initial testing phase can also reveal the importance of tailoring the tool to specific contexts, as emphasized by Puszka et al. (2015). Jujo et al. (2021) further underscore the value of user feedback during pilot testing, which can inform necessary modifications and refinements for subsequent studies. Ultimately, a successful pilot test can lead to the development of a comprehensive framework outlining the activities and expected results for each maturity level within the model (Kırmızı, 2022).

3.2 Data Analysis

Data analysis is the process used to analyze the data gathered during the data collection phase. This process involves inspecting, transforming, and modeling data, ultimately aiding in decision-making and drawing conclusions (Håkansson, 2013). Meanwhile, qualitative analysis involves examining and synthesizing collected data to uncover explanations for phenomena (Fossey et al., 2002). In this research, data analysis includes information gathered from various sources such as company reports, specifically sustainability reports, and relevant scientific literature. Literature review process serves as the foundation for the research, providing essential background knowledge in the area under study (Håkansson, 2013). In the search for relevant scientific literature, keywords such as 'electronics,' 'automotive,' 'multi-tier supply chain,' and 'maturity model' are utilized. By employing multiple keywords, the aim was to gain a comprehensive understanding from various perspectives and converge them into a cohesive topic for this research. A literature review was also expected to help on the engaging writing by sharing the most related and interesting parts to produce insightful discussion (Gioia et al, 2012**).**

Due to the geographical spread of interviewees, qualitative research relied on online interviews or discussions. Responses from these discussions were recorded via voice recordings to facilitate review during analysis, and notes were taken to ensure important information was captured. Similar responses to the same questions from different suppliers led to the creation of grouped responses. Grouping responses related to the same category together enhances analysis efficiency. This grouping process also aids in identifying similarities or patterns (Bingham, 2023), ultimately contributing to the development of findings and reaching a conclusion.

An example of grouping responses in the data analysis process involved a question related to the suppliers' current decarbonization processes. Similar answers emerged, mentioning how suppliers had adopted renewable energy for their production. These similar responses led to the formation of a group focused on renewable energy. The grouping helped to shape indicators or elements for the maturity model, in this example becoming 'renewable energy elements'. This also meant that elements in the maturity model were the processes that influenced the decarbonization journey of the suppliers. Aside from the grouped responses, elements were also strengthened by scientific literature. Scientific literature provides insight into how previous research involving renewable energy was conducted.

The related elements later became one group; for instance, elements of renewable energy and waste reduction became one group called the production dimension. Later on, each dimension consisted of several elements that described the dimension's activities. The maturity model would then have dimensions and elements to assess the suppliers' decarbonization journey.

<u>Research Quality</u>

Research assurance, or quality assurance, involves the process of quality control to verify and validate research material (Håkansson, 2013). Quality assurance for qualitative research includes aspects such as validity, confirmability, and dependability (Håkansson, 2013; Bell et al., 2022).

Validity and Reliability

According to Stiles (1993), reliability and validity are related to trustworthiness but represent different aspects. Reliability pertains to the authenticity of the data, while validity concerns the accuracy of the conclusions drawn. In qualitative research, validity ensures that the authenticity of the research can be confirmed by respondents (Håkansson, 2013). Before the interview begins, an introduction is shared to ensure that the participant is aware of the information they are willing to share. Aside from the interview, some information also from the company website and sustainability report. Therefore, certain information obtained from the interview can be cross-checked to verify its authenticity.

In terms of reliability, trustworthiness of the data is linked to the repeatability of observations (Stiles, 1993; Bell et al., 2022). However, each research project has unique objectives and processes, making replication challenging. While this study delves into a common topic related to sustainability, the specific aspects being investigated are relatively rare. Consequently, finding closely related research for reference poses a significant challenge. Despite this obstacle, various literature sources are being utilized to enhance knowledge in the related topic.

Confirmability

Confirmability refers to minimizing interference or bias from the interviewer when participants or interviewees provide answers (Guba & Lincoln, 1994). Interference from the interviewer could sway the interviewee's original opinion and result in bias. The interviewees on this research are expert in their scope, which is sustainability. The interviewees' familiarity with technical terminology common in the sustainability sector allows them to respond to questions smoothly and without external interference.

Ethical Consideration

Ethical consideration is essential in all research processes. It ensures informed consent and minimizes harm during research (Fossey et al., 2002). Additionally, it safeguards participants from harm and maintains the confidentiality of their opinions throughout the process (Johnson et al., 2020). At the outset of the research, participants are informed of the research objectives for educational purposes. Furthermore, detailed information about confidentiality and anonymity is provided to ensure that participants feel safe throughout the research process.

4 Findings

In this section will present the findings derived from the qualitative research and pilot study conducted with the suppliers of the OEM. The first segment will detail the decarbonization journey and the challenges encountered by the chosen suppliers. Subsequently, an analysis of the gathered data will be provided. The primary insights from the data collection are utilized for a pilot study, which is implemented through a questionnaire. The chapter concludes with a comprehensive analysis of the results from the pilot study.

4.1 Decarbonization Journey and Challenges

Suppliers were selected for data collection, through interviews, with the aim of gaining insight into their key accomplishments in their decarbonization journey, as well as identifying the primary obstacles they encountered during this process. This approach facilitated a comprehensive understanding of their progress and challenges in their pursuit of decarbonization. The OEM has almost 20,000 suppliers for various parts and components.

4.1.1 Tier 1

In the context of the OEM, there exists a multi-tiered supplier structure, with Tier 1 suppliers playing a pivotal role. The emissions from these Tier 1 suppliers directly influence the OEM's emissions, thereby making them a critical focus of this study. Given the thesis's emphasis on the electronics department, the spotlight was on suppliers of ECUs. The objective was to comprehend the diverse decarbonization initiatives undertaken by various ECU suppliers. To gather comprehensive information, a semi-structured interview format was adopted.

The subsequent section presents a summary of the data secured from the interviews conducted with the Tier 1 and Tier 2 suppliers. A brief introduction of each supplier's products is presented, followed by an in-depth discussion of their respective decarbonization efforts. The challenges encountered by each supplier in their decarbonization journey are also elaborated upon in detail.

4.1.1.1 Supplier A

Supplier A, a significant contributor to the OEM’s supply chain, has embarked on numerous initiatives to decarbonize their operations. However, the interviewee was reticent about divulging extensive details, providing only a presentation outlining their decarbonization journey. The insights gleaned from the interview is summarized below.

The manufacturing process of their ECUs is powered by green electricity, procured from renewable sources. Green electricity refers to power generated from environmentally friendly resources such as solar, wind, geothermal, biomass, and low-impact hydro facilities. By 2030, they aim to produce 100% of this green electricity in-house. A noteworthy achievement in their recent history is the procurement of 100% green electricity in 2022. Interestingly, 4% of this electricity is derived from photovoltaic (PV) cells installed at their own facility. They use an external database using critical material mass to evaluate carbon emission, where most organizations in the automotive industry can share their emissions data from their value chain.

When it comes to product design for sustainability, Supplier A clarified that this principle is being implemented across their entire product range, not just limited to ECUs. They also take steps to inform their suppliers about decarbonization. However, they do not actively monitor these initiatives, placing trust in their suppliers to independently pursue their decarbonization efforts. Collaboratively, they work with their suppliers to amass more data for their product's carbon footprint database. On the topic of product reapplication and second-life initiatives, it was revealed that they engage in the recycling of plastics and metals from their products.

In response to inquiries regarding the commencement of their decarbonization journey, it was disclosed that they initiated the practice of issuing sustainability reports in the early 2010s. This was preceded by the launch of Corporate Social Responsibility (CSR) activities around 2005/2006. Moreover, their commitment to environmental stewardship can be traced back to late 1990s when they began the publication of environmental reports.

Challenges

When considering the challenges faced by Supplier A in their decarbonization journey, there was hesitation in sharing their challenges with us and hence could be documented. This made us realize the significance of transparency and communication between the stakeholders to reduce the gap and share knowledge about their challenges which could be potential lessons for other suppliers. Supplier A's experience navigating their decarbonization journey offers valuable insights into a critical challenge: the hesitancy to share information regarding encountered difficulties. This reluctance often translates to limited documentation of challenges and, consequently, a scarcity of lessons learned disseminated across the supply chain.

Transparency between organizations, emerges as a critical driver of sustainable performance and by openly sharing information regarding upstream practices, organizations can promote and monitor environmentally responsible practices across the entire supply chain network. This highlights the paramount significance of fostering transparency and open communication among stakeholders. By openly discussing challenges and potential solutions, a collaborative environment can be established. This knowledge exchange can bridge the knowledge gap within the supply chain, allowing other suppliers to benefit from Supplier A's experiences. Supplier A's transparency has the potential to accelerate collective progress towards decarbonization goals by equipping other actors with valuable knowledge and strategies to overcome similar obstacles.

4.1.1.2 Supplier B

During the engagement with Supplier B, a leading ECU manufacturer, a range of key initiatives and strategies were implemented relating to the execution of their decarbonization process. Their process embodied a holistic approach, inclusive of carbon offsetting, stringent energy consumption monitoring, and the adoption of renewable energy sources. Supplier B has also incorporated eco-design principles into their production methodologies, with the objective of minimizing environmental impact through sustainable product development. In addition, they have invested in sustainable mobility solutions to curtail emissions associated with transportation. Supplier B ensures compliance with various certifications and adherence to compliance standards, reinforcing their commitment to sustainable practices and environmental responsibility.

A notable challenge in Supplier B’s decarbonization endeavors is the inconsistency in supplier engagement, particularly those located in Southeast Asia. Attaining precise information from these suppliers proves to be a challenge, often due to the absence of established communication channels and varying levels of compliance with environmental regulations. However, Supplier B anticipates that as global decarbonization standards become more rigorous and carbon pricing mechanisms escalate, suppliers will become more cognizant of their emissions and more cooperative in providing necessary data. This enhanced transparency and accountability will enable Supplier B to compile more comprehensive information on their supply chain emissions and take more effective measures towards overall decarbonization.

Supplier B employs an in-house tool for conducting LCA to compute the carbon footprint of their products and processes. This tool is complemented by an environmental database provided by one of the major certification service providers, which offers extensive data to support accurate and comprehensive LCA calculations. This also helps in eco designing to evaluate environmental profiles of products and services. By utilizing these resources, Supplier B can identify key areas where carbon emissions can be reduced and monitor the effectiveness of their decarbonization strategies over time. This data-driven approach ensures that their sustainability efforts are both quantifiable and impactful, aligning with their overarching objective of reducing their environmental footprint.

The significance of product design in reducing emissions was emphasized as a crucial component of their sustainability strategy. The company acknowledges that product design significantly influences overall emissions, with designers actively evaluating alternative materials and processes that could diminish the environmental footprint. However, a major challenge identified is the elevated cost associated with these eco-friendly alternatives, which poses a significant impediment to their widespread adoption. Despite this, Supplier B is committed to implementing eco-design principles in the forthcoming years, aiming to integrate sustainability into the core of their product development process.

Looking ahead, Supplier B has delineated comprehensive decarbonization plans that include detailed Scope 3 emissions calculations. These calculations are essential for understanding the full extent of their carbon footprint, as they encompass all indirect emissions occurring along the value chain. Once these calculations are complete, Supplier B plans to set specific targets aimed at reducing these emissions. Eco-design will play a pivotal role in achieving these targets, as it will guide the development of products that are not only innovative but also environmentally responsible.

Supplier B also shared their extensive experience with reapplication and second-life initiatives for their products. Since 2002, they have been engaged in the repair and remanufacturing of their ECUs. This initiative has proven highly successful, with an impressive figure above 100,000 boards remanufactured to date. This practice not only extends the life cycle of their products, thereby reducing waste, but also conserves resources by limiting the need for new raw materials. This long-standing commitment to repairing and remanufacturing underscores Supplier B's dedication to sustainable practices and their proactive approach to reducing environmental impact through innovative solutions.

Challenges

During the meeting with Supplier B, they revealed a recent shift in their corporate priorities. This focus on decarbonization efforts, initiated approximately two years ago, coincided with the arrival of the interviewee at the company. This change in direction appears to be driven by a keen awareness of evolving market dynamics. Supplier B recognized the growing consumer and regulatory pressure for sustainable products, prompting them to implement a series of decarbonization strategies to ensure alignment with these market expectations.

Despite these proactive measures, Supplier B faces several challenges in their decarbonization journey. A significant hurdle lies in the limited availability of competitively priced, low-carbon options within their current supply chain. This necessitates a strategic reevaluation, potentially involving the development of new partnerships with more sustainable suppliers. Another key challenge involves redesigning circuit boards to minimize energy consumption. To address this and comprehensively quantify the environmental impact of their products, Supplier B has developed an in-house LCA tool.

Supplier B further emphasizes close collaboration between engineers and customers. This collaborative approach ensures that boards not only meet specific sustainability criteria but also maintain optimal performance. However, despite their efforts, a persistent challenge remains – the availability of reliable supplier data. Limited data transparency hinders their ability to obtain a clear and comprehensive picture of supply chain emissions. This lack of consistent data makes it difficult to fully assess and mitigate the carbon footprint associated with their products. Recognizing this as a critical barrier to achieving long-term sustainability goals, Supplier B is actively exploring strategies to improve data collection and supplier engagement in this area.

4.1.1.3 Supplier C

In a recent engagement with Supplier C, a prominent ECUs manufacturer, the firm unveiled its extensive decarbonization strategy. The company has pledged to incorporate sustainable materials into its products and aims to derive 25% of its energy from renewable sources by 2025, with a goal of achieving 100% renewable energy usage by 2030. To facilitate these objectives, they have instituted an ISO 50001 certified Energy Management System (EMS) at their top 10 energy-intensive sites by 2025. This system is engineered to enhance energy efficiency and curtail overall consumption. In addition, Supplier C has made investments in carbon offsets, on-site renewable energy generation, power purchase agreements (PPA), and renewable energy certificates (REC) to expedite their transition to sustainable energy.

Supplier C demonstrates a proactive approach to decarbonization, extending their efforts beyond their own operations to encompass their entire supply chain. To equip key suppliers with the necessary tools and knowledge, Supplier C offers sustainability training programs. These programs aim to empower suppliers to reduce their carbon footprint and align with Supplier C's environmental objectives. Additionally, Supplier C establishes carbon reduction targets for its suppliers, incentivizing the adoption of greener practices across the supply chain. For LCA and carbon footprint calculations, Supplier C leverages the external database. This comprehensive tool allows for a precise evaluation of environmental impact throughout a product's lifecycle. By utilizing the extensive data provided by the external database, Supplier C can pinpoint areas for improvement and effectively monitor the progress of their decarbonization initiatives.

A noteworthy achievement in Supplier C's sustainability journey is their accomplishment of exceeding their target which more than 80% waste recycling rate. This translates to a significant reduction of almost 40,000 tons of waste diverted from landfills. This success story exemplifies Supplier C's dedication to resource efficiency and waste reduction, further solidifying their commitment to environmental impact mitigation and overall decarbonization goals. During discussions with Supplier C, the critical role of product design in emissions reduction was highlighted as a core component of their sustainability strategy. The company expressed a strong interest in collaborating with OEMs to develop more sustainable products. This collaborative approach involves incorporating feedback from OEMs to optimize environmental performance. One key area of focus is the utilization of sustainable materials, which not only contributes to emission reduction but also caters to the growing market demand for eco-friendly products. Their proactive integration of sustainability principles into product design underscores their firm commitment to minimizing their overall carbon footprint.

Supplier C has projected ambitious future decarbonization plans, concentrating on reducing CO_2 intensity in metals and committing to emission reduction targets. They have set a vision to achieve carbon neutrality at the company level by 2040, and by 2039 at the product level. This long-term vision exemplifies their commitment to substantial and enduring reduction in environmental impact. Realizing these targets will necessitate continuous efforts to improve energy efficiency, augment the use of renewable energy, and deploy innovative technologies and processes that decrease emissions.

Regarding the reapplication and second-life initiatives for their products, Supplier C has implemented several measures to minimize waste within their manufacturing operations. They are actively reusing and reducing packaging materials, and have made significant strides in using recycled materials, such as copper, in their production processes. A major accomplishment in this area is the recycling of more than 80% of their total waste, considerably surpassing their initial target. This has led to a significant reduction in waste directed to landfills. Furthermore, Supplier C's adoption of renewable energy sources further reinforces their waste reduction and sustainability objectives, reinforcing their holistic approach to minimizing environmental impact across their operations.

Challenges

When asked about the beginning of their decarbonization journey to Supplier C, it was emphasized that the company has been diligently concentrating on decarbonization since 2011. Throughout this duration, they have made considerable progress in diminishing their environmental impact, achieving significant reductions in CO_2 emissions, water usage, and waste disposal. These remarkable outcomes underscore the supplier's enduring commitment to sustainability and its proactive stance in mitigating environmental impact across its operations.

Despite these accomplishments, Supplier C continues to encounter several obstacles in their ongoing decarbonization endeavors. A significant challenge is the absence of a standardized methodology for computing the carbon footprint specific to the electronics industry. This lack of a unified standard leads to inconsistencies and difficulties in accurately measuring and comparing emissions across different suppliers and products. Moreover, some tier n suppliers remain reticent to share detailed data pertaining to their environmental impact, further complicating Supplier C's capacity to procure comprehensive and precise information for their assessments. This reluctance to share data restricts the transparency and effectiveness of Supplier C's decarbonization initiatives, underscoring the need for enhanced industry-wide collaboration and standardized reporting practices to propel collective sustainability objectives.

4.1.2 Tier 2

The OEM’s tier 2 suppliers, who are primarily semiconductor providers, play a crucial role in supplying tier 1 suppliers of the ECU. The following section presents the details from the meeting conducted with one of the leading semiconductor suppliers of the OEM.

4.1.2.1 Supplier D

A leading semiconductor manufacturer, Supplier D, illustrates a multifaceted approach to decarbonization. A meeting with their representatives revealed a comprehensive strategy encompassing renewable energy adoption, waste management practices, and carbon offsetting initiatives. Supplier D is committed to transitioning to 100% renewable energy across all manufacturing facilities by 2025. Their current utilization of a substantial percentage of renewable energy globally and the procurement of a considerable amount through Renewable Energy Certificates (RECs) demonstrates significant progress. This strategy aligns with circular economy principles, exemplified by their effective management of traditional waste streams.

Recognizing the importance of supply chain engagement, Supplier D conducts biennial audits to ensure compliance with the Validated Assessment Program (VAP) and maintains a stringent environmental Code of Corporate Social Responsibility (CoCSR) for suppliers. Vendor selection incorporates environmental performance criteria, and supplier maturity assessments gauge sustainability progress. These practices aim to align their suppliers with Supplier D's goals and facilitate collective environmental impact reduction.

Initial attempts at LCA and carbon footprint calculations using AI tools proved unsatisfactory. Consequently, Supplier D developed their own tools for accurate emission modeling and measurement. Data currently relies on publicly available information from major suppliers. The company plans to update models with actual supplier data as more detailed information becomes available.

The implementation of a new reverse-osmosis (RO) water-reclaim unit exemplifies Supplier D's commitment to resource efficiency. This innovative system will save over 7 million gallons of water annually, highlighting their proactive approach to integrating sustainable practices.

A key hurdle in future decarbonization efforts lies in the low to medium certainty of suppliers' Scope 1 and Scope 2 data. Recognizing the importance of accurate data for effective strategies, Supplier D is actively working to improve data transparency and quality through active supplier engagement. This enhanced data quality is crucial for setting and achieving precise emission reduction targets.

While Supplier D prioritizes water recycling and renewable energy use in manufacturing, they currently lack experience in product reapplication or remanufacturing. Their focus lies on optimizing production processes and minimizing resource consumption within their own operations.

Challenges

Supplier D's commitment to decarbonization has noticeably strengthened over time. The initial phase culminated in the publication of Environmental, Social, and Governance (ESG) reports by 2021. These reports provided a framework for assessing progress towards reduction goals relative to production output. The incorporation of GHG methodologies in their 2022 reporting further exemplifies Supplier D's evolving commitment to transparency and accountability in sustainability practices.

However, embarking on this journey wasn't without hurdles. Limited resources dedicated to sustainability and the significant financial investments required presented initial challenges. Additionally, the relative novelty of decarbonization within the company in 2019 led to a lack of widespread awareness and understanding. This unfamiliarity with established practices hindered effective strategy implementation and garnered broader support for the initiatives.

Despite these early obstacles and ongoing challenges related to awareness, Supplier D underscores the importance of inter-company collaboration. They recognize that knowledge sharing and collaborative efforts across the industry are crucial for accelerating progress and achieving broader environmental goals. Another persistent challenge lies in the absence of industry-wide standards for emissions calculation. This lack of standardization hinders accurate measurement and comparison of Supplier D's carbon footprint. While the company continues to refine its own tools and methodologies, it actively advocates for the establishment of consistent and reliable industry standards. Such standards would not only facilitate improved benchmarking and progress tracking but also enhance the overall effectiveness of decarbonization initiatives within the semiconductor sector.

4.2. Analysis

The data collected from interviews were analyzed to find patterns like commonalities and similarities between suppliers so that the dimensions could be defined for the maturity assessment tool which would be then further developed to a pilot study.

Commitment to Renewable Energy:

The participating suppliers exhibited varying levels of commitment towards renewable energy integration within their decarbonization strategies. Supplier A stood out for its utilization of 100% green electricity, aiming for complete in-house production by 2030. Supplier B demonstrated a broader approach, incorporating renewable energy sources as part of a comprehensive decarbonization plan. Supplier C outlined a staged approach, targeting partial use of renewable energy by 2025 and full integration by 2030. Finally, Supplier D displayed rapid progress, having already achieved almost 60% renewable energy use across its manufacturing plants and aiming for full implementation by 2025. This diversity in approaches highlights the evolving landscape of renewable energy adoption within the electronics supply chain.

Waste Management and Recycling:

The suppliers showcased diverse approaches to resource management within their sustainability efforts. Supplier A focused on material recovery through plastic and metal recycling. Supplier B adopted a second-life strategy, successfully repairing and remanufacturing ECUs to extend their lifespan. Supplier C demonstrated a commitment to waste reduction, achieving almost 90% recycling rate and promoting the reuse of packaging materials. Finally, Supplier D exhibited a holistic approach aligned with circular economy principles. They implemented water recycling systems to minimize resource consumption and prioritized renewable energy usage, aiming to reduce their environmental footprint throughout the entire product lifecycle. This variety of initiatives underscores the potential for the electronics supply chain to contribute to a more sustainable future through innovative resource management strategies.

Product Design for Sustainability:

The participating suppliers demonstrated varying approaches to product design and sustainability focus. Supplier A embraced a comprehensive strategy, integrating sustainability considerations across their entire product portfolio and actively encouraging their own suppliers to decarbonize. Supplier B prioritized eco-design practices, actively seeking alternative materials with lower environmental impact to minimize the footprint of their products. Similarly, Supplier C placed emphasis on sustainable design principles, collaborating with OEMs to develop more environmentally friendly products. In contrast, Supplier D focused on product durability and longevity during the manufacturing stage, aiming to extend the lifespan of their products even in the absence of dedicated remanufacturing initiatives. This diversity of approaches highlights the evolving landscape of sustainable product design within the electronics supply chain, with some companies taking a holistic approach while others prioritize specific aspects like durability or collaboration.

Life Cycle Assessment (LCA) and Carbon Footprint Calculation:

The suppliers exhibited a range of approaches to data collection and analysis for their decarbonization efforts. Supplier A and Supplier C leveraged external database, a collaborative industry platform, for sharing emissions data and calculating carbon footprints. This approach promotes transparency and potentially facilitates benchmarking within the supply chain. Supplier B, however, adopted a hybrid strategy, utilizing an in-house tool alongside an external database for Life Cycle Assessments (LCAs). This suggests a potentially more customized approach tailored to their specific needs. Finally, Supplier D stands out for their independent approach. Having encountered limitations with existing external databases, they developed their own tools to ensure accurate emission models and measurements. This case highlights the potential need for customization and the ongoing development of data collection methods within the electronics supply chain.

Supplier Engagement and Training:

The suppliers employed varying strategies to engage their supply chains in decarbonization efforts. Supplier A fostered collaboration by working directly with suppliers to gather data for their carbon footprint database. This collaborative approach can promote transparency and hold all actors accountable for their environmental impact. In contrast, Supplier B faced challenges in supplier engagement, potentially hindering their ability to obtain comprehensive data. However, they anticipate improvement with the application of stricter sustainability standards within the supply chain. Supplier C addressed this issue proactively by providing sustainability training for key direct suppliers. Additionally, setting clear carbon reduction targets can incentivize suppliers to prioritize decarbonization efforts. Finally, Supplier D implemented a supplier management system, conducting biennial audits to assess compliance with their Code of Corporate Social Responsibility. This approach ensures alignment with broader sustainability goals but may require ongoing efforts to encourage active participation from suppliers. These diverse supplier engagement strategies highlight the importance of fostering collaboration and setting clear expectations for achieving collective progress towards supply chain decarbonization.

The suppliers demonstrate a robust commitment to decarbonization and sustainability through renewable energy adoption, lifecycle assessments, sustainable product design, and effective waste management. Their shared focus on renewable energy and LCA tools underscores the industry's shift towards measurable and impactful environmental strategies. While each supplier faces unique challenges, particularly in supplier engagement and data transparency, their proactive approaches and long-term goals reflect a cohesive drive towards a sustainable future. These commonalities and strengths illustrate a comprehensive effort within the automotive supply chain to mitigate environmental impact and foster a more sustainable industry. The above analysis has been accumulated into a table and presented in Table 4.1 as below.

Table 4.1: Data analysis of Tier 1 and Tier 2 suppliers from interviews.

Category/Supplier	Supplier A	Supplier B	Supplier C	Supplier D
Renewable Energy Commitment	100% green electricity by 2030, with almost 5% from on-site PV cells (2022: 100% green electricity)	Adopts renewable energy sources; integrates sustainable mobility solutions	25% renewable by 2025, 100% by 2030	Close to 60% renewable energy usage, 100% by 2025; purchased electricity through RECs
Life Cycle Assessment (LCA)	Uses external database for emissions data sharing	In-house LCA tool, supplemented by external database	Utilizes an external database	Developed own tools after initial dissatisfaction with AI tools; relies on publicly available data
Product Design for Sustainability	Applies sustainability across all products; engages suppliers in decarbonization initiatives	Integrates eco-design practices; evaluates alternative materials despite higher costs	Collaborates with OEMs for sustainable product design; uses sustainable materials	Focuses on renewable energy and water recycling, indicating a sustainable approach to product design
Waste Management and Recycling	Recycles plastics and metals	Successful reapplication and second-life initiatives, repairing/remanufacturing ECUs (Above 100,000 boards remanufactured)	Recycles almost 90% of total waste; reuses packaging materials; significant waste reduction	Implements advanced water recycling systems, saves 7 million gallons annually
Supplier Engagement and Training	Collaborates with suppliers for carbon footprint data; no active monitoring, relies on trust	Faces variability in supplier engagement; anticipates improvements with stricter standards	Provides sustainability training; sets carbon reduction targets for suppliers	Conducts biennial audits; includes environmental performance in vendor selection; engages suppliers for data transparency
Long-term Commitment	Sustainability reports since 2011; CSR activities since 2005/2006; environmental reports since 1998	Comprehensive decarbonization plans including Scope 3 emissions calculations; repair and remanufacturing since 2002	Aims for carbon neutrality at company level by 2040 and product level by 2039	Committed to achieving 100% renewable energy by 2025; focuses on innovative sustainability practices
Innovation in Sustainability	In-house production of green electricity; recycling initiatives	Repair and remanufacturing of ECUs	Significant waste reduction; sustainable product design collaborations	Advanced water recycling systems; reverse-osmosis units for resource efficiency

4.2.1. Dimensions of maturity model (Tier 1)

The development of a robust maturity assessment tool for evaluating supplier decarbonization practices involved a multi-step process. Following a thorough data analysis, draft dimensions for the maturity assessment tool were established. These initial dimensions were informed by the relevant literature review and tailored to the specific focus of this study. However, recognizing the importance of real-world applicability, further refinement was deemed necessary. To ensure the effectiveness and comprehensiveness of the tool, a pilot study was conducted later. This iterative process involved testing the draft dimensions and their associated maturity levels with a selected sample of participants.

A maturity assessment model could have multiple levels as per the data available. Normally, Level 1 would be represented as a state of limited awareness and non-compliance with relevant regulations and the suppliers at this level would lack any formal sustainability efforts within their operations. Conversely, Level 2 would signify a higher level of maturity, characterized by systematic management processes, a commitment to continuous improvement, and active collaboration across the supply chain. Additionally, suppliers at Level 2 usually demonstrate a leadership role in promoting sustainable practices within their networks.

Table 4.2: Draft dimensions and their respective indicators/elements from interviews.

Dimension	**Indicator/Elements**	**Explanation**
Environmental	Resources	The company's use of materials, energy, and recycling practices.
	Carbon Punch	Signs of operational redesign to decrease their environmental impact/ carbon emissions.
	Waste Reduction	The company integrates a global product lifecycle management service system focused on waste minimization into its overall business strategy.
	Circular Strategy	Remanufacturing minimizes resource use by recovering materials from defective products and implementing standardized, eco-friendly practices.
	Renewable energy	The organization uses renewable energy for their operations.
	Design for sustainability	Creating products through economically sound methods that minimize environmental impact, conserve energy and natural resources
	Second Life products	Reused, refurbished, or recycled products
Calculation tools	LCA	Design teams prioritize sustainable production processes and minimize the environmental impact of the product's use for customers.
	Data for Carbon Footprint Calculations	Does the primary data for carbon footprint calculations come from the suppliers.
	Extend of Carbon Footprint Calculations	How deep the supplier captures the carbon footprint of the entire supply chain?
Cross Organization	Knowledge and Training	Training and sharing knowledge about sustainability with other stakeholders in the supply chain.

	Sustainability Standard	Having certifications or joining associations to set industry standards.
	Transparency and Communication	Transparency in sharing information with other stakeholders in the supply chain and communicating their sustainability journey.

The composition of the draft dimensions and elements in Table 4.2 is derived from a mixture of scholarly articles and details from the interviews done initially. Through the pilot study, the draft dimensions were elaborated upon. This reiterative process resulted in a more refined and complete assessment tool, capturing a wider range of supplier maturity levels, and differentiating specific practices within each level. This refinement ensured the tool accurately reflected the complexities of supplier sustainability performance, providing a more valuable and informative assessment for stakeholders.

4.3 Pilot Study

A pilot study is conducted for this research to finalize maturity assessments suitable for the decarbonization process. Before the pilot study, a visualization of the maturity assessment draft (Table 4.2) is created to facilitate better understanding. The maturity assessment draft will serve as a guideline for creating questions for the pilot study.

The total number of questions will correspond to the number of elements, which are expected to be reliable. This is because the elements are based on actual experiences from previous qualitative research. To test the draft, 25 questions (Appendix B) are created for Tier 1 and Tier 2 suppliers, focusing on their journey in decarbonization. To capture differences between tiers, a question specifically addressing the decarbonization process in Tier 2 is included.

Due to limited access to suppliers, OEM representatives recommended some suppliers based on their transparency experience. After the discussion, the final candidates for the pilot study include four from Tier 1 ECUs and two from Tier 2 Semiconductors. Tier 1 suppliers are contacted directly by the researcher, while Tier 2 suppliers are contacted by the semiconductor specialist within the OEMs who already has established contacts with them. Initially, the pilot study was expected to be completed in 7 days, but due to slow responses from the suppliers, it was extended to 10 days. The OEM representatives, aware of the slow responses, sent reminders to the suppliers, which was very helpful as the suppliers then submitted their responses promptly.

After 10 days of sharing the pilot questions, all Tier 1 suppliers successfully answered all the questions, while only one Tier 2 supplier responded. Tier 1 suppliers answered all the questions directly, whereas the Tier 2 supplier shared links to their reports or company results, which likely addressed the questions. The different responses from the tiers could indicate varying levels of transparency in their sustainability or decarbonization journeys. Moreover, OEM representatives had anticipated different responses from the tiers, with semiconductor Tier 2 suppliers appearing more secretive about their decarbonization efforts. Due to the limited response from Tier 2 suppliers, their data will not be included in the data analysis of the maturity assessment, as input from only one source is insufficient to find patterns.

4.4 Analysis of Pilot Study

This section will present the findings of the pilot study conducted with Tier 1 ECU suppliers. Data analysis will be conducted to decide the maturity level of various suppliers and refine the maturity assessment tool. The maturity dimensions and elements identified through the analysis will be incorporated into a standardized assessment checklist.

4.4.1 Insights from Pilot Data

This section analyzes the pilot study results using the draft maturity model, focusing on Tier 1 ECU suppliers' decarbonization efforts. Some results will help determine whether the dimensions and elements in the draft maturity model are already sufficient or need updates. Thus, the results are expected to provide more information on how suppliers are working on decarbonization.

Understanding their decarbonization journey, including their emission tracking and targets, can provide insights into their efforts to achieve their carbon emission or net zero emission targets. Table 4.3 (below) shows that Supplier F and H have set targets for both 2030 and 2040, potentially indicating a more ambitious decarbonization strategy to achieve 2030 target before fulfilling 2040 target. However, this also means they may face greater commitment and challenges in achieving both targets compared to suppliers focusing on a single year, such as Supplier F and G. Supplier H's data reveals a differentiated approach, targeting Scope 1 and 2 emissions in 2030 and expanding to all Scopes by 2040. This highlights a potential multi-phase strategy for decarbonization for each scope.

Table 4.3: Carbon emission target.

Supplier	Carbon Emission Target
E	2030 and 2040
F	2040
G	Net zero by 2040
H	50% reduction by 2030 (scope 1 +2) + reach carbon neutrality by 2039 (scope 1+2+3)

Figure 4.1 (below) illustrates the level of decarbonization achieved by the suppliers participating in the pilot study. Supplier E and G lead the pack with a decarbonization achievement between 31% and 45%. Supplier H follows closely behind with a range of 16% to 30%, while Supplier F falls into the 0% to 15% range. Although Suppliers E and H initiated their decarbonization efforts by setting two target years, Supplier H

demonstrates a lower level of achievement. One of the results shows that Supplier E had early awareness of decarbonization around 2002. Several factors beyond the initial awareness date could be influencing progress. In 2002, decarbonization regulations may have been less strict, potentially impacting the urgency for early adopters like Supplier E.

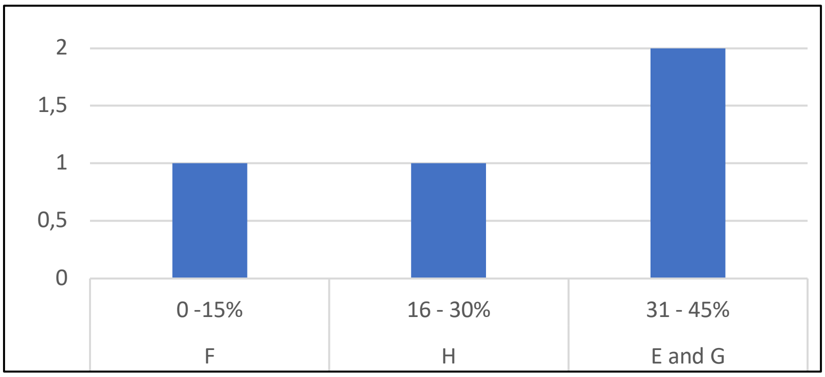

Figure 4.1: Decarbonization strategies achievement.

Figure 4.2 below illustrates decarbonization strategies that suppliers had implemented. It showed that all suppliers had implemented the four strategies: Design for disassembly and remanufacture, Energy-efficient manufacturing processes, on-site renewable energy production, and Renewable energy sources for production. This indicated that all suppliers prioritize these strategies on their decarbonization journey. Supplier E had fewer decarbonization strategies, around six, compared to Supplier H, which had around ten strategies, even though both had the same two-year target. Meanwhile, none of the suppliers were working on carbon offsetting as part of their decarbonization strategy.

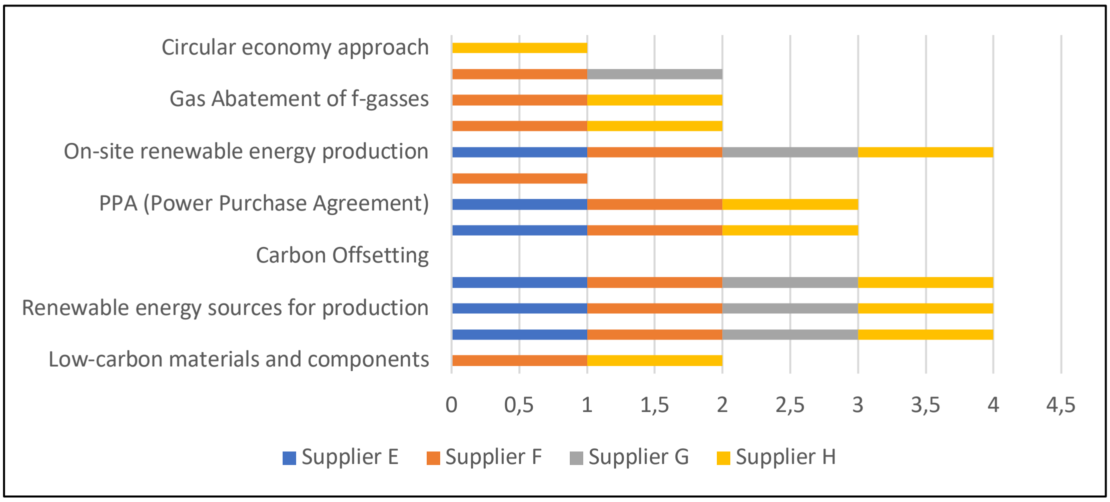

Figure 4.2: Decarbonization strategies.

In Figure 4.3 (below), Circular strategies were shown. The first four strategies—Recycle, Reduce, Refurbish, and Repair—were the common approaches that suppliers had implemented. Remanufacturing was implemented by Suppliers G and H, with Supplier H dominating almost all these strategies. This demonstrated Supplier H's dedication and commitment to decarbonization. Meanwhile, none of suppliers had implemented Repurpose on their product as part of circular strategies.

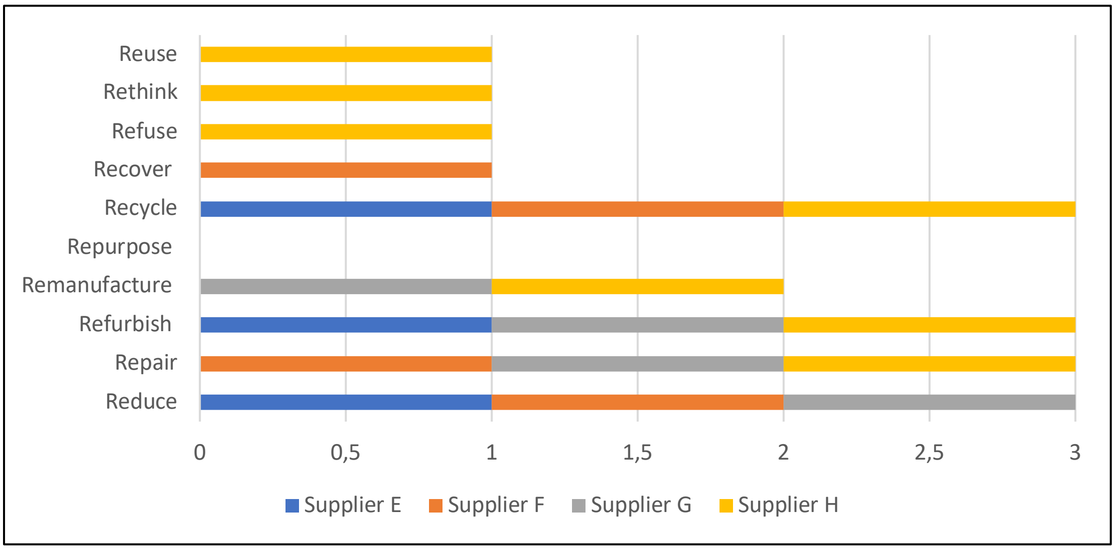

Figure 4.3: Circular strategies

In the journey towards decarbonization, being aware of and controlling emissions is important to achieve net-zero targets. Therefore, calculating carbon emissions is necessary to manage and reduce them effectively. To facilitate this, using LCA as a method and tool to analyze environmental impact is essential. Figure 4.4 (below) illustrates the LCA tools used by suppliers. It shows only Supplier G has developed its own LCA tools, while the others still rely on external tools. Supplier E and F are using Tool A, whereas Supplier H is utilizing Tool C. Meanwhile, none of the suppliers use Tool B as their LCA tools.

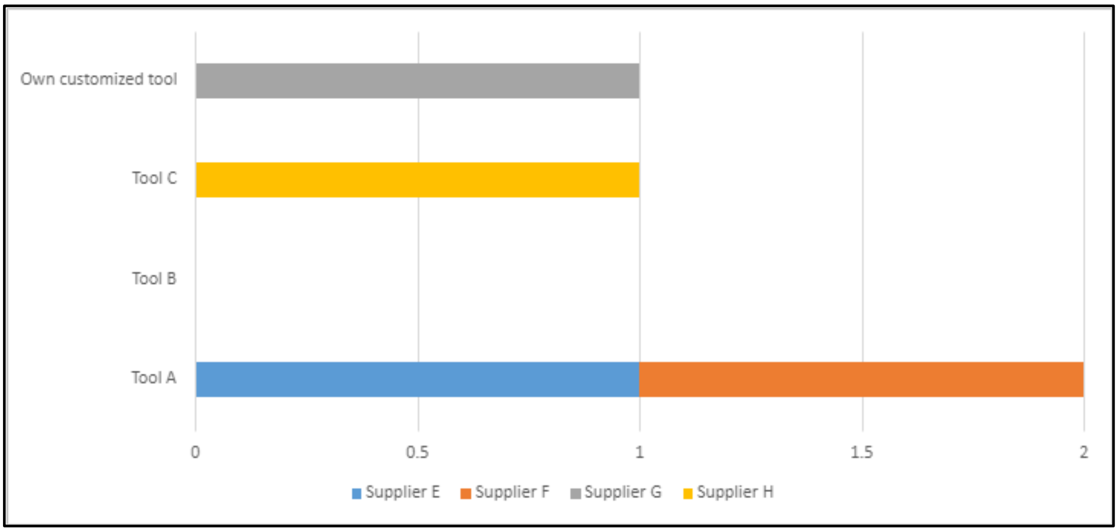

Figure 4.4: LCA tools.

To conduct an LCA, data related to the products' emissions is necessary. However, due to the lack of standardization in calculation methods, each supplier may use different sources to collect this data. In Figure 4.5 (below), Suppliers E and F are both utilizing the same database, Database E. Supplier G, on the other hand, is employing Database

D and data from suppliers. Since Supplier G owns their own calculation tool and may not have all the necessary base data stored within it, the data cannot come from a single source. Therefore, Supplier G collects it from two different sources.

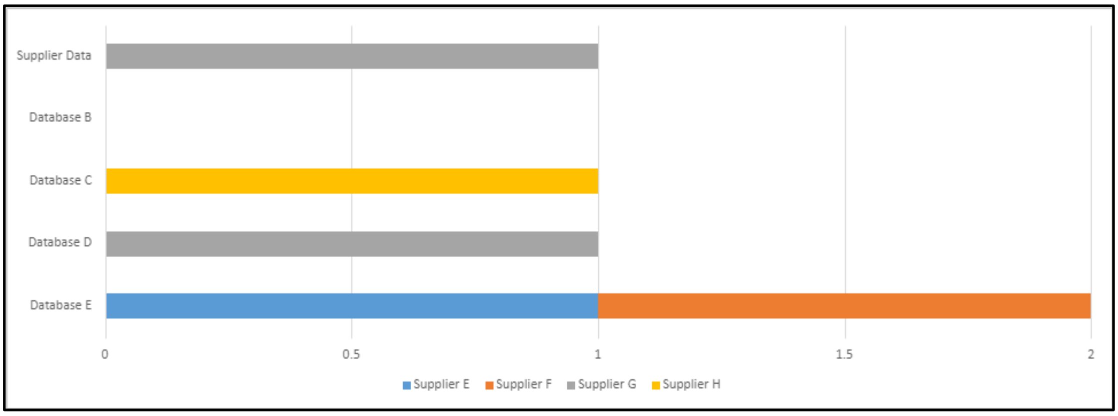

Figure 4.5: LCA database.

Based on the data gathered from Figures 4.4 and 4.5, certain information we attempted to uncover was not found. Specifically, this information concerns the data sources directly shared by their suppliers and the depth of data capture throughout the entire supply chain. Obtaining this data may require further research and additional time to encourage suppliers to be more transparent.

Figure 4.6 illustrates suppliers' on-site renewable energy production and their renewable energy sources. From the left side of the figure, it is evident that all suppliers have their own on-site renewable energy production. Solar energy is the most common source, produced by all suppliers, while wind energy is only produced by Supplier G. It shows suppliers' effort and commitment to have green energy to decrease carbon emission.

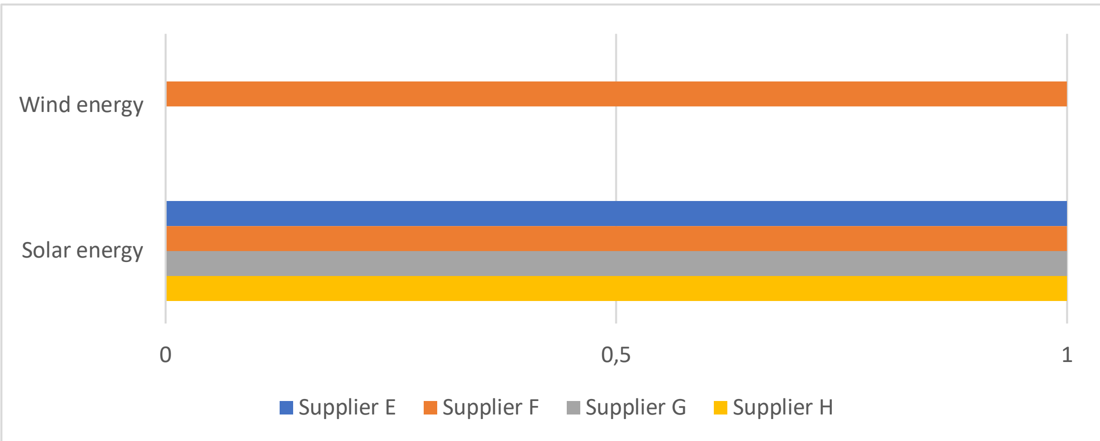

Figure 4.6: Type of renewable energy produced.

Below, Figure 4.7 illustrates another supplier's commitment to green energy or green electricity, focusing on their electricity purchases for production. All suppliers purchase hydropower and solar energy for electricity production. Additionally, Suppliers E, G, and H purchase natural gas. Supplier H explores various types of electricity for production, despite still using coal, which could lead to higher emissions.

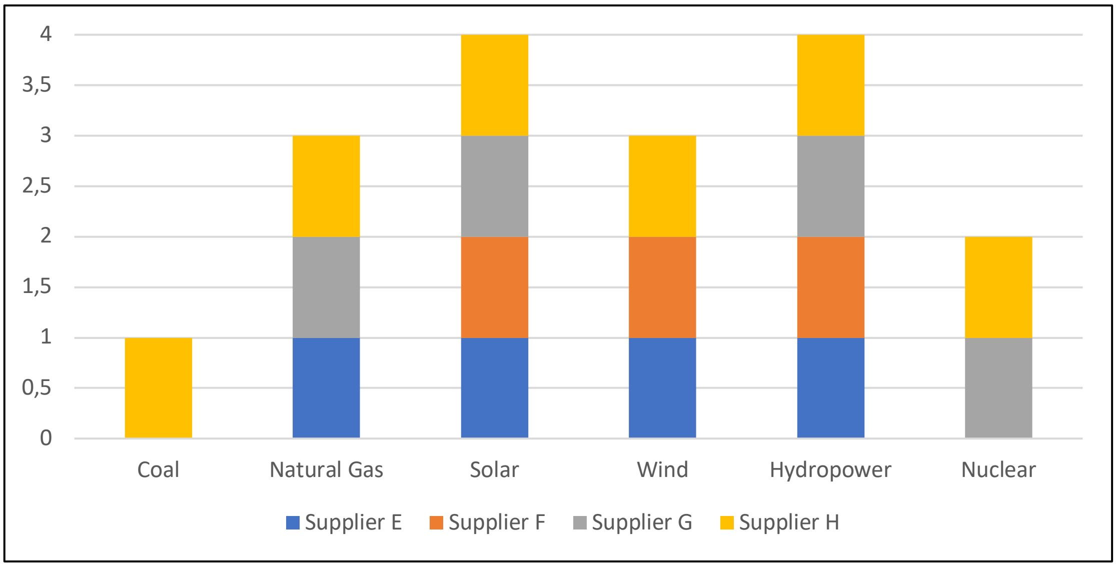

Figure 4.7: Electricity for production is purchased by suppliers.

Suppliers utilize various types of renewable energy, each with potentially different distributions. Table 4.4 illustrates these distributions for each energy source. Supplier F provides allocation details, with solar comprising the highest share at 50%, followed by hydropower (40%) and wind (10%). Suppliers H and E are aware of the plan for renewable energy but lack detailed information on each source. Meanwhile, Supplier G lacks detailed knowledge of the renewable energy plan. Knowing the allocation of renewable energy could help suppliers manage which resources to increase or decrease to achieve their net-zero targets. This raises the concern of how they manage and control their renewable energy to meet these goals.

Table 4.4: Allocation of renewable energy.

Supplier	Allocation of renewable energy
Supplier E	20% of all renewable energy being used is on-site production
Supplier F	Solar: 50% - Hydro-electric: 40% - Wind: 10%
Supplier G	Exact percentages not available unfortunately
Supplier H	Around 70% electricity from renewable sources which around 14 plants use green electricity

Based on Figure 4.7 and Table 4.4, the production process focuses on resources from renewable energy sources. The draft maturity model separates resources and renewable energy into two different parts, but the findings indicate that they overlap. Keeping them in separate parts could lead to redundancy.

Suppliers working on decarbonization encounter obstacles that slow down the process. It is crucial to take significant action to accelerate decarbonization. In Table 4.5, below, suppliers share the most crucial action to accelerate decarbonization. Suppliers H and

E emphasize the importance of data transparency and availability. This indicates that challenges related to data in emission calculation could hinder the effectiveness of the decarbonization process. Supplier F highlights the importance of reducing scope 3 emissions, indicating that not all industry stakeholders currently consider the impact of scope 3 emissions in the decarbonization process. Supplier G mentions the use of recycled materials, indicating that this process might not been adopted by other stakeholders, posing a challenge for Supplier G to implement it independently.

Table 4.5: The most crucial actions needed to accelerate decarbonization in the electronics industry.

Supplier	The most crucial actions needed to accelerate decarbonization in the electronics industry
Supplier E	- Data transparency - Stricter controls - Strong customer requirements
Supplier F	The process reduce scope 3 emission
Supplier G	- Sustainably generated energy for plants - Increasing the energy efficiency of processes - The electrification of a large proportion of products - The use of recycled materials
Supplier H	- Alignment and reliable data availability throughout the value chain and establishment of harmonized metrics and a common calculation methodology framework. - Alignment between Operational and CO2 reduction requirements - Availability at scale of more sustainable and less carbon intensive materials - Support from government and industry to mobilizing investments and access to funding/financing mechanisms (especially at R&D stage)

In Figure 4.8, statements are presented to gauge progress towards decarbonization. On the left side, the statement '*Product design significantly influences the overall carbon footprint of your product*' has been universally agreed upon, particularly by Suppliers E and F, who strongly support it. This indicates that suppliers prioritize product design to reduce carbon footprint. In the middle section, the statement '*Satisfied with the current progress my company has made on decarbonization efforts*' receives agreement only from Suppliers F and G, while the others express neutrality. Suppliers F and G appear hesitant about their progress and results in decarbonization. Lastly, on the right side, the statement '*Confident that your company will achieve its decarbonization goals by the target date*' receives unanimous agreement from all suppliers, indicating confidence in achieving decarbonization goals as targeted.

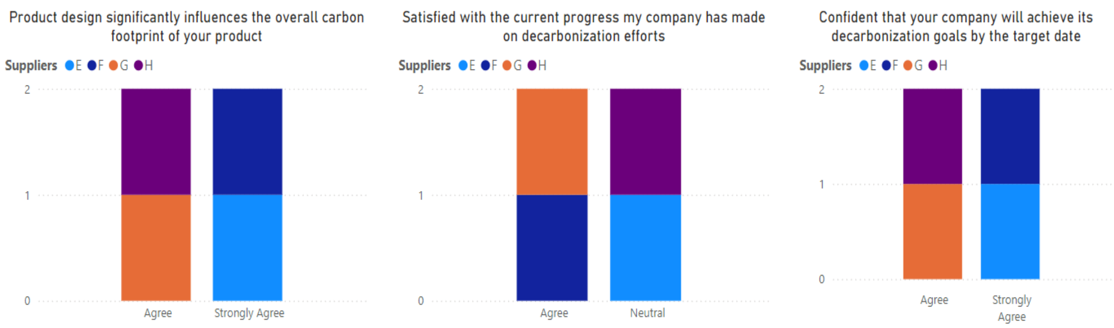

Figure 4.8: Suppliers decarbonization progress

All suppliers agree that there are potential barriers to achieving future decarbonization goals (Table 4.6, below). Each supplier has their own concerns about these barriers. Suppliers G and H highlight the high investment costs, with one considering it from the customer perspective and the other from the company perspective. Supplier E emphasizes the need for collaboration between companies and customers, suggesting that such collaboration is essential and should include suppliers as well. Supplier F is concerned about carbon capture storage, which also requires collaboration among companies, suppliers, and customers.

Table 4.6: Potential barriers to achieve future decarbonization.

Supplier	Potential barriers to achieve future decarbonization
Supplier E	Further push in the supply chain and the collaboration of the suppliers. Net zero is not possible without suppliers efforts in this direction.
Supplier F	Need to expedite technology of carbon capture and storage.
Supplier G	Convincing the end customer to pay the increase in cost that will be the result of full decarbonization.
Supplier H	Many key decarbonization measures require high financial investments.

Overall, this section demonstrates the different types and levels of decarbonization implementation among ECU suppliers. This question-and-answer approach helps determine the maturity of each supplier's decarbonization efforts and challenge, which can later aid OEMs in collaborating on their decarbonization journey.

4.4.2 Refine Maturity Model

In this section, the maturity model will be reviewed and refined based on the pilot study results. The review and refinement will focus on dimensions, elements, and maturity levels.

Elements and Dimensions - Production

This section will discuss each dimension, consisting of several elements from the previous draft maturity model, that may need review and refinement for a more accurate maturity model. In the draft maturity model, the first dimension is 'Environmental,' which includes seven elements: Resources, Carbon Punch, Waste Reduction, Circular Strategy, Renewable Energy**,** Design for Sustainability, and Second Life Products. However, a closer examination and analysis reveals that these elements are not suitable within the same dimension, as they represent different activities in the decarbonization process. Resources, Renewable Energy, and Waste Reduction could be grouped under a 'Production' dimension. Resources would merge and refine into Renewable Energy to identify the type of energy used for the production process. Also as mentioned before, keeping both in one dimension could take to redundancy. Furthermore, the production process generates waste, necessitating continuous reduction efforts, so Waste Reduction should stand alone as an element under the Production dimension. Based on the pilot study, both elements can be tracked down along with the production process. Pilot result also shows suppliers focus on renewable energy for their production process.

Elements and Dimensions - Product

Design for Sustainability, Circular Strategy, and Second Life Products were initially considered separate from the Environmental dimension. However, after thorough discussion and pilot testing, it became evident that they should be consolidated into a new dimension: the Product dimension. Design for Sustainability emerged as a crucial decarbonization strategy adopted by all suppliers. Therefore, failure to implement it may indicate a supplier's lack of maturity in sustainability practices.

Offering products with sustainable design values entails considering the entire product life cycle, from upstream to downstream. The integration of Second Life Products and Circular Strategy into a single element reflects their interconnectedness. Circular Strategy encompasses Second Life Products such as reuse and repair, both of which are commonly employed by suppliers to extend product lifespan and minimize waste. The pilot study revealed that all suppliers possess knowledge of Second Life Products and have implemented strategies to incorporate them into their products. These strategies include reducing, repairing, recycling, and refurbishing, all of which contribute to prolonging product use and reducing waste.

Elements and Dimensions – Calculation Tools

In the draft version of the Calculation Tools dimension (Table 4.2), three elements are present: LCA, Data for Carbon Footprint Calculations, and Extent of Carbon Footprint Calculations. Reflecting on the pilot study, all suppliers are aware of LCA and are already working on their product calculations using data from the LCA database, hence LCA elements keep in the same dimension. However, the element Data for CF Calculations is incompatible because the CF calculation data sources are limited and uniform across suppliers, and rarely come from their suppliers. Similarly, the Extent of Carbon Footprint Calculations element is also incompatible due to limited data sources, which constrain the depth of calculations. Therefore, these two elements are removed from the assessment.

The term 'Carbon Punch,' previously categorized under the Environmental dimension, could be relocated under CF Calculation. Carbon Punch pertains to carbon emission reduction, aligning more closely with the CF Calculation dimension. Within this dimension, Carbon Emission serves to gauge suppliers' comprehension of emissions within their supply chain. Such understanding of carbon emissions is integral to the LCA process, ensuring that the included data is pertinent and impactful for supply chain decarbonization.

Elements and Dimensions - Inter Organizational Relationship

In the draft version (Table 4.2), the dimension was labeled as Cross Organization that contains Knowledge and Training, Sustainability Standard, and Transparency and Communication as elements. Cross Organization dimension naming seems to have a broader scope, covering various internal and external relationships. Consequently, the dimension has been renamed to Inter-Organization Relationship to better emphasize its focus on the specific relationships and collaborations with individual suppliers.

Knowledge and Training, Sustainability Standards, and Transparency and Communication are retained as elements because the pilot results indicate that these factors significantly contribute to the relationships and collaboration suppliers have. The decarbonization process indeed requires collaboration with stakeholders. Reflecting on the pilot results, Transparency and Communication are crucial actions that suppliers find necessary but not well delivered. Sustainability Standards were mentioned as an early commitment to decarbonization by one of the suppliers. Moreover, Knowledge and Training are essential for suppliers to raise awareness among external stakeholders about their decarbonization efforts and to engage stakeholders towards the same goal.

An additional element, Influencing Suppliers, has been added to the Inter-Organization Relationship dimension. This element emerged from the discussion session to understand how current suppliers influence their supply chain or lower tiers, particularly in terms of decarbonization and sustainability. Suppliers mentioned that their decarbonization actions are influenced by customer requests and decarbonization regulations. To fulfill these requests, current suppliers need to have the skills or strategies to influence their supply chain. Hence, this element exists to monitor and assess how decarbonization efforts influence the supply chain.

Maturity Level

This section will discuss the maturity levels within the maturity assessment. Differentiating maturity can be achieved by defining specific levels of maturity. In the draft version, maturity levels are divided into two levels, Level 1 and Level 2, with each level's definition taken from existing references. However, considering the varied levels of decarbonization actions and exploration from the pilot result, two levels are insufficient to elaborate on these differences effectively and extended to four levels.

In Level 0, the maturity level of suppliers is non-existent because, at this level, suppliers have limited, or no knowledge related to the elements. This level may not apply to suppliers who participated in the pilot study but will help assess lower-tier suppliers. It also serves to identify if a supplier is truly at the beginner stage or even less advanced.

Level 1, also known as the beginning level, measures the early stage of the elements. This includes minimal knowledge, basic understanding, and initial experience related to the elements. At this level, suppliers start to gain experience and implement basic practices in each element before advancing to the next level of maturity.

Level 2 is where suppliers build on the knowledge, experience, and understanding gained from the previous level. At this level, suppliers have been on their decarbonization journey for several years but are not yet experts. For example, a supplier might have around three years of remanufacturing experience. Additionally, suppliers at this level are capable of influencing others related to the elements.

Level 3 is known as the leading level, where suppliers have gained expert knowledge and experience. Their sustainability practices and solutions extend beyond ISO standards, including sharing initiatives and exerting greater influence on decarbonization practices. Continuous innovation through transparent communication and data sharing is crucial for sustaining their influence on the sustainability and decarbonization journey.

Based on all the pilot study and discussion, maturity model has been updated for future use, Table 4.7 as below.

Table 4.7: Final Maturity Assessments

Level / Dimension	Elements	Level 0 (Non existent)	Level 1 (Beginning)	Level 2 (Succeeding)	Level 3 (Leading)
Production	**Renewable Energy** (article & interview)	No regulatory compliance, No use of Renewable energy in operations	Have started parts of operations with RE. Uses 0-15% of RE in their production.	Have established goals for increasing RE in operations. Uses 15-30% of RE in their production.	Continuously innovates to further optimize energy efficiency and sustainability. Uses more than 30% of RE in their production.
	Waste Reduction (article & interview)	No waste reduction strategies in place.	A dedicated person to find areas where waste is generated and actively trying to reduce waste	A dedicated department to find areas where waste is generated and actively trying to reduce waste. Has few processes to reduce waste.	Whole organization plans together to reduce waste and has established processes to reduce waste. They also have a KPI for waste reduction.
Product	**Design for Sustainability** (interview)	No consideration of sustainability while designing a product	Limited awareness of sustainability in design and has initial interest in exploring basic concepts	Sustainable aspects are integrated into design and products are designed for durability, repairability and use of sustainable materials. Established framework and processes in place to design products sustainability.	Products are designed with a focus on entire life cycle of product, Priority on resource efficiency, minimal environmental impact and end of life consideration. The whole organization is part of it and has established framework and processes in place to review the design.
	Second Life Products/Circularity (article & interview)	Has no knowledge, nor experience in remanufacturing .	Has the knowledge but has only started to get experience in remanufacturing. (0-3 years)	Has enough knowledge about circularity and has been doing remanufacturing for about 3-10 years.	Has good knowledge about circularity enabling materials and a facility to do remanufacturing activities. Have been doing remanufacturing for more than 10 years.
Carbon Footprint Calculation	**LCA (Life Cycle Assessment)** (article & interview)	No awareness or understanding of Life Cycle Assessment (LCA). No granularity details.	Basic understanding of LCA principles, but would use rough assumptions. Low level of granularity in the calculations.	Good understanding of LCA principles and uses industry wide accepted databases. Medium level of granularity in the calculations.	They get primary data from suppliers and actively refining their LCA methodology. High level of granularity in the calculations.
	Carbon Emissions (article & interview)	Limited understanding about emissions and just getting started. Actively looking to understand emissions sources.	Basic tracking of carbon emissions. Have calculated scope 1 emissions and working on Scope 2 & 3.	Good tracking and calculations has begun, general understanding of emission sources, but actively finding informations. Very good idea of Scope 1 and 2 emissions and learning about scope 3.	Rigorous carbon footprint analysis. And finding new ways to make data more accurate. Scope 1, 2 and 3 emissions are calculated
Inter-Organizational Relationship	**Knowledge and Training** (article)	No knowledge sharing or collaborations with other stakeholders	Limited or occasional knowledge sharing offered on sustainability to stakeholders	Comprehensive knowledge sharing and training programs offered on various sustainability topics OR actively collaborate with stakeholders	Stakeholders actively collaborates to develop joint knowledge-sharing initiatives and training programs for mutual benefit. Participate actively in knowledge sharing initiatives, for example joining associations
	Sustainability Standard (article & interview)	No established sustainability standards or guidelines shared with your organization.	Supplier has few established standards or certifications. For example ISO14001 or ISO50001	Supplier adheres to advanced industry-recognized sustainability standards or certifications. For example ISO14001 and ISO50001 and demonstrates continuous improvement efforts.	Supplier goes beyond industry, For example ISO14001, ISO50001 and more by implementing leading sustainability practices and pioneering innovative solutions.
	Transparency and Communication (interview)	Limited or no communication regarding sustainability efforts.	Minimal communication regarding sustainability efforts. Information might be available upon request.	Proactive and transparent communication regarding sustainability efforts. Regular reports and data on their environmental performance are readily available.	Exemplary transparency in communication. The supplier actively engages in open dialogue and shares detailed data on their entire sustainability journey, including challenges and successes.
	Influencing Suppliers	No initiative to influence lower suppliers	Has the power but not using it to influence the suppliers	Beginning to harness their power to influence their supply chain towards sustainability. They are actively setting expectations and starting to implement policies.	They have lot of power to influence the supply chain and using that power to push suppliers to be more sustainable

5 Discussions

In this section, the findings from the pilot study in the previous chapter that were collected and analyzed as per the scope of the thesis will be discussed along with the frame of reference. Firstly, the various decarbonization initiatives of the suppliers are discussed and compared to the literature that has been referred to in the frame of references. Secondly, the decarbonization measures in the literature is discussed along with the actual measures in the industry carried out by the OEM's suppliers from multiple tiers.

The electronics industry, despite its vital role in modern life, contributes significantly to greenhouse gas emissions. This stems from the energy-intensive processes involved in manufacturing and extracting raw materials, fabricating components, and assembling finished products. Additionally, the industry relies on specific materials, some with environmentally harmful extraction practices or short lifespans leading to increased waste.

Table 5.1: Topics that will be discussed in this chapter.

Discussion Point	Section
To what extent do suppliers comprehend the significance of decarbonization, and are their efforts aligned towards a common objective?	5.1
How are the challenges faced by these suppliers addressed in their decarbonization journey?	5.2
How does these suppliers manage and make sure about the sustainability practices of their multi-tier suppliers?	5.3
How will the maturity model help the OEM in understanding their suppliers decarbonization journey and make decisions accordingly?	5.4

5.1 Supplier Comprehension and Alignment on Decarbonization Objectives

All tier 1 suppliers involved in the interviews and pilot study have established their presence in the industry for a significant period and have set distinct sustainability goals for the future. The journey towards decarbonization in the industry has been embarked upon earlier by some suppliers than others. In the past, some suppliers engaged in Corporate Social Responsibility (CSR) activities, which have gradually evolved into sustainability initiatives over time. Interestingly, Supplier E, who began their decarbonization journey in 2002, is at the same level as Supplier G, who started their journey in 2014. The pace of achieving their goals varied among the suppliers.

As Wilhelm et al., 2016 pointed out, first-tier suppliers are the initiators of sustainability efforts in their supply chain, which they then extend to their multiple tiers of suppliers.

This observation is confirmed by the actions of the first-tier suppliers of the OEM, who, having been informed of the OEM's milestones, have begun their decarbonization processes and set their own goals in alignment with those of the OEM. Villena, 2019, noted that MNCs have begun to instill sustainability norms into their lower-tier suppliers. This is also evident in the case of the OEM, who, after addressing the emissions within their control, are now looking to extend their efforts to multiple tiers of their suppliers. Though this is true in the case of Supplier A there is a small gap, who are not completely transparent with their decarbonization journey which makes it difficult for the OEM to gauge the supplier's maturity.

All suppliers are cognizant of the impact of Scope 3 emissions in their supply chain and are keen to allocate resources to mitigate them, an opinion confirmed in the article by Booth et al., 2023 as it contributes to emissions the most in a supply chain. Some suppliers are currently in the process of quantifying their Scope 3 emissions, while others have already set milestones to reduce these emissions. Additionally, as mentioned by Huidobro et al. (2023), there is an escalating demand for Scope 3 reporting to enhance environmental practices. This trend is clearly reflected among suppliers, who are progressively aligning their operations with this future-oriented approach. With the introduction of these regulations, several suppliers have initiated the necessary calculations and are awaiting results. This will enable them to establish benchmarks for reducing Scope 1 and 2 emissions alongside Scope 3.

The industry's commitment to decarbonization is intensifying daily, with ongoing research into innovative methods to further this cause. This collective effort towards sustainable manufacturing practices is a sentiment shared by all stakeholders, as noted by Abdul-Rashid et al. (2017). This commitment was evident among the suppliers interviewed and those participating in the pilot study, all of whom have implemented initiatives to enhance sustainability. These initiatives include the use of renewable energy sources for production, the generation of their own renewable energy, the implementation of circular strategies, the usage of recycled materials in their products, the design of more sustainable products, and the recycling of water for production processes.

Certain suppliers have integrated circular strategies into their supply chains and have incorporated renewable energy into their operations. Those that produce in their own facilities, as well as a few that purchase renewable energy, have Power Purchase Agreements (PPAs) or Renewable Energy Certificates (RECs). By employing these strategies, they will be capable of utilizing renewable energy for most of their production. However, some suppliers, particularly those with production plants located in the eastern part of the world, do not have access to renewable energy. This challenge, emphasized in an article by Partridge (2013), sometimes necessitates reliance on PPAs.

5.2 Addressing Challenges in Suppliers' Decarbonization Journey

Some of the barriers for future decarbonization mentioned by these actors were that the process itself is expensive and trying to convince the customer that a full decarbonized supply chain would eventually affect them. This is true from the article Dolge & Blumberga, 2021, where they mention it is difficult to maintain a balance between economic growth and sustainability issues. Secondly, expediting the carbon capture and storage options were mentioned by a supplier. This is true as per the article by Iweh et al. (2021), where it is mentioned that as industries move towards a greener approach there should be more options for carbon capture and storage.

Furthermore, the transparency and collaboration between the stakeholders in the supply chain was highlighted to be a barrier to reach complete decarbonization. Hence, it is true that Mukherjee et al., (2022), highlights in the article that because of the non-transparency of information flow in the supply chain, there will be challenges in achieving decarbonization or circularity in the supply chain. The successful implementation of circularity also requires a robust and reliable flow of information among stakeholders. This remains a hurdle for some suppliers. The realization of such a system hinge on the cooperation and collaboration of all stakeholders involved.

As highlighted by Khiewnavawongsa & Schmidt, (2013), the lack of transparency and insufficient information sharing among suppliers presents a significant challenge. This issue is particularly prevalent when attempting to obtain information from lower-tier suppliers for data on carbon footprint calculations. One contributing factor is that many production sites are in countries where sustainability regulations and policies are either scarce or in their initial stages.

5.3 Managing Sustainability Practices of Multi-Tier Suppliers

Supply chain management is fundamental to relationship management, connecting numerous links across multiple tiers (Lambert and Enz, 2017; Jabbour et al., 2019). This interconnectedness requires suppliers to collaborate with various industries throughout the production process. Integrating sustainability and the decarbonization process necessitates coordination across these multiple tiers. However, focal companies often have limited direct authority over the sustainability practices of lower-tier suppliers (Hartmann and Moeller, 2014). Managing lower-tier suppliers presents distinct challenges due to limited visibility into their operations, as companies frequently lack direct engagement with these suppliers (Tse and Tan, 2011; Wilhelm et al., 2016). These statements reflect the actual situation suppliers face during their collaboration with lower-tier partners. Limited direct authority is one of the challenges that suppliers encounter when collaborating on decarbonization efforts, and it can also become a barrier to future decarbonization processes. Transparency is crucial to enabling suppliers to understand where they can contribute during collaboration. Without transparency, innovation and new ideas will be limited, which hampers progress in decarbonization initiatives.

Integrating and aligning sustainability efforts throughout all supply chain tiers is essential for mitigating and minimizing sustainability risks (Zissis et al., 2018). Effective integration and alignment are possible when lower-tier suppliers are aware of the decarbonization process. However, some suppliers have found that their lower-tier counterparts lack this awareness, which becomes a barrier before the process can even begin. Training, workshop or any other sharing knowledge are needed before the integrating and aligning process begins. This will help suppliers understand their lower-tier capabilities and identify suitable decarbonization processes for collaboration. Some suppliers have also mentioned the lack of standardization for CF calculations in the industry. This lack of standardization can hinder the integration of sustainability efforts, as different understandings and processes may render the calculations ineffective. For instance, data transparency is a significant challenge for CF calculation. When suppliers need specific data, lower-tier suppliers might find it difficult to share. However, if there is a standard for the calculation, suppliers will know the exact data required, and lower-tier suppliers might find it easier to share their data, as they will understand the standard practices for calculation.

First-tier suppliers serve as crucial intermediaries in promoting the adoption of sustainable practices across the entire supply chain, including lower tiers (Kähkönen et al., 2023). Suppliers recognize that achieving net zero emissions through their individual efforts alone is not feasible. They also recognize the pressing need for greater momentum throughout the supply chain towards achieving net zero emissions. The proactive efforts of first-tier suppliers are essential in raising awareness about the urgency of achieving net-zero emissions. Moreover, fostering knowledge sharing between first-tier and lower-tier suppliers can facilitate collaborative efforts and provide support for the development of decarbonization initiatives.

5.4 Supplier Decarbonization Unveiled - A Maturity Model Approach for OEMs

Becker (2009) describes methods for crafting maturity models, including literature review, expert interviews, and conceptual modeling. Consistent with these methodologies, this research engaged in interviews and discussions with suppliers. However, the interview process presented challenges, as some suppliers were hesitant or unwilling to share information. Supplementary data were gathered from secondary sources such as company websites. Despite these efforts, some questions might not be fully answered. The reluctance of suppliers to share decarbonization data may signify a lack of commitment to the OEM's decarbonization goals or the existence of strict internal regulations regarding data sharing. Therefore, OEMs need to carefully consider their collaboration choices, as support from suppliers is crucial for achieving better decarbonization results.

Review of Maturity Model for ECU and Semiconductor Suppliers

This maturity model represents the first step in the decarbonization effort to reduce emissions. It is designed to be as general as possible because the suppliers are not exclusively from ECU. Initially, semiconductor suppliers were included in the research, influencing the shaping of the maturity model so that suppliers beyond ECU can also relate to its competencies and elements. Additionally, it is essential to note that the maturity model should be as simple as possible. Schumacher et al. (2016) mentioned that simplifying models helps improve understanding and usability. This is crucial because, as the first step and version, this maturity model will be used not only by the team who designed it but also by other sustainability teams assessing the suppliers.

A review of the maturity model using data from ECU and Semiconductor suppliers is necessary to evaluate the generalization and simplicity of its dimensions and elements. Suppliers who will participate to this review sessions are ECU suppliers, Suppliers E and H, and Semiconductor suppliers, Supplier D. The data for the analysis are a mix of information from interviews, sustainability reports, and pilot sessions. This approach was necessary because some details were missing from the reports and were addressed in the pilot sessions. The maturity model analysis can be referred to in Table 5.2 below.

Table 5.2: Maturity model analysis for existing supplier.

Dimension	Elements	Supplier D	Supplier E	Supplier H
Production	Renewable Energy	Level 3	Level 2	Level 3
	Waste Reduction	Level 3	Level 3	Level 3
Product	Design for Sustainability	Level 2	Level 3	Level 3
	Second Life Products/Circularity	Level 1	Level 0	Level 3
Carbon Footprint Calculation	Life Cycle Assessment (LCA)	Level 3	Level 2	Level 2
	Carbon Emissions	Level 2	Level 3	Level 3
Inter-Organizational Relationship	Knowledge and Training	Level 1	Level 1	Level 1
	Sustainability Standard	Level 2	Level 2	Level 2
	Transparency and Communication	Level 1	Level 1	Level 1
	Influencing Suppliers	Level 2	Level 2	Level 2

Note: Supplier D is Semiconductor while Supplier E and H are ECU

Table 5.2 illustrates the different level of supplier maturity in the different elements. Each supplier has different or the same level for each element or dimensions. Below is an interpretation from the table:

- Production: All suppliers have achieved the highest level of maturity, Level 3, except for Supplier E in the *Renewable Energy* element. This is because Supplier E has shared only a few details across all sources, making some of the conclusions and judgments subjective.

- Product: The maturity levels for each supplier vary in this dimension. In the *Design for Sustainability* element, Supplier D has the lowest level, i.e., Level 2. This is because Supplier D only mentioned they do remanufacture without providing details about which parts are involved. For the *Second Life Products/Circularity* element, Supplier E is at Level 0. One of the reasons could be because they have not implemented a remanufacturing process based on the pilot results.

- Carbon Footprint Calculation: Supplier D has the highest maturity level in this dimension. For the *LCA* element, Supplier D has achieved Level 3 maturity because they have developed their own calculation tool, while others are still using external tools for calculation. For the *Carbon Emission* element, only Supplier D is at Level 2, as other suppliers have calculated Scope 3 emissions, but not validated the calculation outcome with Tier 2 supplier, whereas Supplier D has only just started calculating it.

- Inter-Organization Relationship: The average maturity level for each element in this dimension is between Beginning (Level 1) and Succeeding (Level 2). For the *Knowledge and Training* element, all suppliers are at Level 1 because they mention training but provide limited information about the content of the training. In the *Sustainability Standard* element, all suppliers are at Level 2 because they have achieved ISO 14001 and 50001 certifications and demonstrate continuous improvement, such as obtaining zero waste certification. Regarding the *Transparency and Communication* element, all suppliers are at Level 1 because their communication about sustainability data with stakeholders is minimal and requires more effort to encourage them to share more data. Finally, for *the Influencing Suppliers* element, all suppliers are at Level 2 because they have specific sustainability standards for their products that influence their supply chain to meet those requirements. This influence is more indirect, as they do not explicitly ask the supply chain to adopt sustainable practices, but the indirect pressure has led to greater sustainability than before.

6 Conclusions

The purpose of this thesis is to enhance the knowledge on the decarbonization journey of electronic component suppliers in automotive supply chains from a maturity perspective. To fulfill the purpose data was collected by interviewing the tier 1 and 2 suppliers in order to define the draft dimensions of the maturity model. After the initial interviews were conducted the draft dimensions were defined for the maturity assessment of tier 1 suppliers and then a pilot testing was done to validate these dimensions and the levels of maturity. This aided in refining of the model and elaborating the levels of maturities of the suppliers based on their decarbonization journey.

6.1 Managerial Implications

This research offers crucial insights for managers aiming to accelerate the decarbonization of supply chains. By assessing the GHG emissions and environmental disclosures of suppliers, managers can pinpoint areas for improvement and guide suppliers towards shared decarbonization goals. Specifically, OEMs can apply the maturity model to evaluate their suppliers' understanding and expertise in decarbonizing their supply chains to meet the OEM's. This evaluation can serve as a benchmark for suppliers with lower maturity levels, providing targeted support for those contributing substantially to environmental impact.

The maturity model also reveals the motivations and challenges suppliers face in implementing sustainable practices, allowing for the development of tailored strategies and measures to assist suppliers on their sustainability journey. OEMs can use this model to plan future procurement strategies based on supplier maturity. For example, they may choose to source key products from suppliers with higher maturity levels, strategically reducing the carbon footprint of their products and aligning with global sustainability efforts.

For suppliers, the use of the maturity model can also foster increased communication among them, as the process of assessing and improving maturity levels demands dialogue and collaboration. This interaction can lead to stronger relationships and open new paths for cooperation. A supplier with high maturity might share their best practices with a lower-maturity supplier, aiding their improvement. Alternatively, suppliers might collaborate on joint initiatives to further reduce carbon emissions.

By understanding each supplier's position in various dimensions using the maturity model, OEMs can assist those with lower ratings to improve, creating a mutually beneficial situation. This approach can potentially trigger a ripple effect within the supply chain. Suppliers who actively implement strong control measures, such as clear sustainability policies and targets, can influence the broader network's behavior. This cascading effect highlights the extensive impact that supplier actions can have on the complete environmental performance of the entire supply chain ecosystem. By cultivating a collaborative environment that encourages and enables suppliers to prioritize decarbonization, managers can significantly accelerate progress towards their sustainability objectives.

While the current maturity framework was developed specifically for this OEM suppliers, it is not necessarily applicable to other OEMs. However, this framework offers a valuable foundation. It can be adapted to suit the needs of different departments within the same company. By considering their specific priorities and what they expect from their suppliers in terms of maturity, these departments can modify the framework to create a more tailored assessment tool.

6.2 Limitations

This research acknowledges several limitations that arise from the chosen area of study and the selection of data sources. To begin with, the research is confined to the examination of ECUs and their related components, thus omitting other potential areas within the electronics domain. Furthermore, the suppliers who contributed to the research were selected based on their openness to reveal information, a factor that could potentially introduce bias and limit the generalizability of the findings. Lastly, the interviewees were internally selected by the suppliers, thus limiting the researcher's influence over the selection process, and possibly leaving certain queries unaddressed due to the specific job responsibilities of the respondents.

In the grand scheme of things, these limitations highlight the complex nature of research in the field of electronics, particularly when dealing with ECUs. This emphasizes the necessity for a careful and considered approach when selecting information sources and participants, and they serve as a reminder of the potential biases and gaps that can emerge in the research process. Despite these constraints, the study provides valuable insights into the realm of ECUs, paving the way for future research to build upon these findings and further our understanding of this complex field.

6.3 Future Research

While this research provides valuable insights into the decarbonization efforts of ECU suppliers, it also highlights certain limitations that pave the way for future research. The primary limitation is the study's focus on ECUs, which restricts the applicability of the findings to other tiers of suppliers. Future research could broaden this scope to include a more diverse range of electronics.

The maturity model developed for Tier 1 suppliers has proven effective in assessing their progress in the decarbonization process and the various influencing factors. This model could be extended to include higher-tier suppliers, depending on the specific products they provide to the OEM. Such an extension would provide a comprehensive overview of decarbonization efforts across multiple tiers, thereby assisting the OEM in achieving its carbon neutrality goals. It is critical to note that the current maturity assessment model focuses solely on the environmental aspect of the triple bottom line. However, it could be expanded to include other aspects of supplier operations, providing a more holistic perspective when evaluating supplier sustainability. This comprehensive view is crucial for understanding the overall environmental impact of the supply chain and for making informed decisions about future sustainability initiatives.

Future research could also benefit from engaging with a more diverse range of participants within supplier organizations. Instead of solely interviewing readily available individuals, a broader selection of personnel from various departments (e.g., procurement, engineering, finance) could provide a more comprehensive perspective. This wider range of viewpoints would offer a more nuanced understanding of both the strategies employed and the challenges encountered by suppliers in their decarbonization efforts. This approach would not only enrich the data but also provide a more robust foundation for developing effective strategies to accelerate the decarbonization process.

As the OEM continues to incorporate maturity assessments into their existing model, they can conduct a more in-depth analysis of supplier data. This deeper exploration could uncover additional critical dimensions and elements that could significantly influence the decarbonization journey of their suppliers. For example, the OEM could examine suppliers' operational efficiency, Supply chain mapping, availability of green source of energy, energy consumption patterns, waste management practices, and the granularity in the LCA conducted by the suppliers. These factors could provide a more comprehensive view of a supplier's environmental footprint and their commitment to sustainability.

By identifying these key dimensions and elements, the OEM could develop more targeted strategies and provide more effective support to their suppliers. This could not only help suppliers overcome barriers to decarbonization but also align their efforts more closely with the OEM's sustainability goals. Ultimately, this could lead to a more sustainable and decarbonized supply chain.

By addressing these limitations and expanding the scope of future research, a more comprehensive understanding of supplier decarbonization journeys can be achieved. This will ultimately inform more effective strategies for achieving sustainability goals within the supply chain, marking a significant step forward in our collective pursuit of a more sustainable future.

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Appendix A

1. What are the decarbonization process' that has been implemented for your products?
2. Do your major suppliers have decarbonization milestones and do you push for sustainable solutions from your suppliers? Please share an example if possible.
3. Can you share any success stories or lessons from your efforts to reduce emissions?
4. How are the emission/footprint calculations done?
5. What role does product design play in reducing emissions?
6. What are your future decarbonization plans and have you also set targets for your suppliers?
7. Do you have experience with any reapplication or second-life initiatives for your products?
8. When did your company start paying attention to decarbonization? What was the trigger?
9. What were the challenges when decarbonization started to be implemented? How did you address these challenges?
10. What are the current challenges to implement decarbonization? How do you address the challenges? What are your plans to address the challenges?
11. What are the challenges that remain the same from then to now?
12. Can you share how you overcame a challenge which was hard but was resolved?

Appendix B

Question Form

Thank you sincerely for taking the time to fill out this questionnaire. We are students from Chalmers University of Technology, and we are doing our master's thesis on the topic of Sustainable electronics in the supply chain in collaboration with OEMs. This questionnaire is designed to be quick and easy, taking less than 10 minutes of your time. All the data shared with us will be anonymized and will be used solely for research purposes. We appreciate your participation and thank you in advance for your time and input.

Introduction

1. Which organization do you represent?

   ____

Decarbonization Journey

2. When did your company start paying attention to decarbonization?

   Year:_________

3. Does your company have a set target for reducing greenhouse gas (GHG) emissions by a specific year?

   ○ Yes *(if yes, will continue to '4',if not jump to 5)*

   ○ No

4. If yes, please specify

   Year:_________

5. On average, what percentage of your decarbonization strategies have been achieved?

   ○ 0-15%

   ○ 16-30%

   ○ 31%-45%

   ○ 46-60%

   ○ 61%-75%

   ○ 76-91%

   ○ Others:_____

6. Which of the following decarbonization strategies have you implemented in your products? *(Select all that apply)*

□ Low-carbon materials and components

□ Energy-efficient manufacturing processes

□ Renewable energy sources for production

□ Design for disassembly and remanufacture

□ Carbon Offsetting

□ REC (Renewable Energy Certificate)

□ PPA (Power Purchase Agreement)

□ Energy Management System (ISO50001)

□ On-site renewable energy production

□ Eco-Design practices

□ Gas Abatement of f-gasses

□ Water recycling

□ All of the above

□ Other: ___________

7. Which program does your company utilize to promote the second-life use of your products? *(Select all that apply)*

□ Reduce

□ Repair

□ Refurbish

□ Remanufacture

□ Repurpose

□ Recycle

□ Recover

□ Not doing it yet

8. What Life Cycle Assessment (LCA) tool do you use? *(Select all that apply)*

□ SimaPro

□ Sphera's LCA / GaBi

□ Online tool (e.g: CO2 AI)

□ Own customized tool

□ Other:______

9. What database do you use to calculate product carbon footprint?

□ Ecoinvent

□ CatenaX

□ Sphera / GaBi

□ Others:_____

10. Do you get enough information from your suppliers for the Product Carbon Footprint (PCF) calculation?

○ Yes

○ No

11. What percentage of supplier data do you use in your calculation?

____

12. In which countries are your manufacturing facilities located?

____

13. Do you have on-site renewable energy production?

○ Yes *(if yes, will continue to '13',if not jump to 14)*

○ No

14. Please specify what kind of renewable energy is produced.

____

15. What sources of electricity for your production are purchased? *(Select all that apply)*

□ Coal

□ Natural Gas

□ Solar

□ Wind

□ Hydropower

□ Nuclear

□ Other: ________________

16. Please share the percentage of these sources.

(e.g: 40% on-site renewable energy, 50% coal purchased and 10% wind purchased)

____

17. In your opinion, what are the most crucial actions needed to accelerate decarbonization in the electronics industry as a whole?

____

18. Would you be willing to share any best practices or lessons learned from your company's decarbonization journey that could benefit other industry players?

____

How much do you agree or disagree with the statements

19. Product design significantly influences the overall carbon footprint of your products

(1 - Strongly Disagree, 2 - Disagree, 3 - Neutral,, 4 - Agree 5 - Strongly Agree)

20. Satisfied with the current progress my company has made on decarbonization efforts

(1 - Strongly Disagree, 2 - Disagree, 3 - Neutral,, 4 - Agree 5 - Strongly Agree)

21. Confident that your company will achieve its decarbonization goals by the target date

(1 - Strongly Disagree, 2 - Disagree, 3 - Neutral,, 4 - Agree 5 - Strongly Agree)

Challenges

22. What are the biggest challenges your company faces when collaborating with suppliers on decarbonization efforts? *(Select all that apply)*

□ Availability of data from suppliers

□ Awareness of decarbonization among suppliers

□ Missing standard for Carbon Footprint calculation

□ Others:_______

23. Do you foresee any other potential barriers to achieving future decarbonization goals?

○ Yes *(if yes, will continue to '24',if not jump to 25)*

○ No

24. If yes, what are those potential barriers to achieving future decarbonization?

25. Based on your own assessment, to what extent do you capture the carbon footprint across your entire supply chain? (1 being 10% (just your own operation) - 10 being 100% (the entire supply chain)

Product

26. Which one is your product?

○ ECU

○ Semiconductors

Semiconductor

27. What are the actions taken by your organization to control f-gasses?

____

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