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Decarbonization of manufacturing at Volvo GTO

Master's thesis in Industrial Ecology

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Cover:

Trucks of Volvo Group

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ABSTRACT

Volvo Group Trucks Operations is the industrial entity within Volvo Group responsible for truck manufacturing with 40 facilities under management. The organization's operations span across the globe contributing to carbon emissions and therefore, to climate change. Climate change has and will alter our surroundings by imposing climate patterns such as extreme weather events that put pressure on the survival of humans and our economic system. In response to this, there is an increased demand for a better commitment to environmental practices, including from companies such as Volvo Group. This study aims to contribute to lowering the environmental impact of Volvo GTO by providing a feasibility assessment for the implementation of distinct solutions of decarbonization strategies. For this, a literature review of current methods and practices that aim toward carbon reduction in manufacturing was performed. In addition, several interviews with Volvo GTO employees, as well as external experts, were conducted. Based on the data collected, a decarbonization framework was elaborated containing six strategic areas that are considered key in tackling carbon emissions: Fuel shift; structural change (electrification); carbon capture; process efficiency; technological replacement; and circularity. Each strategy includes multiple solutions that are assessed regarding their feasibility potential using a SWOT analysis. The study concludes that decarbonization at the facility level is achieved through multiple strategies and solutions that must be placed in the context of the local community to help the transition toward a more sustainable society.

Keywords: Decarbonization, sustainability, automotive industry, manufacturing, renewable energy.

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Lucas Albuquerque Wolf & Andreas Serino Olander, June 2022

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List of abbreviations

BEV (Battery electric vehicles)

CCS (Carbon capture and storage)

CCU (Carbon capture and utilization)

CHP (Combined heat and power)

CIF (Coreless induction furnace)

CVA (Cabs and vehicles assembly)

DAC (Direct air capture)

GHG (Greenhouse gas)

GTO (Group trucks operations)

HTC bio-coke (Hydrothermal carbonized)

HVO (Hydrogenated vegetable oils)

IPCC (Intergovernmental Panel on climate change)

LPG (Liquified petroleum gas)

PV (Photovoltaic)

NRV (New River Valley)

RECS (Renewable energy certificates)

SWOT (Strengths, weaknesses, opportunities, threats)

VOC (Volatile organic compound

1 Introduction

This chapter provides background, aim, limitations, and information on the studied Volvo GTO (Group Trucks Operations) facilities. Moreover, it gives an overview of the subject matter and its relevance.

1.1 Background

The following statement was announced by the United Nations Environment Program: "There is a fifty-fifty chance that global warming will exceed 1.5°C in the next two decades, and unless there are immediate, rapid, and largescale reductions in Greenhouse gas (GHG) emissions, limiting warming to 1.5°C or even 2°C by the end of the century will be beyond reach" (United Nations Environment Programme, 2021). Climate change has and will alter our surroundings by imposing climate patterns such as extreme weather events that put pressure on the survival of humans and our economic system. In response to this, many countries and unions around the world are increasingly demanding a better commitment to environmental practices. For instance, policies such as the *European Green Deal* provide a vision for the European Union's member states on how to help Europe transition into a climate-neutral continent. This policy stands for reducing carbon emissions and establishing a circular economy while enhancing the competitive capabilities on a global scale. Other plans that will help the EU transition to carbon neutrality are the Circular Economy *Action Plan*, the *Strategy for Sustainable and Smart Mobility,* and the *Alternative Fuels Directive* (D. Brown et al., 2021).

Sweden is currently on track to meet its environmental targets. Moreover, its progress toward achieving carbon neutrality before 2045 is greater than expected and the cost of implementing fossil-free alternatives is decreasing at a fast rate. For the manufacturing sector, the change consists predominantly of a substantial decrease in production emissions and the procurement of low carbon-intensive materials. The overarching goal of the industry is to lower the emissions of the entire supply chain (The Swedish environmental protection agency, 2022). Regarding the companies within the Swedish industrial sector, Volvo Group is a large company that offers a broad variety of products stretching from trucks to financing and services. Volvo Group has activities on all continents with production in 19 countries and 190 markets. In addition to this, the company has a portfolio that encompasses brands such as Volvo, Volvo Penta, Rokbak, Renault trucks, Prevost, Novabus, Dongfeng trucks, and more. Figure 1 depicts Volvo Group's society commitment goals. It shows that the company includes several focus areas to contribute to a sustainable future, such as transitioning toward fossil-free transport solutions, reducing the environmental footprint, and a step change in circularity.

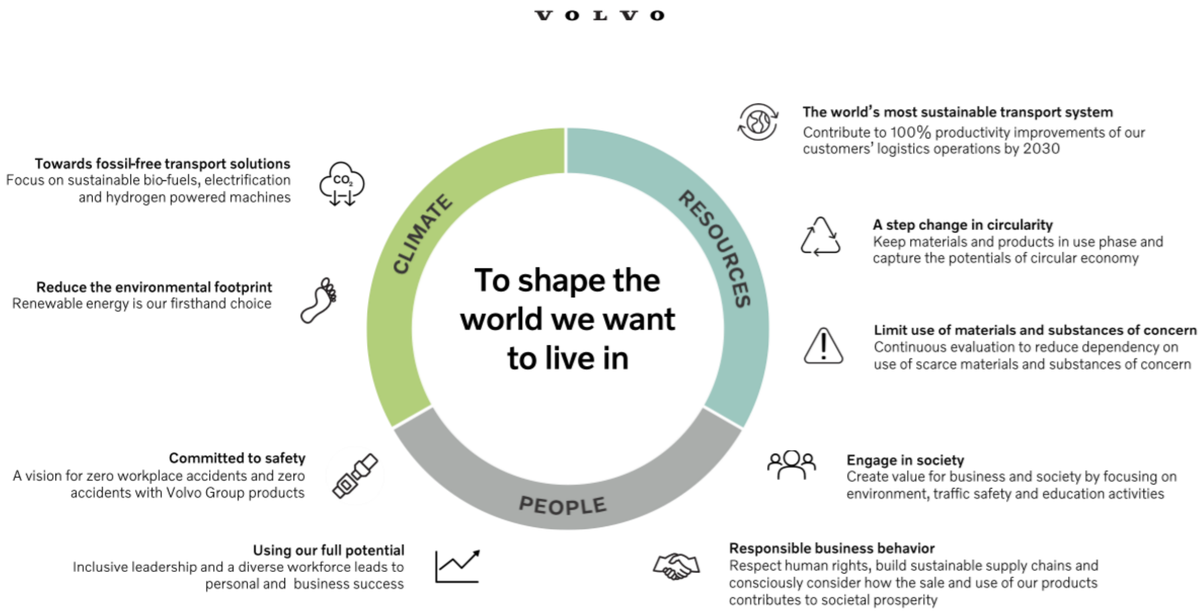

Figure 1. Volvo sustainability framework

Volvo GTO is the industrial entity within Volvo Group responsible for truck manufacturing with 40 plants under management. This includes powertrain production, remanufacturing, cab and vehicle assembly, logistics services, and parts distribution. Volvo GTO's strategy is stated as follows: "Our strategy shows our contribution to the society, to the Volvo Group's strategic direction and priorities, and the part we play to shape the world we want to live in". The strategic direction recognizes that there are certain challenges when dealing with climate and resources, more specifically reducing the CO_2 emissions, and increasing circularity in their operations.

There are several ways to approach the reduction of CO_2 emissions. One of them is decarbonization. The term is used in various manners and can represent slightly different implications depending on the addressed topic. However, the most used term by organizations worldwide is the definition developed by the Intergovernmental Panel on climate change (IPCC) which is the following: "Decarbonization is the process by which countries or other entities aim to achieve a low carbon economy, or by which individuals aim to reduce their consumption of carbon" (Doleski et al., 2022). Decarbonization is also a matter of remaining competitive in a rapidly changing market as is the case for the automotive industry (Giampieri et al., 2020). Volvo GTO has established environmental targets that stretch toward 2025 which include carbon emissions reduction of 30% while increasing the share of renewable energy usage by 75%. Therefore, it is of interest for both the company and the global community to determine the feasibility of decarbonization in the manufacturing operations at Volvo GTO.

1.2 Aim and objectives

This study aims to contribute to lowering the environmental impact of Volvo GTO by providing a feasibility assessment for the implementation of distinct solutions of decarbonization strategies, elaborated under a developed framework. To support the aim, the following research questions should be answered:

1. *What recurring decarbonization strategies and solutions are being considered for the industry according to the literature?*

This research question will help provide an overview of decarbonization strategies and solutions that are currently being considered and implemented across various industries.

2. *How are these strategies applied and how can they be grouped in a new framework to make them applicable for Volvo GTO?*

This second research question will help understand how the decarbonization strategies are implemented and provide preconditions for creating a framework that can be applied to Volvo GTO.

3. *What is the feasibility of the identified decarbonization solutions based on their strengths, weaknesses, opportunities, and threats?*

This research question will help determine the feasibility of the identified decarbonization solutions and deliver to what extent they can be implemented from a SWOT perspective.

1.3 Limitations

The greatest opportunity for change within the GTO is found in the facilities that contribute to the largest emissions. Therefore, the study covers the facilities with the highest emission rates, starting with 1200 tons of CO_2 emissions in 2021 as a baseline. This covers 13 plants across multiple countries. Moreover, this work approaches decarbonization from a carbon dioxide emissions perspective. Methane emissions, for instance, are generally considered part of the decarbonization strategy. In the case of Volvo GTO, emissions of this gas are minimal and have therefore been left out. Nevertheless, this study acknowledges that CO_2 decarbonization strategies can also impact all sorts of GHG emissions.

To enable Volvo GTO to use this study as a guidance tool for future decarbonization decisions, preference is given to the general feasibility of solutions, rather than specific technical and engineering considerations that are required to accommodate the implementations. This is because each solution deserves in-depth investigation on its own and the results of the study provide information based on the data collected within limited time scope.

Most emissions in the lifetime of vehicles are Scope 3 emissions (indirect emissions that are outside the companies' direct control such as the CO_2 footprint of purchased products). However, Scope 1 emissions (Direct emissions arising from company-owned/controlled sources) and Scope 2 emissions (Indirect emissions arising from heating, cooling, and purchased electricity) are the ones that Volvo has a direct impact on. A lot of investments are ongoing to reduce emissions in the use phase, but it is also important to look at what can be done to reduce Volvo GTO's direct emissions. This means that

Scope 1 and 2 emissions are the most relevant ones to examine when it comes to Volvo GTO's direct influence. These scopes include emissions from internal logistics but not the ones from outbound logistics. Lastly, is worth noting that certain decarbonization strategies can impact Scope 3 emissions, both positively and negatively. If a more efficient solution is implemented, for instance, it may create a need for specific materials that may have a larger footprint. These implications will not be accounted for.

1.4 Facilities Overview

Table 1 gives an overview of how the different facilities can be categorized according to their functions and manufacturing operations. One can extrapolate a solution based on a specific facility to others that share the same activities. For instance, a solution identified for assembly in Curitiba could apply to assembly in Bourg En Bresse. Even if the regional differences are significant, some activities might not vary considerably across locations.

Table 1. Broad classification of selected Volvo GTO facilities.

Operation	Manufacturing operations	Location
Cabs and Vehicles Assembly	Assembly	Wacol, Australia Lehigh Valley, USA Bourg En Bresse, France
	Assembly + Welding & painting	Curitiba Brazil New River Valley, USA
	Stamping + Welding & painting	Umeå, Sweden
Powertrain	Assembly	Vénissieux, France
	Assembly + Machining	Köping, Sweden St. Priest Axle, France Hagerstown, USA Curitiba Engine, Brazil
	Assembly + Machining + Foundry	Skövde, Sweden
Warehouse	-	Lyon, France

Figure 2 brings the facilities into perspective when it comes to Scope 1 and Scope 2 emissions. Moreover, it also shows where these emissions arise from. One can see, for instance, that most of the Skövde facility's emissions are attributed to coke combustion and that natural gas is a widely used fuel in most of the facilities. Multiple facilities offset their purchased electricity emissions. Therefore, electricity-related emissions do not appear in all locations.

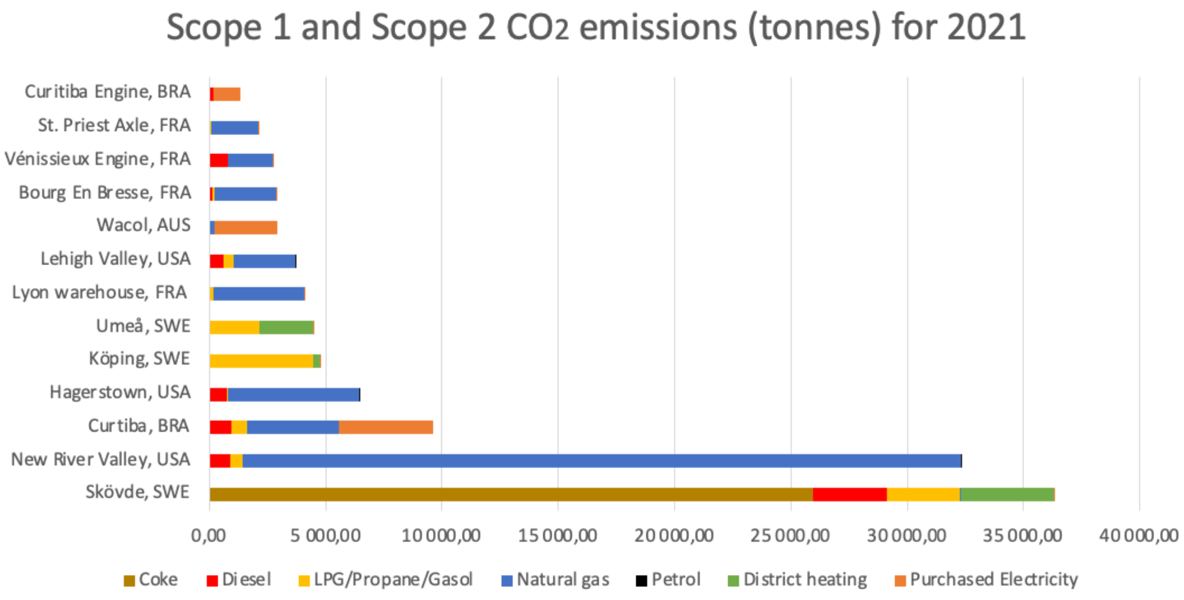

Figure 2. Scope 1 and scope 2 emissions for selected facilities in 2021

Table 2 provides information about the facilities that are used as the study object in this project. They are listed in descending order of emissions. In the right column, a brief energy profile for each plant is also provided. This information helps to put the results in perspective.

Table 2. Facilities overview and energy profiles

Facility	Energy profile
Skövde – The Skövde engine factory is part of powertrain production in Sweden. With 2800 employees, engines are manufactured with a production capacity of 155 thousand engines per year. The main activities are assembly, machining, and foundry. The foundry process produces iron castings for cylinder heads, flywheels, cylinder blocks, and other engine components.	District heating is used for heating and cooling while coke and Liquified petroleum gas (LPG) are used for production. Diesel is used both for internal logistics and product testing while biodiesel is used for product testing. The electricity is 100% renewable and has marginal CO_2 emissions. 80% of it is used for production, 15% for heating and cooling purposes, 4% for product testing, and the rest is used in other internal processes.
New River Valley (NRV) – This plant is in the state of Virginia, USA. It has 2975 employees and covers approximately 230 Ha. It is a CVA (Cabs and vehicle assembly) plant where Volvo trucks and multibrand cabs are produced. The main activities are assembly, welding and painting. Due to its energy efficiency improvements, it has earned the U.S. Department of Energy's Superior Energy Performance Platinum certification.	About 30% of the natural gas is used for heating and cooling while 70% is used for production. Diesel is mostly used for internal transport. LPG is used in heating and cooling and for some process purposes. When it comes to electricity, 100% of it is renewable. 76% of it is used for production, 22% for heating and cooling, and the rest is used for internal transport.

Curitiba – This plant is in Paraná, state of Brazil. It is a CVA plant that assembles Volvo trucks and cabs. In addition to assembly, welding and painting processes also take place there. With 1350 employees, the production capacity is about 30 thousand cabins, 30 thousand complete trucks, and 4000 bus chassis a year.	Electricity and natural gas are used for production while diesel is used for product testing. The majority of LPG is used for internal transport and the rest is used for production, heating, and cooling. 89 % of the electricity is used for production, 6 % for product testing, 3% for internal transport, and 1 % for heating and cooling.
Hagerstown – The Hagerstown facility is in the state of Maryland, USA. It is part of powertrain production where both engines and transmission equipment are produced. The main processes that take place are machining and assembly. 1300 employees work at the plant.	Most of the natural gas is used for heating and cooling while a smaller amount is used for production. LPG is used for internal transport and diesel is used for product testing. 100% of the electricity is renewable. 45% of it is used for production, 42% for heating and cooling, 12 % for product testing, and the rest is used for internal transport.
Köping – This plant is located in Sweden, and it is part of powertrain production. Transmission products such as gearboxes and marine drives are manufactured here by 1650 employees. The main processes are machining and assembly.	At the Köping site, LPG is used for production and district heating is used for heating. Diesel is used for internal transport. Electricity is 100% renewable. 91% of it is used in production, 8% is used for heating and cooling and the rest is used for internal transport.
Umeå – The Umeå factory is in Sweden and has approximately 1450 employees. It is part of CVA and it produces 75 thousand Volvo cabs per year. The main processes are stamping, welding, and painting.	Approximately 54% of the district heating is used for heating and cooling while the remaining is used for production. LPG is used for production and HVO (Hydrogenated vegetable oil) is used for internal transport. Electricity is 100% renewable. 81% of it is used for production, 17% for heating and cooling, and the rest is used for internal transport.
Lyon CDL warehouse – The Lyon CDL warehouse is positioned in France and supplies several facilities both outside and inside the GTO organization.	At the warehouse, natural gas is used for cooling and heating and LPG is used for internal transport. All electricity is renewable. 80% of it is used for heating and cooling, 16% for processes and 4% is used for internal logistics.
Lehigh Valley – The Lehigh Valley plant is located in the state of Pennsylvania, USA and has 2100 employees for assembly of Mack trucks and cabs. The facility covers 12 Ha. Due to its energy efficiency improvements, it has earned the U.S. Department of Energy's Superior Energy Performance Platinum certification in the Mature Energy Pathway.	At the Lehigh Valley site, natural gas is used for heating and cooling. Diesel is used for production and internal transport. LPG and Petrol are used for internal logistics. The electricity used is 100% renewable. 49% of it is used for heating and cooling, 44% for production and 6% is used for internal transport.

Wacol – The Wacol plant, in Australia, has 600 employees. It is part of CVA and assembles both trucks and cabs of multiple brands.	Natural gas and diesel are used for production. Electricity is not renewable, and it is mostly used for processes and a smaller share is used for internal transport.
Bourg En Bresse – The facility is in eastern France, northwest of Lyon in the province of Bresse. It is a CVA facility that assembles Renault trucks. With 1450 employees and an area of 129 Ha, the plant has a designed capacity of producing 31,400 trucks/year.	Natural gas is used for heating and cooling, LPG is for internal logistics and diesel is used for engine testing. Electricity is 100% renewable. 50 % of it is used for heating and cooling, 43 % for production, 4 % for transport and 1% is used for product testing.
St. Priest Axle – St. Priest axel is currently part of CVA. However, there are plans for categorizing it as powertrain due to the activities of machining & assembly. This plant produces axels. The building it operates in is old.	72 % of the natural gas is used for cooling and heating. Both LPG and diesel are used for production. The electricity used is all renewable and around 61% of it is used for heating and cooling, 36% is used for production and 3 % is used for internal transport.
Curitiba Engine – Curitiba engine is part of Powertrain production and produces both engines and transmission equipment. Main processes that take place are machining and assembly. There are 350 employees working with cylinder block machining, engine, transmission assembly, gearbox installation and remanufacturing.	Most of the electricity is used for production and a smaller share is used for product testing. Diesel is used for product testing and LPG is used for internal transport. 87% of electricity is used for production, 12% for product testing, and 1% is used for internal transport.

2 Methodology

This study followed a case study approach in which selected scientific literature was reviewed and used as a reference point for interpreting the collected data. To answer the aim, three research questions were formulated as shown in Figure 3.

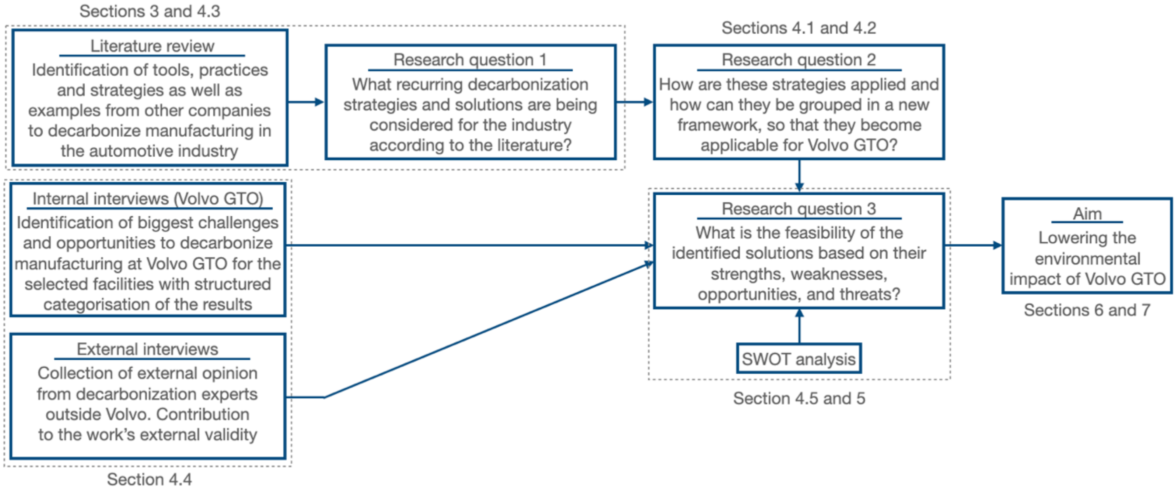

Figure 3. Methodological approach

To answer the first research question, a literature review was conducted so that solutions and practices contributing to decarbonization were identified. Moreover, an investigation was conducted to identify decarbonization practices within the automotive industry. This was done by reviewing other companies in the sector.

Decarbonization contains a wide variety of solutions that can be applied in manufacturing operations. To structure these solutions and answer the second research question of this study, a framework was elaborated. For that purpose, eight frameworks identified in the literature that address decarbonization in multiple industries were studied and compared. This allowed for identification of recurring strategies and solutions and finally, the development of a new and automotive specific framework. This framework was then related to Volvo GTO's sustainability strategies and analyzed in relation the various automotive companies.

To answer the third research question, the main challenges, and opportunities that Volvo GTO faces in decarbonizing its manufacturing activities were identified. For this purpose, interviews were conducted with both Volvo employees and external experts using Zoom and Teams video calls. In addition, Volvo-specific data was collected from the company's online platform. The interviews contributed to the identification of new decarbonization solutions in addition to those found in the literature. The most recurring decarbonization solutions in the interviews and literature were prioritized and their feasibility was assessed by utilizing the SWOT analysis methodology. This contributed to formulate some recommendations for Volvo GTO. Finally, the results of the study were discussed, and a conclusion was presented with the aim of contributing to decrease the environmental impact of the Volvo GTO.

2.1 Literature study method

The literature review was ongoing during all stages of the project. Most of the literature was sourced from ScienceDirect and Google scholar. In addition, reports from international organizations such as the IEA (International Energy Agency) were included in the study. Different keywords and searches were used to identify the most recent literature available. Some examples of keywords used in the literature study were: *Fossil-free production; Automotive industry; Manufacturing decarbonization; Low carbon manufacturing; Carbon neutrality in the industry; Green manufacturing; Renewable energy; Sourcing of renewable energy; Energy efficient production; Automotive manufacturing; Foundry; Biogas; Bio-coke*. Searches were combined, the following is an example of a search strategy that was used by combining different keywords: *(Decarbonization OR carbon-neutral OR fossil-free) AND (manufacturing OR production) AND Industry.*

2.2 Case study methodology

A case study methodology is a useful tool for studying a contemporary real-world occurrence while considering its conceptual surroundings. It considers previous research theories while including data from separate and multiple points of view (Yin, 2018). The author lists several components that need to be considered when developing research methodology which are presented below:

1. *Research questions:* Formulate research questions that starts with words such as “Who”, “What”, “Why” and “Where”. Using these formulations strengthens the overall *external validity* of the study.
2. *The proposition of the study:* In addition to the formulated research question, a proposition or a formulation that guides the research in a certain direction is advised to be included.
3. *The case at hand:* There is a risk that the studied case becomes too broad. Therefore, generalized research questions and aims are to be avoided. Different types of boundaries (Temporal, Spatial and things that are not being considered) are important to establish to enable a more precise case.
4. *Connecting the data to the proposition of the study:* Choose a relevant tool for processing the data that is well in line with the proposition of the study.
5. *Establishing criteria for evaluating the findings:* Establishing a structure for handling findings that diverge and stand out from most of the findings.

The research questions of this study were formulated following Yin’s (2018) approach. What Yin (2018) calls the proposition of the study was framed as the project’s aim. To define the case at hand, limitations were established to restrict the scope of the project. Finally, to connect the data to the study proposal and to evaluate the findings, a SWOT analysis was selected as the most suitable tool.

2.3 Quality of research

According to Yin (2018), the quality of a conducted research can be tested by employing four distinct aspects. These are: Construct validity, internal validity, external validity, and reliability.

Construct validity

There are certain measures that can be employed to avoid subjectivity in a case study. For example, multiple sources of evidence help to strengthen the validity of the study Yin (2018). In the study, multiple literature sources were reviewed. For developing a framework that establishes an optimal pathway toward decarbonization at Volvo GTO, eight different frameworks were analyzed and documented in a table, which included direct observations of their content. Other sources employed were archival records from Volvo Group.

Interviews play a major part in the methodology of a case study. More specifically interviews that have a conversation-based format with a red line that reflects the research data collection. In other words, open-ended interviews (Yin, 2018). For this study, semi-structured interviews were conducted, including some more generic questions giving space for open discussions. In this manner, aspects related to research questions could be answered while new insights could be brought up by the interviewees. When conducting the interviews, an effort was put to select the greatest number of interviewees ranging from different areas. A total number of 17 persons have been interviewed. Moreover, all the interviews were recorded and transcribed for inspection and review.

Internal validity

Thematic analysis is a way to structure qualitative data. This method can be broken down into four distinct steps according to Miller and Parsons (2020). First, understand and review the data and secondly group the data by theme. The third stage is to review the different themes and see which ones can be further aggregated. The last step is to understand how the themes are connected to each other (Miller & Parsons, 2020). When structuring the interview's content, the first step was to review all the recorded interviews and manually transcribe the answers. At this stage, the following issues were identified:

- Many interviewees had several responsibilities that were not limited to a single facility.
- Several interviewees had knowledge that extended beyond their current employment titles.
- Answers were often not facility specific.
- Most of the environmental managers who were interviewed had connections to the GTO environmental community, which made their perspective more holistic.
- Multiple emission challenges had the same problem source.

Then, using the comment function in Microsoft Word, the themes were assigned to different transcribed sections. The selected themes were decided to be based on production and functional areas. This enabled the interviewee's answers to be contextualized. Specific explanations of technological or technical functions were excluded for not being relevant to the aim of the study. Answers based on solutions and methods for CO_2 reduction were prioritized. Lastly, different themes were brought together under the SWOT analysis.

External validity and reliability

The quality of research can also be increased through external validity, which means that the logic behind it is replicable in other cases. In other words, the study's findings should be generalizable beyond itself (Yin, 2018). To make the study more easily applicable to changing variables and thus useful in future scenarios, a framework was created that is collectively exhaustive for decarbonization solutions.

According to Yin (2018), there are several ways to increase the reliability of the study. One way to do this is to keep track of the data collected. Notes taken during data collection should be systematized in way that makes them accessible to interested parties. In this study, a case study protocol was employed to categorize different findings and make them easily accessible in a table, thus creating a chain of evidence. For instance, a table was used to organize the interviewees, which made it easier to keep track of them. In addition, all interviews were saved and stored.

2.4 SWOT analysis

SWOT is a well know and widely used decision making tool for analyzing business environments where it enables the identification of factors that influences companies' strategic capabilities. It can be regarded as a holistic tool due to its consideration of both external and internal factors. The internal factors are classified as strength (S) and weakness (W). On the other hand, the external factors i.e., factors with external origin attributed to the environment are classified as opportunities (O) and threats (T). One must care for some limitations regarding the use of the SWOT methodology. Certain factors can be more defined than others, unmotivated prioritization can occur and lastly, biases can influence the previous mentioned limitations. There are, however, certain measures that can be taken for improving the quality of the SWOT analysis such as incorporating probability and impact dimensions or incorporating the significance of each factor (Pickton & Wright, 1998). In the SWOT analysis performed in this study, the results were ultimately given a score to highlight their feasibility which translates into their significance as decarbonization solutions. The results ranged from not feasible to highly feasible.

2.5 Process for structuring the Interview questions

For this project, the development of the interviews followed two different approaches. As previously mentioned, a semi-structured format was chosen as the primary interviewing method, which was used with Volvo employees. With industry experts, the interviews did not follow a structured format. However, they were all asked the following question: "Can you tell us about how decarbonization has been achieved in the industry, more specifically in the manufacturing/automotive manufacturing sector?". This question gave the interviewed expert the possibility to emphasize what they thought was important and gave space for a more open discussion.

Regarding the semi-structured interviews, the questionnaire was framed in five question areas: Introductory questions, Volvo specific questions, SWOT related questions, framework related questions and finishing questions. The questions were introduced firsthand at the interviews. To start, the introductory questions were selected to understand what role the interviewee had in the company and to get an insight in what projects the person had worked with and was currently working on. The

Volvo specific questions were developed with the reviewed emission data from several facilities in mind. With these questions, the goal was to give the interviewed person a possibility to frame the emission problem and explain what type of measures had been taken or was going to be taken to decarbonize the facilities. The SWOT based questions were developed with emphasis on the aim of the study and were used as a tool to conceptualize the different decarbonization measures in context both within and outside of the boundaries of Volvo GTO. Regarding the framework specific questions, they were prepared to assist and act as a way for examining a certain pathway if the interviewed person seemed to have specific knowledge. The finishing questions were used to conclude the interview. The last question was included to engage and give the interviewee an opportunity to include missing points. Table 3 summarizes all questions.

Table 3. Questionnaire for Volvo employees.

Volvo interviewees questionnaire	
Introductory questions	
1	Could you please tell me about yourself, your role in the company and which manufacturing facilities do you work with?
2	Are you currently working on any sustainability related project toward decarbonization?
3	What are your thoughts on Volvo's progress to decrease CO_2 emissions?
Volvo specific questions	
4	What do you feel is the most important decarbonization issue to address at Volvo GTO?
5	Most of your CO_2 emissions come from these sources [<u>list emission sources collected from Volvo's databank</u>]. What are the processes contributing to them?
6	What measures is Volvo taking for decarbonizing manufacturing? What sort of actions are required to reach the targets?
SWOT related questions	
8	Within Volvo GTO's industrial facilities that you work with, what do you think are the main challenges and opportunities to achieve the emissions targets in manufacturing? In other words, what internal aspects do you think put Volvo GTO ahead or behind toward achieving its goals?
9	Outside the company boundaries, many things are happening and evolving. We live in a well-connected world with complex interactions. Regarding these, what do you think are the main opportunities and what are the challenges for the facilities to decarbonize their manufacturing?
Framework questions	
11	You seem to know a lot about [<u>replace by specific strategies from the newly developed framework</u>]. Could you tell us a bit more about how that can translate to the goal of reducing carbon emissions?
Finishing questions	
13	Regarding your answers to the previous questions, what do you think are more urgent issues?
14	How do you think the manufacturing of electric vehicles will alter carbon emissions? Will it require changes in the manufacturing? If so, what changes?
15	Are there further issues you want to discuss that you feel we have missed?

3. Literature review

In this section, firstly, the concept of decarbonization is contextualized. Following, a review about different decarbonization frameworks is presented and several solutions that can contribute to reducing carbon emissions are investigated. This includes energy system, manufacturing processes and carbon capture solutions.

3.1 Decarbonization

Industrial GHG emissions have decreased more than almost any other sector since 1990 according to the IPCC database. Nevertheless, industry still accounted for almost one fifth of emissions in 2014. To stay in line within the 1.5°C target, the global industry market must decrease its carbon emissions within a range of 50% to 93% before reaching 2050 in comparison to the emission quota of 2010 (European Environment Agency, 2016). Today, decarbonization is a megatrend that has been progressively pushing its way onto the political agenda and that has been assumed to be “The largest transformation project of this century“ (Doleski et al., 2022).

Electric solutions increase the energy demand in the supply chain. When compared to a conventional combustion engine, the manufacturing of an all-electric vehicle is more CO_2 intensive. The reason for that is mainly the lithium-ion batteries, which require a lot of energy in their production process (Automotive World, 2020). Eliminating activities that generate emissions and minimizing resource demand are the most straightforward of the solutions to bring down emissions. However, there are other ways of doing so without changing the production volume. When talking about carbon reduction, multiple technologies are available or under development (Doleski et al., 2022).

To recognize the dynamics of change and that these dynamics themselves will change as industry transformations and technological developments occur, developing a framework has been selected as the best way of framing the solutions further provided in this study. When talking about carbon reduction, multiple technologies are available or under development. To be able to recognize the dynamics of change and that these dynamics themselves will change as industry transformations and technological developments occur, developing a framework has been selected as the best way of framing the solutions further provided in this study.

3.2 Review of frameworks

By proposing a framework applicable to Volvo GTO, this work attempts to become comprehensive and unfold from time to be applicable regardless of the type of technological development. Therefore, this study is shaped around strategy categories rather than technologies to be evaluated for feasibility.

To elaborate an own framework that is applicable to the automotive industry, more specifically to Volvo GTO, a variety of existing frameworks available from the literature are collected and examined in Table 4. The Frameworks are retrieved from general industry studies or from more energy-intense industries. Thus, many examples from the heavy industry are represented including iron and steel, cement and clinker, chemicals, pulp, and paper industries have recured in the investigation. These industries are known to have large carbon emissions and therefore can provide valuable insights into decarbonization. A summary of each source investigated is given below, including the authors, title, type of study and industry investigated, the decarbonization strategies mentioned, and finally a brief explanation of why these sources and examples were considered.

Table 4. Overview of frameworks identified in the literature

Fitzpatrick & Dooley, 2017	Rootzén, 2015	Brown et al., 2012	Ministry of the environment, 2020
Holistic view of CO_2 reduction potential from energy use by an individual processing company	Pathways to deep decarbonization of carbon-intensive industry in the European Union	Reducing CO_2 emissions from heavy industry: a review of technologies and considerations for policy makers	Sweden’ s long-term strategy for reducing greenhouse gas emissions
Technical approaches to reducing scope 1 CO_2 emissions from energy in the process industries. This study has the Irish dairy industry as a case study.	This doctoral thesis performed at Chalmers investigates how the European steel industry can achieve deep decarbonization.	Research project performed at the Imperial College of London that examines how industrial emissions from the heavier industry can be reduced in OECD countries.	Led by the Swedish ministry of the environment, the purpose of the report is to establish long term strategies that will contribute toward reaching the Paris agreement targets for the Swedish industry.
• Energy generation approaches to reduce CO_2 emissions • Improving energy efficiency • Carbon capture and storage • Cleaner product technology	• Improved energy efficiency • Fuel shift • CCS • Structural change • New steelmaking processes	• Maximize the energy efficiency potential • Fuel switching toward low carbon energy • Increasing investments in CCS research • Altering waste protocols and product design to aim toward the closing of the material loop	• Transition from fossil based raw materials and energy toward renewables • Improved process and material efficiency • Electrification • Introduce CCS technologies
This framework was applied toward the process industry with a holistic view of CO_2 reduction potential approach.	By being a framework that was applied to a specific industry, it gives guidance on how to interpret decarbonization frameworks based on a specific industry.	This framework was developed with focus on OECD countries which contributes to a nuanced perspective when used in consideration toward the study of an internationally based automotive industry.	This framework was developed by the Swedish government as a country specific strategy. Even though Volvo GTO has a vast international operation area, it is primarily a Swedish company. It is believed that to some extent, the company reflects values from the Swedish society.

Lane, 2019	van Sluisveld et al., 2021	Doleski et al., 2022	Bauer et al., 2022
Assessment of broader the broader impacts of decarbonization	A race to zero - Assessing the position of heavy industry in a global net-zero CO_2 emissions	Digital decarbonization	Assessing the feasibility of archetypal transition pathways toward carbon neutrality – A comparative analysis of European industries
The framework is grounded in a European research collaboration that studies innovations related to decarbonization in energy-intensive industries such as iron and steel, cement and clinker, chemicals, pulp, and paper.	Framework developed for decarbonization pathways of four carbon and energy-intensive industries (iron and steel, cement and clinker, chemicals, pulp, and paper) for achieving global net zero emissions by the year 2050.	In their book, the authors investigate how decarbonization and digitalization can help achieving the climate targets globally. Independent of location and industrial sector, there are certain core elements that are needed for reaching carbon neutrality. These are listed by the authors.	The study investigates the European steel, plastic, pulp & paper, and meat & dairy industries emissions
• Technological replacement • Process Improvement • Demand management • Circular economy	• Energy and carbon efficiency • Fuel switching • Technological choices	• Substitution of fossil energy carriers • Use of renewable process heat • Replacement of basic materials that cause emissions • Separation of produced emissions • Reduction of the production volume • Increase in energy efficiency • Improvement of energy conversion • Optimization of existing plant facilities • Avoidance of process related emissions	• Production and end-use optimization • Electrification with CCU (Carbon capture and utilization) • Carbon capture and storage • Circular material flow • Diversification of bio-feedstock use
Although the framework was developed based on the heavy industry it is still broad and general which makes it useful for the automotive industry.	The study' s global perspective makes it particularly useful for Volvo GTO. In addition to this, the general nature of the framework makes it useful for studying the automotive industry.	The framework was developed without a specific industry sector in mind. This makes the framework interesting and open regarding how it can be studied with the automotive sector in mind.	This study was conducted with a European perspective on the heavy industry. The framework is interesting for making distinction between CCU and Carbon capture and storage (CCS).

Source	Title	Type of study and industries	Identified strategies	Relevance

3.3 Energy system solutions

Some countries have more low-carbon energy options available than others. In 2019, Sweden had a low carbon source share of 69% in their energy mix, France 49%, Brazil 46%, the United States 17%, and Australia 9%. As in the case of primary energy, the electricity mix also differs between countries. In 2021, 98% of Sweden's electricity came from low carbon sources. That value was 90% for France, 86% for Brazil, 40% for the United States and 25% for Australia (Ritchie & Roser, 2021). Based on this, it is important to keep in mind that sourcing renewable energy is not the same in different places. Some facilities will benefit from being located in countries that have more availability of this resource. Therefore, the options and solutions for supplying manufacturing operation with low carbon or renewable energy vary broadly and needs to be accounted for.

3.3.1 On-site/off-site renewable energy production

There are several ways for companies to source renewable electricity. One way is to purchase electricity from an independent green power producer with so-called power purchase agreements (PPAs). Second, one can continue to consume standard electricity but invest in renewable energy certificates, such as renewable energy certificates (RECS) and guarantees of origin (GOs) to offset emissions. Thirdly, renewable electricity can be sourced by purchasing green tariffs from companies that offer green electricity contracts in addition to conventional ones. Lastly, there is the possibility that the companies invest in on-site and/or off-site technologies that produce renewable energy (Renewable Energy Agency, 2018).

Agreements and sourcing possibilities for companies differ between countries. For example, the United States, Sweden, France, Brazil, and Australia have PPAs and utility green procurement programs. Having said that, sourcing of renewable energy has not reached a mature stage yet and there are both financial and technical risks connected to it (Renewable Energy Agency, 2018). When it comes to RECs, they are considered a fast way to offset electricity-related emissions, but they are not free from criticism. Some entities claim misuse and that it is not an ideal way to deal with emissions. Although purchasing credits for offsetting emissions is considered a common procedure, it does not change the fact that companies continue to emit carbon dioxide (Doleski et al., 2022).

On-site renewable energy production can be installed within or on top of buildings or somewhere on the site. In this case, both transmission and distribution losses are minimized through direct supplying to the building system. Among the renewable energy possibilities, wind energy is a viable alternative where there are favorable conditions. It is harnessed by wind turbines of varied sizes. There are both benefits and drawbacks to this technology. The biggest benefit is that it has marginal CO_2 emissions. However, the biggest drawback is that wind power produces inconsistent yields. The average payback period for a wind turbine has been estimated to be around 13 to 19 years on average. Photovoltaic (PV) panels and solar thermal panels are technologies that harness solar energy. In addition to the technical differences between these two technologies, there are also efficiency and application variations. PVs are usually used for generating electricity with an energy efficiency of 46% and constantly increasing. They can be utilized for instance, in thermoelectric cooling systems. Solar thermal panels are used for heat generation, with an efficiency of up to 70% and the system can be connected to boilers. They can be integrated with thermally driven air conditioners. Their average payback period has been estimated to be 7 to 10 years (Ahmed et al., 2022).

When considering increasing the share of renewable technologies, energy storage is a key factor to include. It is a tool for countering the fluctuations of demand and price of the energy system. There are several ways for storing energy and batteries are among the most common ones. However, there are certain tradeoffs when it comes to battery size and cost. Therefore, energy storage with battery should be optimized according to several parameters such as technical and financial factors (Ahmed et al., 2022).

3.3.2 Biofuels

Biomass or more specifically biofuels are considered a “bridge” solution, which should eventually be phased out over time in favor of cleaner energy sources. Biofuels are renewable, and they are necessary because they can provide electricity on demand without the need of substituting most of the existing infrastructure. Nevertheless, biomass requires fertilizers which are connected to emissions. Moreover, biomass production competes over land with biodiversity and contributes to soil erosion along with other environmental issues (Hawken, 2017). When combusted, biofuels also contribute to air pollution (Wei et al., 2019). Nevertheless, biofuels still emit approximately ten times fewer carbon emissions per MWh in comparison to fossil fuels (Ahmed et al., 2022).

Biogas is a viable alternative when considering the decarbonization of fuels. It is derived from biomass gasification as well as methane obtained from landfills (Wei et al., 2019). Biogas is produced by facilities that range from small to large scale. Central Europe has the largest presence of plants in the world followed by the US. This resource is still marginally used in Australia. However, it is estimated that it has the potential to cover 9% of the country's energy needs. It is forecasted that countries such as Germany and Sweden will spearhead the development and establishment of biogas (Abanades et al., 2022). Regarding the global market, Europe has 16% the share, the US has 16% of the share and Brazil has 12% of the share (IEA, 2020).

Biomass is produced in several ways and consists of different compositions. Therefore, the lifecycle footprint has a large spread profile (Ahmed et al., 2022). In the case of liquified biomethane as an alternative to fossil-based gases, studies have shown that it has low production costs, low GHG emissions, decreases nitrogen oxides and decreased particulate matter (Verger et al., 2022). There are several applications for biogas both for private use and for societal applications. For example, it can be used for heat generation in specific boilers, or it can be used in modified natural gas boilers. Another application is creating biomethane from biogas which is a novel technology that is growing in popularity. Biomethane can be used as a vehicle fuel. Additionally, biogas can be used in combined heat and power (CHP) systems to reduce energy conversion losses when biogas is converted to heat or electricity. It is especially interesting for processes that require elevated temperatures (Abanades et al., 2022).

Although biogas is widely known and used for different applications, the production volumes are yet to grow considerably. There are several barriers that are hindering the growth of the biogas industry.

The technical barriers are primarily related to the supply chains of the industry and the details surrounding the production of biogas. For example, cold winters often lead to lower production rates. When it comes to cost, there are several drivers and barriers that play a significant role in the competitiveness of biogas. High investment costs, scarcity of loans/subsidies and land competition are several examples of cost drives. In some cases, as it was in Germany in 2018, the cost of electricity for different biogas technologies was among the highest and surpassed PV, wind, brown coal, and hard coal. In addition to this, the cost of biogas is higher than the cost for natural gas. Furthermore, policy is playing a major part in the establishment of biogas. More specifically, uncertain, and unclear policies have a negative impact on established actors and newcomers (Nevzorova & Kutcherov, 2019). It is globally forecasted that by 2040, the biomethane potential is going to increase with 40% and the price is set to decrease with 25% (IEA, 2020).

In addition to the type of biomass application previously mentioned, there are several types of biomass-based fuels available on the market such as HVO (Hydrogenated vegetable oils), (Hydro processed esters and fatty acids), biodiesel, and bio-coke. These fuels have the possibility to either be utilized at the concentration of 100% or be blended with fossil fuels. The foremost advantage of biomass-based fuels is that they do not damage or require modifications to engines. However, there is a large spread in production costs that are dependent on the level of technology readiness and on what production processes are being utilized. This is also the case regarding GHG emissions where there is a large spread for each of the alternatives. The conducted study showed a large spread in GHG emission for HVO (5kg CO_2/GJ – 76 CO_2/GJ) while biodiesel showed a smaller spread (39 kg CO_2/GJ – 45 kg CO_2/GJ) (Verger et al., 2022).

3.3.3 Hydrogen

Sustainable hydrogen is a viable alternative for decarbonization in the industrial sector (Rissman et al., 2020). Despite being a colorless gas, hydrogen carries different color designations depending on its origin in the production process. The division consists of green, blue, grey, and brown hydrogen. In its least polluting form, green hydrogen is produced through the electrolysis of water using 100 % renewable electricity thus with no CO_2 emissions. Grey hydrogen is produced from methane, coming either from natural gas or biogas in a process called gas or steam reforming and some CO_2 is emitted. Blue hydrogen is produced the same way as grey hydrogen with the only difference being advanced gas reforming CCS or CCU. Because in practice, no technical process has perfect efficiency, a residual amount of carbon dioxide naturally always is emitted (Doleski et al., 2022). Lastly, brown hydrogen is produced from coal by reacting coal with oxygen and steam under high heat and pressure in a process called gasification. The production price varies depending on the method, with the least polluting alternatives being more expensive than more polluting ones (Johnson Matthey, 2022).

The costs associated with hydrogen have difficulties in competing with natural gas, especially when it comes to costs for transportation and production equipment (Rissman et al., 2020). Moreover, regulatory barriers and permits are unclear and vary depending on country legislations which makes the technology difficult to implement within different sectors. In addition to this, there are logistical issues due to the inherent properties of the fuel. Despite having high energy content, it must be cooled down to increase its density for enabling transportation. This has been considered a main barrier for it to become widespread adopted, especially talking about large scale application. Today, hydrogen is almost entirely supplied from fossil fuels. Therefore, the production of hydrogen is now responsible for CO_2 emissions of around 830 million tons of carbon dioxide per year (IEA, 2019).

As previously mentioned, hydrogen power can be produced in various ways and with various fuels. Brown, grey, and blue hydrogen all rise above the low carbon threshold. Therefore, Longden et al., (2022) claims that there is the possibility to integrate hydrogen production with CCS. If that is considered, hydrogen from natural gas with a CCS capacity of 90% is the only way to make it a low carbon alternative, considering emissions such as direct emissions, process emissions and fugitive emissions. However, emissions from transport and storage of the captured CO_2 were not included and can look different depending on the scenario (Longden et al., 2022).

When considering green hydrogen, the biggest factors regarding cost are the price of electricity, the capital cost of the actual electrolyzers and at what capacity they are utilized. However, for the last decade costs for generating electricity through PV and wind have decreased substantially and projections have predicted additional cost decrease for LOCE for both alternatives by the year 2030. Moreover, the increased implementation of electrolyzers is predicted to further lower the capital cost by the year 2030. This is predicted for both alkaline electrolyzers and polymer electrolyte membrane electrolyzers (Longden et al., 2022). Regarding storage of renewable energy, hydrogen can be used as an energy storage solution when more renewable electricity is being produced than being used. It is regarded as becoming one of lowest-cost alternative to store electricity, especially for longer time frames (IEA, 2019).

3.3.4 Sector coupling

Sector coupling refers to the integration of energy system components related to natural gas, electricity, and petroleum infrastructure. It comprises the integration of energy end-use (buildings, transport, and industry) and supply sectors (power-producing) with one another to further achieve decarbonization. Considered key technologies to reduce GHG emissions, electric equipment and boilers, heat pumps and electrolysis for hydrogen production can be coupled to the energy system (Doleski et al., 2022). Sector coupling tends to relate to higher electricity demand, and consequently the need for more renewable electricity generation. According to the literature, a fully decarbonized energy system will require more electricity than today's consumption, meaning that extra flexibility will be needed to manage all the intermittent electricity sourced (Kerstine Appun, 2018).

To achieve strong sector coupling and to realize its full benefits, a comprehensive model is needed that represents the whole energy system. This model would include the major supply sources including electricity, refined petroleum products and the natural gas sectors and on the output side, representation of the usage. Such a model brings multiple benefits, such as understanding the interactions across the system, identifying challenges and opportunities that would not otherwise be apparent, avoiding over or undercounting of costs, GHG, benefits, etc., establishing where best to focus, where to get the highest return on an investment, etc., and understanding all the consequences of decisions (Doleski et al., 2022).

3.3.5 District heating

District heating operation can vary depending on geographical location. In some places, it is powered by CHP plants, in others by waste to energy plants. The generated heat is transported to both private and public facilities. Approximately 90% of the world's district heating system is powered by fossil fuels, while for Europe it is approximately 70%. Certain facilities have started to increase their share of renewable energy to reduce CO_2 emissions. Certain energy mixes have a larger share of renewables, nuclear power, and biogas. Most district heating systems are already integrated with power generation, which further facilitates the transition toward an increasing share of renewable energy (Werner, 2017). There are several advantages to district heating. It is usually cheaper than electricity and, in the case of Sweden, it has a good environmental profile (Swedish Energy Agency, 2015). However, the price for district heating changes with geographical area and supplier. Moreover, there is only one supplier for every designated geographical area which eliminates the opportunity of choice. Sourcing is only possible if there is an adjacent network (Swedish Energy Markets Inspectorate, 2021).

Because district heating is an efficient heat supply option for both the industrial and residential sectors, multiple countries in the world are implementing or expanding their capacity. In addition to being energy efficiency, district heating is regarded as a valuable tool for societal decarbonization. It can be integrated with innovative and sustainable technologies for decreasing the overall fossil utilization. These solutions range from implementation of solar thermal capacity, bioenergy, and utilization of excess heat (EIA, 2021). In Sweden, district heating companies are looking to completely replace fossil fuels in the coming years once the emissions from this sector are for most parts derived from the burning of plastic waste. In addition, CCS can be integrated to district heating. As an example, a Stockholm based district heating company is developing pilot programs regarding the integration of bio-CCS negative emissions from their operation. It is forecasted that Swedish district heating will be CO_2 emission free by 2050 (Fossil free Sweden, 2021).

3.4 Manufacturing processes solutions

In the production of trucks and other vehicles, there are several activities involved that are responsible for CO_2 emissions. Common manufacturing processes are assembly, welding, painting, stamping, casting, and machining. In addition, building control systems also contribute to manufacturing emissions through heating, cooling, lighting, etc., (Giampieri et al., 2020).

Most of the manufacturing processes listed above are included in the powertrain and vehicle body shop. The vehicle body shop is where most of the welding, and joining processes take place and for the most part, these are powered by electricity. Also, in stamping, where steel coils are turned into parts of the vehicle such as the roof or hood, compressed air is used which is generated by electrically driven machines. Powertrain production is responsible for the production and assembly of transmission gears and engines. Activities taking place within the powertrain are, for instance, metal casting, machining, and assembly. These activities are for the most part electrified, except for casting, and certain steps are energy demanding, which is the case of engine casting. After the vehicles are painted, the final assembly takes place to put every component together into the final product. In this step, electricity is mostly consumed to supply compressed air and for powering conveyor belts and robots (Giampieri et al., 2020).

The electricity usage has a varied application. In general, it is used to compress air, provide ventilation and lightning, and metal forming. In addition, motors are responsible for powering compressed air solutions, robots, and pumps found in activities such as stamping, and assembly and they also consume a large share of electricity. Painting activities have the possibility to make 27% to up half of a facility's electrical consumption, heating, and cooling from 11 to 20%, lightning 14 to 15%, compressed air 9 to 14%, and welding and other material handling tools 7 to 8%. The averages of these shares are depicted in Figure 4. It is important to mention that this does not consider foundry-related activities (Giampieri et al., 2020).

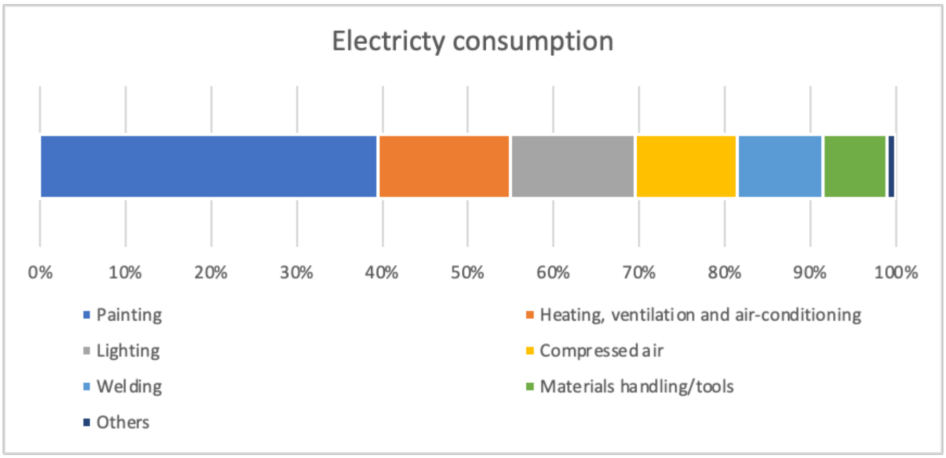

Figure 4. Electricity consumption in the manufacturing processes.

3.4.1 Assembly, welding, and stamping

As previously mentioned, assembly, welding and stamping operations are for the most part, already electrified in the automotive industry. Therefore, the decarbonization focus for these operations lies in reducing electricity consumption. One of the main uses of electricity is by compressed air systems, which are used in multiple processes. Despite its wide application, they have a low efficiency of power converted to useful energy which is around 10%. There are measures usually taken to enhance the efficiency such as maintenance of the leaks in pipes and minimization of the pressure drop. However, these are considered low hanging fruits which in most cases have already been implemented. The high inefficiency of compressed air systems creates an opportunity for heat recovery, which can be used to turn efficiency losses in form of heat into thermal energy that can be used in other processes (Giampieri et al., 2020).

Assembly operations are a large part of the automotive manufacturing process, and it will need to be mostly reframed as additional components become part of future vehicles. With greater electrification of transportation, certain changes will take place in the manufacturing to accommodate the requirements of the next generation of vehicles. Devices such cameras, radar and batteries for electric vehicles, and the related electronics will contribute to the complexity of the assembly process and further to the vehicle’s end-of-life inspection (Giampieri et al., 2020).

Welding in the automotive manufacturing processes is often highly automated and high yields of energy efficiency have already been achieved. There are, nevertheless, other technologies in the development phase that could further reduce energy consumption, such as it is the case of rapid freeform sheet metal forming (RAFFT). This technology is based on the production of sheet metal parts with double-sided incremental forming instead of using stamping and forming dies. Energy consumption could be reduced by 50–90% in comparison to the conventional technology. In a longer time perspective, joining processes will require significant changes as conventional techniques will not be feasible due to the use of varied materials and differences in their melting point. New approaches for mixed materials include adhesive, fasteners, and laser welding, but more research is needed to meet the energy consumption compared to the current efficient spot-welding technique. The new generation of vehicles will contribute with changes in the stamping process. Due to increased usage of advanced high-strength steel (AHSS), carbon composites and plastics, methods such hot stamping will have to replace cold stamping techniques. This technology has not yet reached maturity and is expected to reach it by 2025. The hot stamping technology will increase the energy use and will have to be integrated with waste heat recovery to increase the energy efficiency. In turn, the recovered waste heat will be able to power applications such as heat pumps (Giampieri et al., 2020).

3.4.2 Painting

Paint deposition and curing processes involve many steps accounting for significant consumption of electricity, fuel, compressed air, hot and chilled water when producing vehicles. Electricity is used mostly to power fan motors and produce secondary energy sources in the painting process while natural gas is consumed to heat up the air used in the paint spray booth and in the curing ovens. Moreover, gas is used for heating up water, which is necessary for pre-treatment during the painting process. In a smaller amount, approximately 2% of it is also used to remove VOC emitted during the process (Giampieri et al., 2020).

Renewable energy has an enormous potential to be integrated into the paint shop. An example is a solar thermal technology developed by Dürr, which is the world's largest paint shop builder worldwide. This uses Fresnel collectors, which are basically linear concentrating solar thermal collectors optimized for industrial applications, to produce superheated water up to 400 °C which can be delivered to the ovens for the paint curing process. Following this, a heat cascade strategy can be established taking into consideration the different temperature requirements in the paint shop. Alternatively, other curing techniques, such as infrared (IR) and ultraviolet (UV) curing, can be employed to reduce energy consumption by substituting conventional curing techniques. These technologies require lower temperature and time compared to conventional (Giampieri et al., 2020).

Another effective strategy for reducing emissions in the painting process is the reformulation of the paint composition and the paint drying process. As a common practice, preference is given to paints with low VOC emission, which is usually the case of water-based paints when compared to solvent-based ones. However, water as a diluent requires that it be evaporated through a drying process that consumes large amounts of energy and emits CO_2. Therefore, the key issue to be addressed is how to use water-based paints that greatly reduce VOC emissions while reducing the CO_2 emissions that result from producing the required energy. This is way the reduction of painting process complexity is the top strategy for energy consumption reduction in this process (Giampieri et al., 2020). One technology used in this sense is the three-wet painting. This technology not only presents low energy consumption and less CO_2 emissions, but it also has a better performance when it comes to VOC emission than conventional painting processes. This system applies all three paint layers, primer, base and clear top coat while still wet and requires only one drying process to finish, reducing energy requirements and bringing CO_2 emissions down by more than 15% and volatile organic compound (VOC) by as much as 45% compared to conventional painting processes (Mazda, 2022).

A second innovative process related to the painting was developed by Mazda in the 2010s, called aqua-tech paint system. This process is based on efficiency gains along with two new types of top coat paint that were developed specifically for this system: a water-based color basecoat and a urethane clear coat. These paints also exhibit additional properties that are usually provided by the primer paint, which becomes unnecessary and reduces the painting process and by doing so, curtailing energy consumption and CO_2 emissions without affecting quality. The efficiency gains refer to air-conditioning the paint booth, which produced a 34% reduction in CO_2 emission in comparison to conventional water-based paint booths. The paint booth is a large space that can hold an entire vehicle body. That requires a large-scale air conditioning system and a large amount of energy, particularly during warmest and coldest seasons. The new system developed by the company "constantly controls the maximum water vapor absorption volume by monitoring external conditions and making the minimum necessary adjustments to temperature and humidity inside the paint booth" (Mazda, 2022). This results in further reductions in energy consumption during the painting process. This is considered one of the most environmentally friendly automotive paint systems in the world (Mazda, 2022).

Another solution to decarbonize the paint shop includes heat recovery. Recovering the thermal energy that would have otherwise could be beneficial in terms of curtailing natural gas requirements. The recovery can occur through recuperative heat exchangers, regenerative heat exchangers, thermal wheels, and heat pumps (Mohammadpour & Hane, 2020). The selection of the heat recovery method lies on the temperature range, the intended application (cooling or heating) and the required working fluid. From the regenerative thermal oxidizers (RTO), compressors, ovens, and dryers from the paint shop, thermal energy can be recovered and used for heating up water, which could then be employed for space or processes heating. For that purpose, heat pumps are a usual technology used. Heat could also easily be recovered from the process involved in oxidizing the VOCs present in the exhaust air and used to heat up air used in the paint booth. The potential reduction of natural gas consumption is reported to be around 16%. A second example of heat recovery lies within the paint curing oven, from where heat can be used to precondition outdoor air, particularly during winter. The reported heat recovery efficiency is 45% but contaminants in the exhaust air must be filtered or removed before the process (Giampieri et al., 2020).

The investment capital cost of heat recovery technologies limits the economic benefits of the process. However, it is proven as economically advantageous in the design phase of a new paint shop, while it is limited in retrofitting. Another issue when working with heat recovery, is that two or more different processes might have to be integrated. Different processes can work at different rates and in that case, it is not guaranteed whether it is possible to completely synchronize, shut down or alternate the operating pace of heating, ventilation, and air conditioning of different processes to match heat recovery strategies (Mohammadpour & Hane, 2020). Also, Heat recovery is largely dependent on the economy- of -scale.- Equipment costs favor large -scale heat recovery systems and create challenges for small-scale operations (U.S. Department of Energy, 2008).

3.4.3 Casting processes

Casting processes usually take place in foundries for cast iron production, where either scrap or ingots can be used as starting material. Firstly, the scrap or ingots must be melted at a temperature of about 1450 to 1500 degrees Celsius in furnaces, which can have various designs. Some examples are the cupola furnace and the CIF (Coreless induction furnace) (Stefana et al., 2019). The cupola is considered one of the most effective melting units and it is powered by coke, which is a coal-based material. The disadvantages with the cupula furnace are that the high-quality coke that is required in the process is becoming scarcer and that the emissions from the process are quite significant (Campbell, 2015). On the other hand, CIFs produce heat without combustion since they are powered by electricity, and they require elevated raw material quality compared to the cupola. The quality of the input materials regulates the output of the melting process such as the quality of the metallurgical waste. Lower quality of metallurgical waste decreases the possibility of recycling. Energy losses associated with CIF furnaces are heat losses, more specifically radiation and transmissions losses (Stefana et al., 2019).

Molding is a parallel activity to the melting that produces molds where the melted metal is shaped (Stefana et al., 2019). Molds can be produced with different techniques and consist of different materials. Greensand, which is a mixture between clay and water, is often used as a molding medium for having several benefits. It is highly effective, it can be recycled, and has minimal environmental impact. Furthermore, it is economically advantageous due to its low costs. Thereafter, the melted scrap and the produced molds are sent to the casting shop where the casting if performed (Campbell, 2015).

The casting process consists of several steps such as pouring, cooling, the shakeout (Separation of the casting and molding material) and the casting cooling. Regarding the emissions from the casting process, it is strongly related to the molding material choice. Furthermore, combustion gases are generated from the preheating of ladles and cooling process. Sand casting makes it possible to not only recycle the scrap from the process but also recycling the sand that is used as molding material. The two last steps of the foundry process are the finishing shop and quality control. Activities found in the finishing shop is sand removal, removal of burns and heat treatments such as hardening. Emissions from the heat treatment varies depending on the type of fuel that is used, how the burners are designed and the maintenance activities (Stefana et al., 2019).

There are several possibilities to reduce emissions in blast furnaces, such as using biofuel alternatives. Bio-based alternatives include several alternatives produced from different methods and feedstocks. The most suitable feedstock for metallurgical applications is wood based due to its favorable chemical composition. Regardless of the type of feedstock, the biomass must undergo several processes for reducing the moisture content and increasing the carbon content. There is a broad range of thermochemical processes involved such as hydrothermal carbonization (HTC), slow pyrolysis, fast pyrolysis, and gasification. These processes result in different products. Some of the main products are HTC biomass, resulted from hydrothermal carbonization; biochar, obtained from slow pyrolysis; bio-oil from fast pyrolysis; and syngas, obtained from gasification. Life cycle CO_2 emissions of these bio-based alternatives vary significantly. For example, biobased charcoal ranges from about 4 to 18 gCO_2/MJ while coal has a life cycle footprint of 115 gCO_2/MJ (Suopajärvi et al., 2018).

In addition to the previously mentioned biobased alternatives, bio-coke is a viable alternative for substituting fossil-based coke. This is due to beneficial properties such as similar energy, low moisture, high carbon content, and high compressive strength. In addition to this, bio-coke has shown good storage and transportation possibilities due to its properties (Mansor et al., 2018). As for supply chains of bio-based alternatives for blast furnace applications, there is large scarcity of actors in Europe which inhibits large scale implementations (Suopajärvi et al., 2018).

3.4.4 Building control systems

Building control systems are used to regulate environmental conditions inside buildings. They are required in all vehicle production plants for operation to provide an optimal working condition in terms of safety and comfort. These include heating, ventilation and air-conditioning and lighting (Giampieri et al., 2020). Integrated building design, retrofitting, and energy conservation strategies help achieve more energy efficient buildings. Simple examples of strategies include implementing advanced insulation and under floor heating (Ahmed et al., 2022).

Heat pump is a viable technology for satisfying heating and cooling needs. They can replace boilers that are usually powered by fossil fuels. However, there are limitations to certain heat pumps such as air-source pumps that cannot be operated efficiently in cold climates (Ahmed et al., 2022). Even if heat pumps are regarded as a promising technology, factors such as high electricity prices, high initial investments costs and cheap natural gas can be hindering for large scale implementations in most markets (IEA, 2021c). However, if both electricity and fuel prices are high, it is more worth using heat pumps since higher energy prices increase the value of cost savings relative to capital cost, which improves the payback (U.S. Department of Energy, 2003). It is predicted that heat pumps could satisfy 90% of the global water and space heating. This can be achieved with lower emissions in comparison to gas boilers (IEA, 2021c).

There are several types of heat pumps available. Ground source heat pump (GHPS) is a technology that utilizes thermal heating and can be seen as available option for replacing boilers that are gas driven which functions well in cold climates. It functions by harnessing constant soil, rock, and water temperatures below the surface. However, it requires electrically driven pumps to power the heat collecting pipes that contain both water and antifreeze. On the other hand, air source heat pumps (ASHPs) utilize outside heat to power underfloor heating systems, water, and radiators. ASHPs can be powered by renewable, and it does not require complicated installation. In addition, it can deliver warm water and heat depending on it type. However, it generates relatively high emissions and is not suitable for cold climates. The average payback period of heat pumps has been estimated to be 5 to 15 years. (Ahmed et al., 2022).

3.5 Carbon capture

Carbon capture is a technology that recovers carbon emitted by processes and it is categorized as a negative CO_2 emissions technology. When it comes to the industry, there are some major widespread solutions to sequester carbon. It might be directly from the air, also known as direct air capture (DAC), through biomass, in a process called bioenergy with carbon capture and storage (BECCS), or through end-of-pipe technologies at point emitting sources (Hawken, 2017).

Despite offering a promising solution to handle emissions, a major issue that has prevented end-of-pipe solutions from being widely used in the industry is the techno-economic feasibility. Its scalability is limited to large point sources and the technology available is simply not ready for small emitters. As an example, a study conducted by Leeson et al (2017) stated that the 180 biggest steels mills in the world average 3.5 Mton CO_2 emissions per year and there are multiple other sites with a smaller production capacity that average CO_2 emissions of 170 000 tons/year. The smaller facilities were left out of the study due to them not showing economic feasibility. Another factor mentioned in the study above is infrastructure. Despite big steel mills being large point sources of emissions, there still must be methods for either combing the streams of the flue gasses or constructing multiple carbon and capture installations to handle the different point sources. Also, transportation and storage costs must be considered. Lastly, high purity of CO_2 is an important factor for economic feasibility (Leeson et al., 2017).

One alternative to end-of-pipe solutions is DAC. It functions as an extraction technology that captures CO_2 from the atmosphere and does not require adjacency to specific industrial sites. There are currently 19 DAC facilities in operation with an operating capacity of 0,01 Mt CO_2/year. When it comes to cost, there is a large spread in cost estimations that depend on the assumed technological development. For the net-zero emissions scenario in 2050, this technology must grow to have the capacity of capturing 85 Mt CO_2/year by the year 2030. In addition to DAC, forests can naturally capture $CO_{2,}$ in methods such as afforestation or methods that enhance natural processes that transform vegetation into biochar (IEA, 2021a).

Another aspect about CCS is that it can be differentiated among natural sinks vs technical sinks. Natural sinks include afforestation and reforestation while a technical approach is handled with end of pipe solutions that sequester carbon from flue gases (Doleski et al., 2022). In the case of technical sinks, the challenges coupled with CCS concern the lack of infrastructure for transportation and storage. These serve as a crucial factor to determine the viability for industries or clusters to support and invest in CCS solutions (F Bauer et al., 2022). Also, the opportunities for CO_2 capture for instance in steel production vary depending on the process and the feedstock used (Rootzén et al., 2011). The largest flow of CO_2 in a conventional steel mill is generated in the blast furnace. Recovery of CO_2 from the blast furnace gas is a feasible capture option by applying current end-pipe technologies so that around 30% of the overall CO_2 emissions from a conventional integrated steel plant could be captured and prevented to be released into the atmosphere (Rootzén, 2015).

4. Results

In section 4.1, the decarbonization frameworks reviewed in the literature are gathered and a framework is developed. After identifying, comparing, and understanding the different decarbonization strategies across industries, an inquiry is presented consisting of solutions that are considered pivotal for bringing emissions down specifically for manufacturing in the automotive industry. Thereafter, the interviews are presented following a SWOT and feasibility assessment of the identified decarbonization solutions.

4.1 Framework

The trajectories toward industry decarbonization found in the literature and listed in Table 4, were put together for comparison in the Table 5.

Table 5. Classification of strategies identified in the studied frameworks.

Strategies / Frameworks	Fuel shift	Structural change (electrification)	Carbon capture	Process Efficiency		Technological replacement	Circularity	Others
				Material	Energy			
Richard Lane, 2019			X	X	X	X	X	Demand management
van Sluisveld et al., 2021	X	X	X	X	X	X		
Doleski et al., 2022	X	X	X	X	X	X		Reduction of the production volume
Bauer et al., 2022	X	X	X	X	X	X	X	
Fitzpatrick & Dooley, 2017	X		X		X	X	X	
Rootzén, 2015	X	X	X		X	X		
T. Brown et al., 2012	X	X	X		X	X		Alter product design and waste protocols
Swedish ministry of the environment, 2020	X	X	X	X	X		X	
Total	7	6	8	5	8	7	4	

As one can observe, certain strategies that have been pointed out in the energy-intensive industry or in the industry, in general, seem to be recurring among the different sources. Fuel shift; structural change; carbon capture; process efficiency, including both material and energy efficiency; technological replacement and circularity were inductively identified as the six major pathways that span across different industrial sectors and can be thought of as strategic transition pathways to reach carbon neutrality in the manufacturing. Therefore, they have been framed in an own framework presented in Figure 5. Overall, the framework consisting of six strategies, can be considered applicable to the automotive industry and relevant to Volvo GTO. Other strategies that have been listed in the literature but do not seem to be relevant to the framework, are listed under 'others' in the last column of Table 5. These are considered less related to manufacturing but rather to the designing phase or volume reduction in production.

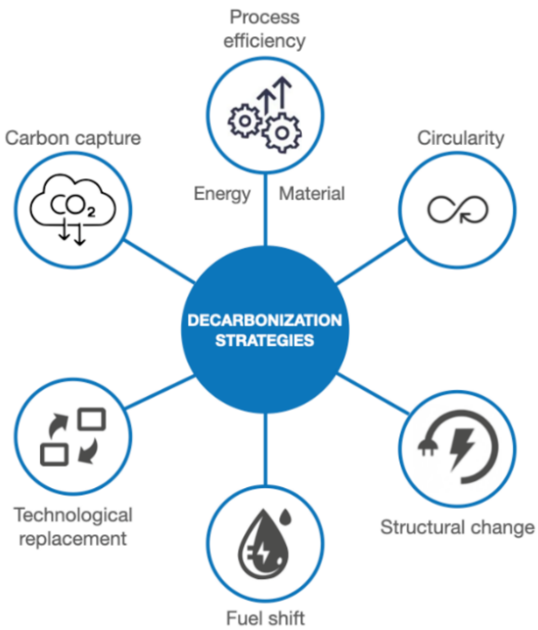

Figure 5. Decarbonization framework.

The strategies are collectively exhaustive, but not mutually exclusive. In other words, all the solutions found in the literature are accounted for in the framework, but some strategies may overlap. With that said, one technical solution can be assigned to multiple strategies. For instance, electrification can be responsible for an increase in energy efficiency and may require technological replacements. Nevertheless, to keep the solutions framed in a structured way, they will be presented belonging to a certain major strategy. In the example above, electrification can be considered before anything else, a major structural conversion of manufacturing; thus, it would be considered a structural change. Another example is LED. These light bulbs increase the efficiency compared to incandescent bulbs. However, they rely on a different working principle i.e., a different technology. Thus, they would be treated as a technological replacement. Lastly, If LED would be replaced with newer iterations of LED lights, this would be considered as energy efficiency, since no working principle has been altered. A more detailed explanation of each decarbonization strategy is provided in the sections below.

Fuel shift

This strategy entails a shift from fossil energy carriers toward less polluting alternatives or in the best case, by renewable fuels without the need to modify the process entirely. Therefore, it gives the possibility to continue utilizing the same technological processes with less or no emissions depending on the quality of the renewable fuel.

Fuel shift is mentioned by all authors but Lane (2019). Some authors have dedicated a specific strategy for fuel switching (T. Brown et al., 2012; Rootzén, 2015; van Sluisveld et al., 2021), while others have incorporated it in other strategies definitions. Doleski et al. (2022) mentions replacing basic materials that cause emissions and explains it as exchanging fossil-based materials used in manufacturing operations. This is addressed by Bauer et al. (2022) in what it is called diversification of bio-feedstock use. This strategy's goal is to give preference to fuels contributing to the bioeconomy. Fitzpatrick & Dooley (2017) includes fuel shifting as part of energy generation approaches to reduce CO_2 emissions. Lastly, the Swedish ministry of the environment (2020) proposes in their framework the strategy for transition from fossil based raw material and energy toward renewables, which can considerably lower emissions for heating purposes.

Industrial actors accustomed to using fossil resources have been cautious toward biobased resources due to its low carbon density, seasonal availability, and variable quality. Political acceptability is generally seen as well-developed but since the land required for its production is a scarce resource, there will always be issues around conflicting interests for instance when it comes to biodiversity and nature preservation (F Bauer et al., 2022). Nevertheless, great potential lies within this strategy. Fossil fuel can gradually be phased out by incrementally increasing the share of renewable resources. Also, co-firing of biomass and waste could significantly reduce fossil fuel usage and unlike biofuels, purpose grown crops are not required. The use of agricultural residues reduces concerns regarding land use and competition for food production (T. Brown et al., 2012).

Structural change (electrification)

Structural change refers to electrification of manufacturing operations and in what way the electricity is provided. In that case, fossil driven technologies are replaced with electrically driven ones. This strategy highlights the need for an increased power capacity and the presumption that renewable electricity with low GHG emissions will be available at low costs.

Structural change has only not been mentioned by Lane (2019) and Fitzpatrick & Dooley (2017). The other authors have all mentioned electrification as a key step to bring down emissions in the industry. It has been often addressed as a strategy on its own (Bauer et al., 2022; Rootzén, 2015; Swedish ministry of the environment, 2020) while other authors have included it as an alternative form of fuel (T. Brown et al., 2012; Doleski et al., 2022). In the developed framework in this report, electricity is not considered part of the fuel shifting strategy once it requires more complex modifications to be implemented. Van Sluisveld et al. (2021) lists direct electrification as part of a process innovation, which falls under the strategy technological choice. However, the framework developed by Van Sluisveld et al. (2021) has only three strategies included, what can be considered as a highly aggregated approach. This study aims toward delivering a more disaggregated framework. Therefore, structural change is categorized as an own strategy while other authors have included it as an alternative form of fuel (T. Brown et al., 2012; Doleski et al., 2022). In the developed framework in this report, electricity is not considered part of the fuel shifting strategy once it requires more complex modifications to be implemented. Van Sluisveld et al. (2021) lists direct electrification as part of a process innovation, which falls under the strategy technological choice.

Structural change in manufacturing entails a drastic shift in the way things are produced. A big topic when it comes to manufacturing is the transition toward electricity. Currently, the technologies and solutions needed are mature, but many of them have not been previously implemented in the scale relevant for big industries (F Bauer et al., 2022). Also, it requires major investments and planning to implement them, which might not always be in line with desired decarbonization schedules. For instance, capital expenditures for changing fuels are often high and natural gas is often the best economical alternative. Moreover, if variable renewable energy is sourced then the challenge is to adapt the manufacturing to cope with fluctuations in demand that can counter the variation in electricity cost (Wei et al., 2019).

Despite all the risks, this strategy presents an enormous potential for transitioning manufacturing processes to carbon-free ones. Electrification has the potential to substitute fossil energy use in many existing processes. In the industrial sector, the biggest application for fossil fuels is in boilers and for heating different processes. Through electrification, heat supply can, for instance, be provided either directly, through microwave or infrared heating, or indirectly through producing hot water and steam with electric heat pumps and boilers instead of burning fossil fuels (Rissman et al., 2020).

Carbon Capture

The IPCC states that current measures to reduce carbon emissions will not be sufficient to meet climate targets and therefore carbon capture technologies are needed. This strategy, also called carbon sequestration, entails the process of capturing carbon dioxide emissions before (or after) they enter the atmosphere. Within this strategy, two processes are currently used at an industrial scale . Carbon capture and storage (CCS) involves storage of carbon dioxide in geological structures after sequestration and carbon capture and utilization (CCU) recycles the sequestered CO_2 for later usage (Doleski et al., 2022).

Carbon capture has been addressed in all frameworks included in the study. It has been named as a strategy on its own by most of the authors (Bauer et al., 2022; T. Brown et al., 2012; Doleski et al., 2022; Fitzpatrick & Dooley, 2017; Rootzén, 2015; Swedish ministry of the environment, 2020). Bauer et al. differentiates CCU from CCS and categorizes it as part of the electrification strategy while Lane (2019) sees CCU as part of a circular economy strategy, which is a sound assumption. However, due to its novelty nature and technological proximity to CCS technologies, it has been decided to include it as a carbon capture technology in the here developed framework. Lastly, two authors have categorized carbon capture as being part of other more encompassing strategies (Lane, 2019; van Sluisveld et al., 2021). Lane (2019) categorizes CCS as process improvement and van Sluisveld et al. (2021) frames it as part of several distinct groups of production technologies that aim toward a decarbonized industrial system falling under the strategy technological choices. Nevertheless, all iterations of carbon capture operate on the same overlying principle which motivates the choice of including them as one strategy in the framework developed in the study.

Carbon capture is a pathway that is primally geared toward industries with processes that heavily rely on fossil fuels for instance. It allows them to continue using fuel-based technologies but with low to zero emissions and processes whose emissions are difficult to reduce in other ways (Bauer et al., 2022). It is believed that less attention has been given to carbon capture in the industry compared to the power sector despite the crucial role that it is required to play in reducing CO_2 emissions (T. Brown et al., 2012). However, carbon capture plants are not 100% efficient as it is the case of any practically implemented technical process. Therefore, they capture only part of the emitted carbon dioxide (Doleski et al., 2022). Nevertheless, carbon sequestration technologies are an interesting solution that could contribute to the automotive industry to reduce emissions. All studies analyzed have included this kind of technology in their frameworks, suggesting that it is valuable for the industrial sector.

Process efficiency

Improving process efficiency has always been part of production systems. It is the most straightforward way to increase productivity without having to alter much in the processes. It basically encompasses any incremental, technical process innovations that can contribute to efficiency gains. Process efficiency can be improved, among many things, through resource management. The amount of energy consumed and the total material requirement to conduct a certain process upholds the overall optimization of industrial processes (Doleski et al., 2022). The two areas, material and energy, are where efficiency gains can be obtained. Since they are closely associated, it has been decided to keep them under the umbrella term 'Process efficiency'.

The strategy of improving efficiency spans across all the studied frameworks. Most of them include material efficiency and all of them mention energy efficiency as a keyway to minimize carbon emissions. The differentiation between material and energy is implied in most of the studies and therefore motivated the decision to include them as subcategories. All the authors mentioned in the framework development have a dedicated strategy for process efficiency and underline the need for it. Some authors have a close definition of what process efficiency has been defined in this study (Bauer et al., 2022; Lane, 2019; Rootzén, 2015; Swedish ministry of the environment, 2020; van Sluisveld et al., 2021). The remaining authors have associated process efficiency more closely with the need for replacing and implementing new technologies for increasing the process efficiency (T. Brown et al., 2012; Doleski et al., 2022; Fitzpatrick & Dooley, 2017). By classifying process efficiency as a separate strategy in this study, it gives additional attention for considering improving the existing system without having to invest in different processes.

Integrating improvements into existing structures should be implemented before investing in new technologies, which might have limited testing and find themselves in pilot or demonstration phase. It also usually requires high investment costs and encounters market entry barriers (Lane, 2019). This is supported by F Bauer et al. (2022), who assumes that "efficiency gain follows a well-established pattern of focusing on incremental improvements of existing industrial processes, with only some innovations requiring more change to the processes".

The minimization of electricity and material usage can be achieved in various processes, and it goes beyond installing efficient equipment. Storage, distribution, and conversion are just a few examples of areas where improvement can be obtained. Some other options are exemplified by Doleski et al. (2022) such as installing efficient equipment; designing an efficient distribution system; selecting correctly sized equipment that provides the desired utility; controlling the system for efficient operation; and planning for efficient equipment upgrades. Control of the system for efficient operation can be achieved for instance, by avoiding inactivity of equipment. Planning for efficient equipment upgrades includes having a budget for decommissioning obsolete equipment and designing an efficient distribution system includes appropriate sizing, smaller distances, insulating pipes, avoiding 90° bends in pipes and ducts (Doleski et al., 2022).

Technological replacement

Technological replacement is about innovation. According to van Sluisveld et al. (2021), this is the strategy in which the industry pursues alternative production routes to replace unsuitable ones. It concerns the shift of current production systems by alternative ones with the implementation of new technologies that contribute to emissions reduction.

All authors have explicitly mentioned the adoption of new technologies in their frameworks without a direct correlation to carbon capture or electrification, except for the Swedish ministry of environment (2020) who incorporates the need for new technologies under carbon capture or within electrification. However, this study will not limit technological replacement to these areas. On the other hand, Richard Lane (2019), van Sluisveld et al. (2021) and Rootzén (2015) have all a specific strategy destined at technological replacement with a similar framing to what is defined in this study. The remaining authors have this strategy implied under efficiency gains (Bauer et al., 2022; T. Brown et al., 2012; Doleski et al., 2022; Fitzpatrick & Dooley, 2017). According to them, replacing technologies by less polluting ones, is part of a greater purpose that is about process efficiency gains. T. Brown et al. (2012) mentions that maximizing energy efficiency potential includes the replacement of old processes and technologies with Best Practice Technologies (BPT) and Best Available Technologies (BAT). This study differentiates technological replacement from process efficiency due to the scale of changes required. The former demands more modifications than the latest for the simple fact that it revolves new working principles.

New technologies might have high market entry barriers which have limited testing and find themselves in pilot or demonstration phase (Lane, 2019). Thus, technological replacement might come later in the priority of strategies to be implemented since such changes require new knowledge and time to mature (Bauer et al., 2022).

Circularity

Circularity is a broad strategy that ranges from circular product design to closed production cycles. Bauer et al. (2022) define circularity as shifting from methods that use resources in a linear manner into a more integrated use and reuse that potentially eliminates or at least reduces the use for virgin resources including both energy and materials.

Circularity has only been mentioned in four of the assessed studies tackling decarbonization strategies and it is therefore the least mentioned strategy (Bauer et al., 2022; Fitzpatrick & Dooley, 2017; Lane, 2019; Swedish ministry of the environment, 2020). Nevertheless, some circular solutions such as recycling and industrial synergy have been addressed in some of the other studies (T. Brown et al., 2012; Doleski et al., 2022). Circularity aims to reduce both material and energy use by closing the loop and could be considered the most comprehensive strategy when it comes to decarbonization. Therefore, it has been designated a strategy on its own.

4.2 Framework relation to Volvo GTO strategies

There are several internal methods and practices used within Volvo GTO sustainability practices. For example, Volvo GTO uses the so-called “Energy hierarchy” which aims to reduce the quantity of natural resources needed by minimizing losses. Firstly, the strategy builds on conservation. For instance, using “treasure hunt” routines to reduce losses from idling machines, leaks and systems running after production. Thereafter, the focus falls on increasing efficiency of the resource usage, cost, and environmental impact by utilizing the best available resources technologies and practices. The last step is to switch to renewable resources, and to implement closed loop and regenerative technologies to achieve CO_2 neutral emissions.

In addition to the energy hierarchy, Volvo GTO uses a mitigation hierarchy for lowering value chain GHG emissions. According to this hierarchy, the priority is to reduce GHG emissions within the value chain through energy efficiency and the introduction of new technologies. Secondly, the focus is to replace fossil fuels with renewable energy and fuels and thirdly, to compensate or neutralize activities by atmospheric CO_2 removal and storage as a last resort. In addition to this, there are circular economy practices in place for every step of the value chain. More specifically, remanufacturing strategies are used toward carbon neutrality.

When relating the different Volvo GTO strategies with the decarbonization framework, there are similarities and differences. Differently from Volvo’s strategies, which follow a top-down approach, the decarbonization framework is not hierarchical. However, each of the categories presented in the decarbonization framework are imbedded in the Volvo GTO frameworks. Consequently, the decarbonization framework provides an overview of strategies that combine ways for both increasing energy efficiency and reducing emissions.

4.3 Manufacturing patterns in the automotive industry

The decarbonization state of the art in the automotive industry can be obtained by looking into what technologies and strategies the largest vehicle manufacturers worldwide have been employing and investing in. The subchapters below attempt to collect general and updated information on decarbonizing strategies from an array of car and truck manufacturers, based on data gathered from their respective websites and annual CSR reports. In addition, the measures have been featured according to the developed decarbonization framework, serving as a benchmark for Volvo GTO. This is shown in Figure 6. The companies investigated are Toyota, Daimler, Volkswagen Group, BMW, Ford Motor Company, and CNH Industrial.

Toyota motor company

Toyota is increasing the renewable share of electricity and has introduced it at sites in Europe, Asia and South America. Furthermore, several low carbon production methods have been introduced. For example, hydrogen-based technologies for production have been tested at the Honsha site (Japan) and at the Motomachi (Japan) plant. More specifically, in house power generation facility consisting of stationary fuel cell generators and water electrolysis machines for hydrogen generating and filling purposes. One reason revealed for implementing the aforementioned innovation is to be able to power the forklift in the facilities with internal hydrogen production from renewable energy sources, such as solar panels. Furthermore, there are plans to utilize hydrogen fueled burners for the combustion processes. It will enable the sites to utilize waste heat and cofiring gas engine generators (Hydrogen and natural gas) for both electricity and heat generation. (Toyota Motor Corporation, 2022).

In some locations, wind power generators and solar panels will be implemented. Moreover, there are plans for developing CCS and CCU solutions (Toyota Motor Corporation, 2022). Regarding efficiency measures, improved lightning, better insulation, and close monitoring will lower the overall energy consumptions. There are plans to implement solar walls that can reduce the need for heating purposes. Where possible, natural gas boilers will be replaced with biomass boilers (LPG replaced with liquid biogas). Another example of a new implantation is the new painting technology which is based on an airless paint atomizer that promotes energy saving through static electricity (Toyota Motor Corporation, 2022)

Volkswagen Group

Traton is subsidiary of the Volkswagen Group and is one of the largest commercial vehicle manufacturers in the world that encompasses brands such as Man, Navistar, Scania and Volkswagen trucks and buses in Brazil. Volkswagen Group is planning to either reduce or offset their emissions. Unavoidable emissions will be offset by different international climate protection programs. Volkswagen is initially concentrating on active forest protection and reforestation in the tropics. Electricity used at all their European production sites will become renewable sourced. For the company, emission free power supply is a priority, which will mostly consist of sourcing renewable electricity (Volkswagen AG, 2021).

Several measures are planned such as improved LED lightning, modern heat and cooling solutions, further optimization of washing and drying procedures. For example, there are several efficiency measures planned such as for optimization of the thermal afterburning for the painting process, smarter fans, and improved air compressors. In addition, several manufacturing processes at the Porsche site run on biogas. Another example is the Zwickau (Germany) electric vehicle plant has CHP system that will in the future only run-on carbon neutral gas. Regarding circular solutions, Volkswagen is increasing their usage of secondary materials and is closing several material loops. For example, an aluminum closed loop project is focusing on closing the loop by delivering scrap from the press to the original supplier (Volkswagen AG, 2021). The sustainability approach that Traton Group employ follows a decentralized pattern where the different brands set priorities and implement measures based on their organization. Therefore, it becomes interesting to review brands individually such as Man and Scania.

Man Trucks & Bus

MAN truck & Bus is aiming to shift toward green electricity and source heat from carbon neutral sources. For example, purchasing of green electricity for the sites in Salzgitter (Germany), Starachowice, Krakow (Poland) and Resende (Brazil). The Nuremberg plant will source energy from district heating. There are several plans to increase the efficiency of the production sites. For example, new production system in Resende that follows the industry 4.0 concepts. This system will run on increased efficiency, productivity and generate less waste. Regarding the recycling and waste management, prioritization for the reuse of metals in the foundries are being made. In addition to this, the Nuremberg site has started purchasing reutilized scrap from processes that are external to the company. Overall, there is an increase in recycling of chips and scrap within the sites (MAN SE, 2021).

Measures used for lowering CO_2 emission that have been listed are utilizing cogeneration plants, utilizing groundwater for cooling applications and excluding diesel for engine testing purposes. Also, the production in Pinetown (South Africa) is going to solely be powered by solar energy. MAN truck & Bus is slowly moving away from offsetting emission techniques such as CO_2 certificates and considers it only as a mean to deal with residual emissions, since it is considered “very critical and no longer acceptable” (MAN SE, 2022).

Scania

The company aims by implementing continuous improvements, eliminate energy waste and improve the energy efficiency by measures such as optimizing heat, production processes, lightning, and ventilation. Sourcing of fossil free electricity is a priority of all the production sites. For example, in the production site of Oskarshamn all paint shop ovens are powered by fossil free fuels. Circular economy is emphasized through the activities present within the whole company. For example, maximization of resources and minimization of waste are pointed out as relevant measures (Scania AB, 2021).

Ford Motor Company

The overall strategy for reducing carbon is framed in two categories. These are clean energy and energy waste reduction. Clean energy is achieved by sourcing renewables that have zero to low emissions. Energy waste reduction is achieved by increasing the energy efficiency. The renewable energy is planned to be sourced from local providers and independent developers. Goal to use 100% locally sourced, renewable electricity at all Ford plants by 2035. Installation of 13.5 MW of solar electricity in parking bays, delivering part of the plant's annual electricity requirements in South Africa. In the Michigan assembly plant, the renewable energy will consist of solar power, wind, and hydrogen. Energy efficiency measures consists of improvements for compressed air, pumps, and heating systems. To increase the availability of renewable energy sources, parking spaces are being converted to solar PV areas (Ford Motor Company, 2021).

Ford is reviewing 3D printing production methods for commercial vehicles parts and tools to help close the loop and increase material efficiency. In addition to this, the close loop aluminum recycling system has been expanded where it can recover the material at a higher quality (By keeping the aluminum alloys separated) during the stamping process (Ford Motor Company, 2021).

CNH industrial

Within CNH industrial there is a division reasonable for commercial vehicles. This division manages brands such as IVECO which is a large manufacturer of commercial vehicles. The company has implemented nanotechnologies in their painting processes. More specifically it is used in the pretreatment of surfaces. This method has several benefits due to the process taking place in spaces with room temperature. Thus, there is no need for heating which saves energy requirements. This technology is currently being used in 33 paint shops around the world (CNH Industrial N.V, 2021).

There are several projected in the field of waste management that aims toward waste minimization. For example, the Cordoba (Argentina) plant has implemented machines that recycle metal scraps and recovers cutting oils. Another example is the project at the Indian plant where a composting unit produces biological waste that is converted to manure for fertilizing the areas around the site. Another priority is decreasing the use of fossil fuels and optimizing the energy consumption. This partly done by sourcing renewable electricity and increasing renewable energy sources. In addition to this, there are technological measures being implemented for increasing the energy efficiency and decreasing the emissions. Among these measures such as replacement of old heating systems, increasing the efficiency of compressed air and replacement of burners (CNH Industrial N.V, 2021).

Daimler

Within Daimler Group there are several brands such as Mercedes-Benz, Freightliner and Fuso. The company focuses on eliminating GHG emissions that derive from the energy supply and the production of vehicles. Its goal, called ambition 2039, includes having all European plants have CO_2-neutral production and all plants worldwide have a carbon-neutral energy supply by 2022. It is planned that sustainable energy will be supplied for all the German locations with hydroelectric, solar and wind power for the manufacturing plants that can sustain energy needs up to 100% of the electricity demand. There are also plans to build PV systems in multiple international locations. The new factory number 56 located in Sindelfingen is focused on energy-efficient solutions. In addition to this, a PV system has been installed on the roof of the building. The power that is generated from the PV system is directly transmitted to the direct current network which eliminates losses up to 10-15%. Furthermore, to achieve supply security a battery storage unit has been installed at the facility (Daimler AG, 2021).

Daimler Group has also been investing in the realization of sustainable heat supply. This will be accomplished by usage of biomass, biogas, and geothermal energy. Furthermore, heat pumps powered by renewable electricity will be deployed in the manufacturing facilities. For example, the Jawor (Poland) site derive heat from biomass pellets and a boiler that is powered by renewably sourced biomethane. Certain emissions are classified as unavoidable, such as for the natural gas-powered cogeneration plants. Therefore, different projects are being implement for offsetting carbon emissions that follow gold standards. For example, Daimler is involved in projects that both offset CO_2 emissions and promote renewable based energy supplies for countries such as Indonesia (Daimler AG, 2021).

		VOLKSWAGEN	MAN	SCANIA	Ford	CNH INDUSTRIAL	DAIMLER
Fuel shift	Making their own hydrogen to power forklift trucks using electricity from solar panels and utilised hydrogen fuel burners for combustion processes. Natural gas will be replaced by biogas in boilers.	Several manufacturing processes at the Porsche site run on biogas.	Excluding diesel for engine testing purposes.				Sustainable heat supply with biomass, biogas and geothermal energy. Use of renewable sourced biofuels such as biomass pellets for heat pumps and biomethane for powering boilers.
Structural change	Toyota is increasing the renewable share of electricity. In different locations, wind power generators and solar panels will be implemented.	Electricity used at all their European production sites will become renewable sourced. For the company, emission free power supply is a priority, which will mostly consist of sourcing renewable electricity.	MAN truck & Bus is aiming to shift towards green electricity and source heat from carbon neutral sources. Moreover, the production in Pinetown (South Africa) is going to solely be powered by solar energy.	Sourcing of fossil free electricity is a priority of all the production sites. For example, in the production site of Oskarshamn all paint shops ovens are powered by fossil free fuels.	Use 100% locally sourced, renewable electricity at all Ford plants by 2035. Installation of 13.5 MW of solar electricity in parking bays, delivering part of the plant's annual electricity requirements in South Africa.	Decreasing the use of fossil fuels by sourcing renewable electricity.	Renewable energy sourcing. Buying hydroelectric, solar and wind power for the plants and investing in in-house power generation (solar cells). Heat pumps powered by renewable electricity will be used in the facilities.
Carbon capture	Plans to develop CCS and CCU.	Carbon credit projects. Unavoidable emissions are compensated by climate protection projects. Volkswagen is initially concentrating on active forest protection and reforestation in the tropics.					Implementation of projects to offset CO2 emissions. For instance, Daimler is involved in projects to promote renewable based energy supplies for countries like Indonesia.
Process efficiency	Close monitoring, smart insulation, and state-of-the-art lighting.	Optimization of the thermal afterburning for the painting process, smarter fans, and improved air compressors Further optimization of washing and drying procedures.	Plans to increase the efficiency of the production sites. For example, new production system that follows the industry 4.0 concepts. This system will run on increased efficiency, productivity and generate less waste.	Implementing continuous improvements, eliminate energy waste and improve the energy efficiency by measures such as optimizing heat, production processes, lightning, and ventilation.	Improvements in key areas: lighting, compressed air, rotating equipment (fans, pumps and motors) and heating systems.	Optimization of the energy consumption. Replacing old heating systems, burners, and increasing the efficiency of compressed air and replacement of burners.	Continuous increase in the energy efficiency. Example: Directly transmission from in-house solar cells to the network which.
Technological replacement	Implementation of new painting technology, based on airless paint atomizer that promotes energy saving.	The Zwickau (Germany) electric vehicle plant has CHP system that will in the future only run-on carbon neutral gas.	The Nuremberg plant will source energy from district heating .		Ford is reviewing 3D printing production methods for commercial vehicles parts and tools to help close the loop and increase material efficiency.	Implementation of nanotechnologies in the painting processes for the pretreatment of surfaces. No need for heating, which saves energy.	
Circularity		increasing their usage of secondary materials and closing several material loops. For example, aluminum closed loop project focusing on closing the loop by delivering scrap from the press to the original supplier.	Prioritization for the reuse of metals in the foundries are being made. Overall, there is an increase in recycling of chips and scrap within the sites.	The role of circular economy is emphasized through the activities present within the whole company. For example, maximization of resources and minimization of waste are pointed out as relevant measures.	Close loop aluminum recycling system has been expanded where it can recover the material at a higher quality.	Waste minimization. Recycling metal scraps and recovering cutting oils in Cordoba, Argentine and composting unit to reduce biological waste and converted it to fertilisers in India as examples.	

Figure 6. Overview of automotive companies' relation to the developed framework.

4.4 Interviews

In this section, the interviews have been collected and categorized. An overview of all interviews in provided in Table 6. This includes the departments where the interviewees are employed at, their positions as well as a short description of their work and the relevance to their inclusion in the study. A summarized view of the interviews transcriptions is provided in the appendix.

Table 6. Overview of interviewees

Interviewee	Department	Position	Description and relevance
A	Volvo GTO Brazil and Europe Manufacturing	EBM Regional quality & environmental manager	Interviewee A is employed as a coordinator for sustainability for facilities under Europe & Brazil manufacturing, having knowledge on Bourg En Bresse, Curitiba, Ghent, Tuve and Umeå. This employee has a broad overview of common practices when it comes to CVA plants across continents.
B	Volvo GTO Quality and Engineering	Head of environmental acting	Works with coordination and support for the environmental community within GTO. This employee has an elevated position within the GTO environmental community and functions as a coordinating actor, having knowledge on recurring environmental measures.
C	Volvo GTO Powertrain Production	Environmental manager powertrain	Has an overview of several powertrain facilities. More specifically, this interviewee is knowledgeable about the Curitiba engine plant.
D	Chalmers University of Technology	Doctoral student	This interviewee is a doctoral student within the department of energy technology at Chalmers, having extensive knowledge on CCS when it comes to the industry.
E	Volvo GTO Powertrain Production Skövde	Process engineer	Has worked at the foundry for more than 30 years as a manager. However, for the last years the employee has been working with R&D with the aim of reducing CO_2 emissions. Has valuable knowledge regarding the melting process and environmental concerns regarding it. This employee was interviewed two times.
F	Volvo GTO Umeå	Masterplan & Investment coordinator	Works with investments and changes related to the Umeå plant. This employee has knowledge on how environmental investments and implementations are prioritized.
G	Volvo Group Real Estate	Sustainability manager	Works predominantly with projects handling sustainability issues connected to real estate and property management. This interviewee has insights on how different energy supplies are sourced and the difficulties associated with it.
H and I	Vinnova	Program managers, industrial technologies	Interviewee H is a program manager, with a PhD in production engineering and an industry background with sustainability questions.

			Interviewee I is a deputy area director for sustainable industry, also holding a PhD in production engineering. Both are leading several projects for green industry transitioning. Both were able to give an outside perspective to the project.
J	Volvo Group Real Estate France	Property project manager	This employee works in Lyon as a project manager for real estate. Oversees energy optimization and management for the Lyon site, including production facilities both inside and outside GTO. Has extensive experience in increasing energy efficiency of systems.
L	Volvo GTO North America Manufacturing	Director quality	Interviewee L Is part of the quality and engineering organization, a member of the GTO environmental community and has worked as an ISO 14001 auditor. This interviewee brings the North American manufacturing perspective to this report.
M N	Volvo GTO Powertrain Production Hagerstown	Environmental manager & Environment, energy, and sustainability engineer	Work with permitting, regulations, air quality, wastewater discharge permits, hazardous waste streams and others on the regulatory side. Both employees work with the Hagerstown facility and can give good insights in how the facility has decrease its emissions.
O	Mack Trucks	Health, Safety, Environment & Energy management	Has worked with health safety and environmental questions for 37 years. In the last 10 years, the interviewee has worked with energy decarbonization issues. This employee has a board overview of the energy system and plans for energy management in North America.
P	Volvo GTO Powertrain Production Skövde	Experienced engineer environment	Is employed at the Skövde site and oversees several environmental projects. Works directly with environmental projects regarding the most emitting facility in the GTO organization.
Q	Fossil Free Sweden	Project manager	Works at fossil free Sweden to coordinate Sweden's effort to decarbonize society. Gives a good insight on implemented measures and issues regarding decarbonization in Sweden.

4.5 SWOT & Feasibility assessment

The solutions that are investigated with the SWOT analysis have been selected based on two criteria. First, they were identified based on the information that was provided by the interviews. Since the interviewees constituted a crucial source of data in this study, a preference has been assigned to the topics in which the interviewees could comment on. Second, the topic's relevance for Volvo GTO was considered when deciding upon the solution as well. In total, 14 solutions are analyzed.

Figure 7 exemplifies how the solutions are presented once the SWOT analysis is undertaken (Tables 7 to 20). The scale shows the result of the feasibility score for each solution that has been analyzed. Zero stands for a solution that has been deemed unfeasible for weaknesses and threats posing major setbacks that cannot be balanced by strengths and opportunities. Otherwise, a value between one and three has been assigned. One represents low feasibility, two a medium range and three meaning that the selected solution offers great chances of success. This is applied to Figures 8 to 13.

In order to consider the knowledge perspective of Volvo for each solution, which can be seen as a strength, the dots that mark the feasibility show how far the organization has come with the implementation or consideration of each solution. The darker the dot, the further has Volvo come with the solution. It ranges from having not considered it at all to having already implemented the solution. In between, one can have 'has been considered' and 'under trial'. Overall, if a solution contributes to decarbonization for one specific facility alone, it has been considered that this given measure also contributes to the overall GTO community. Thus, increasing the total feasibility.

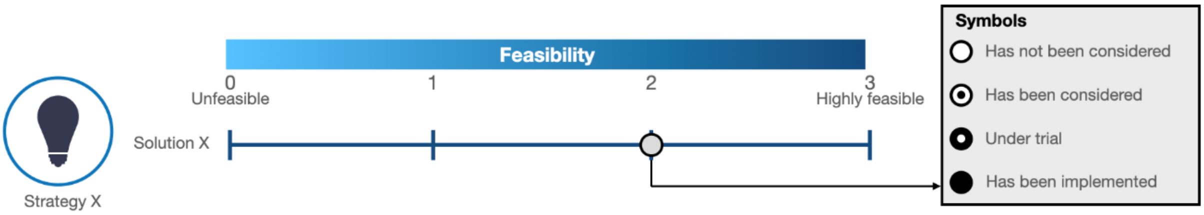

Figure 7. Example of feasibility presentation.

4.5.1 Fuel shift

Biodiesel, HVO 100, biogas, HTC bio-coke and hydrogen are considered fuel shift due to their ability to be integrated in the existing infrastructure without requiring major technological replacements. Figure 8 depicts the results of the SWOT analysis. As seen, a feasibility score of two is assigned to Biodiesel and HVO 100, both of which are already implemented in the organization. The HTC bio-coke is assigned a feasibility score of one and is currently under trial. When it comes to hydrogen, it is assigned a feasibility score of one and it has been considered but not implemented.

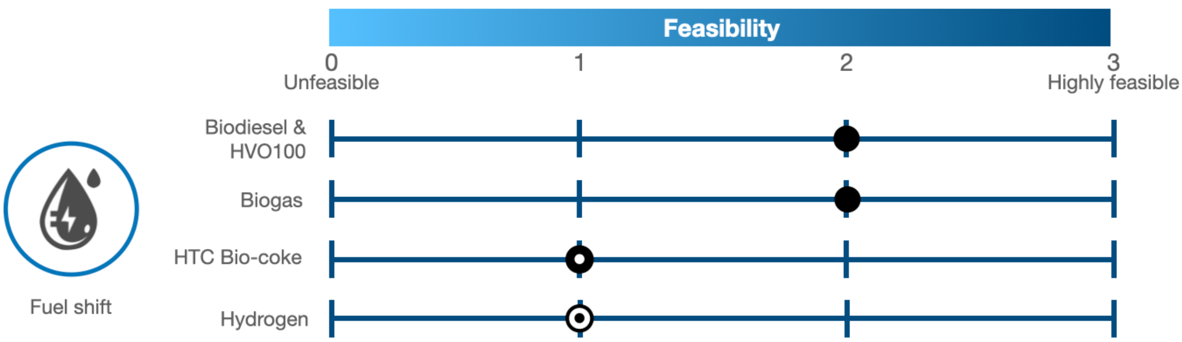

Figure 8. Feasibility for solutions under fuel shift strategy.

Table 7. SWOT analysis for Biodiesel (B100) & HVO100.

Biodiesel (B100) & HVO100
Strengths
These fuels have the possibility to be either utilized at the concentration of 100% or be blended with fossil fuels. The foremost advantage of biomass-based fuel is that they do not damage or require modifications to the engines (Verger et al., 2022). For instance, interviewee L states that HVO100 runs on Volvo engines, without need for modification. This is particularly valuable since these engines have already been validated according to EPA and Euro 6 standards.
Weaknesses
Biofuels contribute to air pollution when combusted (Wei et al., 2019).

Biomass requires fertilizers that are connected to emissions, so they are not entirely carbon-free (Hawken, 2017). For instance, interviewee F mentioned that HVO100 has been used to fuel transportation for internal logistics at the Umeå site. However, the HVO100 powered vehicles will be replaced with electrically driven ones in the long run since HVO100 is not one hundred percent emissions free. In this case, there were good renewable energy alternatives in the vicinity provided by the local energy companies.
Interviewee I mentioned that it will be impossible to replace all fossil fuels with bio alternatives for the simple fact that there is not enough biomass for that. According to Hawken (2017), biomass production in general competes over land with biodiversity and contributes to soil erosion along with other environmental issues.
There is a large spread in GHG emissions coming from HVO and biodiesel depending on how they are sourced and processed. Moreover, there is a large spread in production costs depending on the level of technology readiness and what production processes are being utilized. Thus, emissions and costs are not fixed (Verger et al., 2022).
Opportunities
Despite being responsible for much less emissions compared to natural gas at the selected Volvo facilities, diesel still accounts for among the largest emissions at multiple facilities, as it is the case for Curitiba Engine, Hagerstown, Lehigh Valley, NRV, Vénissieux, Bourg En Bresse, Curitiba CVA, Skövde and Wacol. Therefore, B100 and HVO 100 provides an opportunity for Volvo GTO to lower emissions across multiple facilities.
Biofuels in general have already a great market development in the United States, Brazil, Central Europe**,** and Sweden (IEA, 2020). These are places where Volvo GTO has wide operations with expressive emissions. In addition, Brazil even holds large growth potential.
Threats
Market price fluctuation. Extreme weather often leads to unsteady production rates of biofuels. In this case, Volvo GTO might just buy it from another country instead, but this will increase the emissions and costs derived from transportation (Nevzorova & Kutcherov, 2019)**.**
Interviewee L mentioned that HVO100 has been difficult to get approved on the East Coast of the United States. Volvo GTO has been active in advocating for approval since much effort is being put to adopt HVO100 as an alternative to diesel at the Hagerstown facility according to interviewee M.
According to interviewee P, demand for biobased diesel is rapidly increasing. The demand could soon surpass the market availability. Thus, prices for biobased fuels have been rapidly increasing.

Feasibility: There are several benefits with HVO100 and Biodisel100. The major benefit is that they can be used for multiple purposes such as engine testing, truck tank filling and internal logistics. This is valuable once diesel, which is usually used in these processes' accounts expressively for Volvo GTO’s emissions. However, there are several weaknesses such as not being emission free which made the Volvo Umeå facility discontinue the use for internal logistics purposes. Moreover, there are ethical concerns regarding the biomass cultivation and there are large inconsistencies on price and quality of the fuels. Furthermore, there are legislative constraints for its usage in certain facilities within the Volvo GTO network that are currently being resolved. However, the Volvo GTO facilities are in geographical areas where there is large potential for market growth. Therefore, B100 and HVO100 was given the second highest feasibility score.

Recommendation for Volvo: The diesel emissions from the Skövde facility alone contribute to an expressive share of the total emission from Volvo GTO. Therefore, B100 and HVO 100 could potentially contribute to a large reduction in Scope 1 emissions there.

Table 8. SWOT analysis for Biogas.

Biogas
Strengths
Liquified biomethane as an alternative to natural gas presents low GHG emissions, decreases nitrogen oxides and decreased particulate matter emissions (Verger et al., 2022).
In addition to replacing natural gas in processes, biomethane can offer a solution for logistics according to interviewee E. For instance, biomethane refilling stations can be constructed outside the facilities to also provide fuel for freight transports.
Biogas has great application potential for heat generation in e.g., specific boilers, or it can be used in modified natural gas boilers. Also, it can be used in CHP systems to reduce energy conversion losses when converting fuel to heat or electricity. This is particularly interesting for processes that require elevated temperature in the system (Abanades et al., 2022). Interviewee B mentioned that there are several ongoing investigations for replacing natural gas for heating, with many facilities looking into biogas as an alternative. The Gent site is using bio-propane for facility heating purposes.
Weaknesses
Interviewee E confirms that certain modifications will be required to accommodate the fuel change and not all processes can run on biogas due to certain technical requirements. For instance, old burners would have to be replaced in some cases and piping infrastructure such as nozzles would have to be adapted. This is because biogas often contain lower energy content compared to LPG.
Opportunities
Natural gas accounts for most emissions of Volvo GTO and when processes cannot be replaced or altered for specific reasons, they may just be powered by biogas instead. This is particularly pertinent for sites located in the US and Brazil, countries whose biofuel markets are sizeable and well developed.
The conflict in Ukraine has led to soaring prices for natural gas. According to interviewee G, this could imply that costs for bio alternatives will become more competitive compared to their fossil alternative.
Biogas is a resource already explored in various automotive industries. At Toyota, for instance, gas boilers that run LPG will be replaced with boilers running on liquid biogas. At Porsche, several manufacturing processes already run solely on biogas and the CHP system at the Zwickau electric vehicle plant from Volkswagen in Germany will run on biogas in the future. Lastly, Daimler Group has also been investing the realization of sustainable heat supply using among various renewable energies, biogas.
The production of renewable gases is yet to grow considerably with the price set to decrease by 25% by 2040 (IEA, 2020).

Interviewee L mentioned that by joining "Better Climate challenge" deal, Volvo at North America compromises to reduce 50% of its emissions by 2031 while getting aid from the US government in form of technical, research and development support. This will be deployed in further developing biogas projects.
When it comes to biogas, Central Europe has the largest presence of producing plants in the world. Moreover, the United States has around 2200 large-scale biogas plants (Abanades et al., 2022). The fact that Volvo GTO has major operation facilities in these areas gives it a great opportunity to regionally source this biogas.
The projected landfill gas pipeline will offset the emissions from the previous use of natural gas at the NRV and Lehigh Valley facilities. As previously shown, natural gas usage at the NRV is among the highest emitters. NRV is known to have the largest paint shop in the US according to interviewee O, currently making use of c natural gas in its processes.
Interviewee L states that in the US, landfill gas costs about five to six times more than natural gas, while biomethane costs more than ten times of what natural gas does. Nevertheless, Volvo GTO is ready to invest in greener options, even if that demands higher investments.
Threats
Like biodiesel and HVO100, the supply chain and consequently the prices for biogas are heavily dependent on weather conditions. With more extreme weather events expected to occur because of climate change, the uncertainty in supply will become a bigger threat.
Not all facilities have access to this resource. This situation could only be amended in case local governments start investing in it.
Demand for biogas is only expected to increase (Johnson Matthey, 2022). For instance, its application in grey hydrogen production is gaining ground.
One threat identified based on Volvo interviewees responses is that different views on biogas as a decarbonization solution exist.
According to interviewee B, the criteria for biogas being approved by the real estate organization within Volvo GTO is strict due to certification requirements and further specifications.

Feasibility: As seen in the SWOT, there are several alternatives viable under the umbrella term biogas. Both biomethane and landfill gas are viable alternatives for the facilities depending on where they are located. Also, the organization is willing to pay a higher price for biogas in certain instances to decrease the emissions. However, the employees have different views and understanding on where biogas should be implemented. This could be seen as a threat, thus hindering its implementation. In addition to this, there are market availability concerns. Having said that, biogas provides a feasible alternative to replace LPG or natural gas in several processes that require heating such as ovens without much altering the processes.

Biogas provides a substantial possibility to lower emissions in the second most emitting facility within Volvo GTO, in NRV. Moreover, led by the war in Ukraine, biogas can become more competitive compared to natural gas in central Europe. For having the possibility to substantially contribute to the decrease of carbon emission within Volvo GTO, it is given the second highest feasibility score.

Recommendation for Volvo: The results show that biogas initiatives vary depending on purpose and location. Therefore, it is important that there is enough support for each of the facilities to find local and reliable supplier that can provide a reliable supply of biogas. Processes that consume natural gas are the most suitable ones to operate on biogas. When electrification is too expensive or other alternatives are not suitable to implement, biogas can offer a fast and more economic bridge solution toward decarbonization. For the North American facilities, particularly NRV where natural gas emissions are very large, it is important to secure funding for the ongoing landfill gas sourcing project. Facilities that only have access to an electricity mix with a large carbon footprint, could potentially benefit from biogas supply. If this is not available locally, it might be interesting for the plants to work toward a partnership sourcing in purchasing. In this way, facilities would build a collaborative business approach with small local suppliers in which it would work closely together in sharing the risks and rewards associated with a cooperative arrangement that promotes continuous improvement.

Table 9. SWOT analysis for HTC bio-coke.

HTC bio-coke
Strengths
Similar energy content, low moisture content, high carbon content and high compressive strength make HTC bio-coke a viable alternative to fossil coke. In addition, bio-coke has shown mostly good storage and transportation possibilities due to its properties (Mansor et al., 2018).
As mentioned by interviewee E, lab scale test has successfully replaced 40% of the fossil coke with bio-coke. This means that the emissions derived from the fossil-coke at Skövde can be reduced accordingly which represents a substantial decrease of emissions within the GTO network.
Weaknesses
Despite having a relatively high carbon content, bio-coke still has a lower energy density compared to its fossil alternative according to Interviewee E. As of now, the carbon content in the bio-coke investigated by Volvo has a 70% fixed carbon composition compared to 89% in fossil coke.
As mentioned by interviewee E, the HTC bio-coke must be of a certain quality to sustain the melting process. It has to its shape under 2000 degrees Celsius and under tons of overlaying material. This is something that can be hard to accomplish depending on the situation at hand.
Opportunities
As explained by Interviewee E, the biobased alternative for replacing fossil coke that has showed the best promise has been the HTC bio-coke.
According to interviewee E, the project is partially funded by a Swedish governmental entity and there is interest from the steel industry for this project to succeed. This means that there is high interest in the project from external actors.
According to interviewee E, HTC bio-coke allows the foundry at Skövde to keep operating the Cupola furnace. The benefits of the foundry are that it has the capacity to produce high quality iron at low cost and a high maintainability potential compared to other alternatives. In addition to this, the environmental advantages include the usage of a lower grade of raw material, enabling the use of external scrap, thus recycling the scrap from production. Another advantage is that by maintaining the cupula, the current knowledge among the foundry operators is conserved.
Threats

Interviewee E has been working closely with the project to implement bio-coke and it is only up to research collaborations in a specific department to ensure success of this endeavor. Also, this is considered a pioneer project at the company which has multiple uncertainties, among which lies the sourcing of bio-coke. This product is not widely available in the market; thus, it has been manufactured through cooperation between Volvo and German and Swedish manufacturers only, without any perspective on well-established and competitive suppliers.
As expressed by interviewee E, projects such as HYBRIT pose a threat to the foundry process. This is due to the steel industries intension to start utilizing scrap at higher rates which could create a scrap shortage. In turn, this decreases the benefits for utilizing a cupola foundry for melting the ore. Thus, making electrically powered furnaces a viable alternative that does not require bio-coke.

Feasibility: The HTC-bio-coke is the only promising alternative for reducing fossil-based coke and it can keep the cupola furnace in operation. However, the HTC-bio-coke is currently not ready for replacing 100% of the fossil coke and there are several properties that must be improved. Furthermore, there are no suppliers available in this case which makes it completely up to Volvo GTO to succeed in this project. In turn, there are several opportunities making the project a good initiative for helping the industry transition toward sustainable manufacturing practices. Therefore, due to the uncertainties HTC-bio-coke has been given a low feasibility score.

Recommendation for Volvo: As the main point source contributing to carbon emissions within the Volvo GTO, the cupola furnace in Skövde still offers multiple advantages compared to, for example, an electrified alternative. With that said, conserving the cupola is reasonable. Therefore, it is important that the Volvo GTO continues to support the HTC-bio-coke project.

Table 10. SWOT analysis for hydrogen.

Hydrogen
Strengths
Hydrogen is a fuel that can be produced without carbon involvement. It is burned with oxygen to produce energy and water (Rissman et al., 2020).
Hydrogen can be used as an energy storage solution when more renewable electricity is being produced than being used. It looks promising to be the lowest-cost alternative to store electricity, especially for longer time frames (IEA, 2019). This is endorsed by Interviewee H, who mentioned that hydrogen closes the gap and fills in the requirements not provided by electricity alone.
Interviewee E, who works directly at the Skövde foundry, mentioned that hydrogen would have been a better alternative to biogas in terms of being CO_2 emission-free and requiring no to little retrofitting. The ability to replace LPG or natural gas with hydrogen in burners with no to slight modifications was further strengthened by Interviewee D.
Weaknesses
Excessive costs associated with hydrogen production makes it difficult to compete with natural gas (Rissman et al., 2020). Higher costs are due to electricity price, the capital cost of the actual electrolyzers and their utilized capacity (Longden et al., 2022).

Interviewee D mentioned that although hydrogen does not produce CO_2 when combusted, it still produces nitrogen oxide emissions when combusted with air, requiring further treatment solutions which must be invested in.
Hydrogen has a major logistical setback. Despite having high energy content, it must be cooled down to have its density increased so that it becomes a viable alternative. Transportation is also problematic for the same reasons. This has been considered a main barrier for it to become widespread adopted, especially talking about large scale applications (IEA, 2019).
Opportunities
Dropping prices in renewable energy technology will make hydrogen more affordable in the long term (Longden et al., 2022).
Hydrogen-based technologies for production have been tested already in other automotive companies, such as at Toyota. This includes in-house generation facility with solar panels in Japan for forklift fueling applications. Furthermore, there are plans to utilize hydrogen fueled burners for the combustion processes (Toyota Motor Corporation, 2022) .
Threats
Hydrogen is currently not being deployed at Volvo GTO facilities, which means that there is a lack of knowledge and practice in utilizing this fuel. At Volvo GTO Lehigh Valley facility, interviewee O states that there have been some considerations to use fuel cell powered forklifts, but battery alternatives were lastly preferred for being a more straightforward solution
Even if Volvo GTO finds hydrogen to be a viable option, regulations are still limiting the development of a clean hydrogen industry in most places (IEA, 2019).
If green hydrogen is to be used, in-house production is subjected to the same conditions and factors revolving around on-site energy production, in addition to other hydrogen-specific bottlenecks.
Hydrogen can be categorized into green, blue, grey**,** and brown categories. However, only the green alternative presents zero emissions (Johnson Matthey, 2022). Today, Hydrogen is almost entirely supplied from fossil fuels. Therefore, the production of hydrogen is now responsible for CO_2 emissions of around 830 million tons of carbon dioxide per year (IEA, 2019)

Feasibility: Hydrogen offers several opportunities and benefits due to its inherent properties and applications. Furthermore, it is a promising solution when it comes to storage of energy which is increasingly becoming a challenge that needs to be solved. Moreover, there is an increasing interest within the automotive industry which helps to develop the applications further. However, there is a lack of experience within the Volvo GTO community when it comes to utilizing hydrogen in the manufacturing. Other important factor are the large costs associated with in-house production, storage, and distribution. Lastly, by being an international organization, Volvo GTO is subjected to different legislations in the different countries which decreases the feasibility of large-scale implantation of hydrogen related infrastructure. Other green fuel alternatives listed above have come further when it comes to hydrogen's major setbacks. Thus, a feasibility degree level of one has been assigned to this fuel.

Recommendation for Volvo: Volvo GTO should study how Toyota makes use of hydrogen in its manufacturing operations. However, it must acknowledge its limitations since Toyota operates in Japan, which is highly favorable to hydrogen utilization. Moreover, Volvo GTO should follow up on developments in hydrogen technology and be able to identify when it could become more attractive than other fuel alternatives. Even if its feasibility ranks low now, the scenario will become more promising over time, particularly when it comes to on-site renewable energy generation storage and as a logistic fuel.

4.5.2 Structural change (Electrification)

Solutions considered for structural change are all topics that contribute to electrification. These are on-site renewable energy, off-site renewable energy, heat pumps and CIF. Figure 9 depicts the results of the SWOT analysis for each of these solutions. Overall, they have a rather high feasibility, particularly off-site renewable energy investments and using heat pumps. All the solutions have already been implemented to some extent at Volvo GTO.

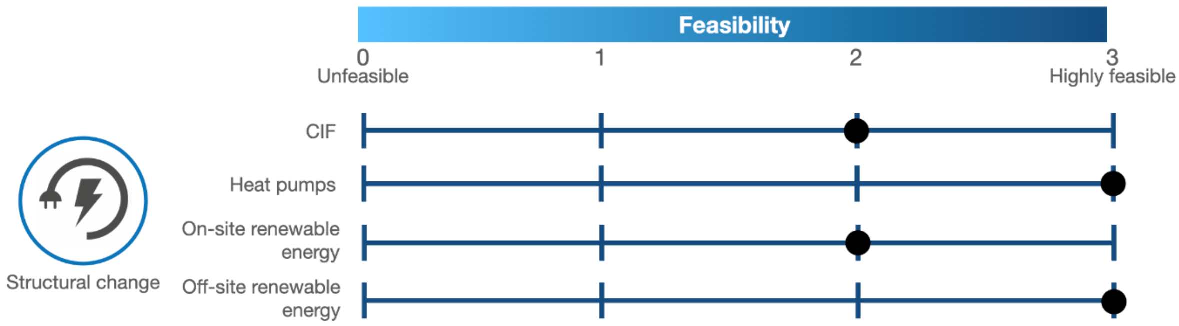

Figure 9. Feasibility for solutions under structural change (electrification) strategy.

Table 11. SWOT analysis for coreless induction furnace.

Coreless induction furnace (CIF)
Strengths
CIFs is a technology that eliminates the need of fossil coke or other fossil fuels for the melting processes that take place in a foundry. This decreases the emission for melting processes considerably. In the case of the Skövde facility, it decreases coke related emissions by 100%, which is Volvo GTO's largest point source of CO_2.
Weaknesses
CIF's electricity consumption stands for 55% to 80% of the entire energy consumption in a typical foundry (Stefana et al., 2019). Thus, making the electrified melting process highly energy demanding.
As stated by interviewee E, replacing the melting process with CIFs usually require a high investment cost. This will be the case for the Skövde facility.
As explained by interviewee E, the material quality requirements of CIFs are higher and more costly. This is further evidenced by the need of high-quality scrap which is both scarcer and more expensive. In addition to this, the quality of metallurgical waste is lower compared to the waste produced by the cupola furnace. This means that the possibility to recycle the scrap in-house is decreased.
Opportunities

According to interviewee E, about 10% of the cast iron at the Skövde facility is produced by electric CIF furnaces. This means that there is already knowledge inside of the company making a good opportunity to scale up.
Energy losses associated with CIF furnaces are heat losses (Stefana et al., 2019), offering an opportunity for heat recovery solutions.
As explained by interviewee E, from the perspective of upper Volvo management, investing in CIFs is the preferred option and the high investment cost is not seen as a barrier.
There are employees inside Volvo GTO who are working with securing governmental funding that stretches up to 30% of the investment cost for completely replacing the cupola furnace with CIFs.
Threats
As previously mentioned, the increased material quality requirements of CIFs are higher and scarcer. This could lead to the increased logistical activities such as increased transports and longer routes that have the possibility to impact Scope 3 emissions.
According to interviewee E, the complete replacement of the cupola furnace with CIFs at the Skövde facility will require an increased installed power capacity of 40 MW which is a considerable amount of power that further increase the strain on an already volatile local electrical grid.
The foundry personal will have to be increased with 15 employees which represents an increased cost for the company.

Feasibility: CIFs represent an advantageous alternative for Volvo GTO to reduce all the emissions produced from fossil coke, putting the organization on track with the goal of reducing 30% of the total emissions by 2025. Moreover, it is the preferred alternative from the perspective of the organization which is working on securing funding for the investment cost. However, there are tradeoffs for replacing the cupola furnace with CIFs. Two of the biggest tradeoffs are that the material requirements are higher, and the circularity of the melting process is decreased. In addition to this, this replacement will require a considerable increased installed power capacity that will have to be accommodated by the local energy supplier. The electricity consumption will be increased significantly which either must be offset by RECs or by expanding the on-site renewable energy. To conclude, the CIFs were given the second degree of feasibility due to the identified tradeoffs.

Recommendation for Volvo: The organization should secure funding for investment costs. In addition, it should continue to dialogue with the local power supplier to find ways to accommodate the electricity production required for the CIF in order to avoid strains on the local power grid.

Table 12. SWOT analysis for heat pumps.

Heat pumps
Strengths
Heat pumps are more efficient and therefore use less energy than conventional heating systems. In this sense, even if they do not run on renewable energy, they produce fewer emissions (IEA, 2021c).
If powered by carbon neutral electricity, heat pumps offer a carbon free solution to heat transfer.

Since heat pumps run on electricity, they might offer a more reliable form of heat transfer than e.g., gas boilers if the local energy supply is resilient. Gas boilers rely on gas whose prices are susceptible to geopolitics. As an example of the conflict in Ukraine, fuel prices have soared, making heat pumps a cheaper alternative.
There are several types of heat pumps and each of them can be used for specific applications and in different climates. In addition to this, they can satisfy both heating and cooling needs (Ahmed et al., 2022).
Weaknesses
According to interviewee G, the cost of heat pump solutions can be substantial if the heat pumps are used for replacing natural gas-powered burner systems. The high cost is attributed to the need for installing new heat-driven water systems. This is particularly the case for buildings within the Lyon site that lack heat-driven water systems.
A setback of heat pumps, especially when compared to boilers is that they cannot produce heat with an elevated temperature difference in a very short space of time. Therefore, their usage for some manufacturing processes which require fast and high heat is limited
Opportunities
If both electricity and fuel prices are high, it is more worth using heat pumps since higher energy prices increase the value of cost savings relative to capital cost, which improves the payback (U.S. Department of Energy, 2003).
It is predicted that heat pumps can satisfy 90% of the global water and space heating (IEA, 2021c) and according to the International Energy Agency, a 30% penetration of the building sector by heat pumps could reduce the world's CO_2 emissions by six percent, which is believed to be one of the largest contributions of any technology currently on the market (Hawken, 2017).
Threats
Interviewee G: Heat pumps are viewed as viable alternatives. However, their feasibility can be lowered depending on the size of the facility due to large sized facilities requiring larger and more numerous pumps.
Heat pumps are a technology that requires electricity to operate. This means that large scale deployment increases the strain on the electrical grid. Especially in locations such where the electrical grid is unstable, and prices are volatile.

Feasibility: Heat pumps are overall, very efficient heating system solutions. They also offer a carbon-free alternative for heating and cooling applications when powered by renewable electricity. However, initial investments might be too high for this alternative to become economically viable and in places where gas prices are low or energy prices are high, they will not find much application once gas boilers present a cheaper option. This is the case for the North American and French facilities, as identified with the interviewees' responses. In addition to this, scarcity of renewable electricity could be seen as a threat. However, the French facilities are starting to increase their heat pump solution to decrease their natural gas usage. Heat pumps are, in addition, a great option for heat recovery, which has major potential in curtailing emissions. Thus, a score of three has been given to its feasibility.

Recommendation for Volvo: Heat pumps are an interesting solution that has a great potential for decarbonizing heating and cooling. Therefore, it is recommended that Volvo GTO investigates the possibility to increase their investment in this technology at locations where the technology is not widespread. Some examples are the North American facilities, which are also places with scarcity of renewable electricity. Also, other sites are suitable for its implementation such as Curitiba and the European sites. Emission from increased electricity use could be initially offset by I-RECs or GOs.

Table 13. SWOT analysis for on-site renewable energy.

On-site renewable energy
Strengths
On-site renewable energy can be harnessed through PV and windmills that can be put on top of buildings or somewhere on the facilities' site using unused space (Ahmed et al., 2022).
If implemented close enough, both transmission and distribution losses are minimized through direct suppling to the building system (Ahmed et al., 2022).
Weaknesses
The Volvo GTO facilities might not be located in places with optimal features for solar or wind energy production. Moreover, these are intermittent energy sources, meaning that the energy supply can vary with weather conditions. In that case, energy storage solutions would have to be implemented, creating a need for expensive storage systems.
Opportunities
Volvo GTO has defined targets to increase the share of renewable energy usage by 75% toward 2025. On-site renewables can contribute to this share.
Solar thermal panels could be used for heat generation, with an efficiency of up to 70%. This system can be connected to boilers or integrated with thermally driven air conditioners (Ahmed et al., 2022). This will lower electricity requirements.
Renewable energy has been shown to have an expressive potential to be integrated into the paint shop. A solar thermal technology developed by Dürr and presented in this report can provide heat to ovens for the paint curing process. Following this, a heat cascade strategy can be established taking into consideration the different temperature requirements in the paint shop (Giampieri et al., 2020).
There are several facilities within Volvo GTO that are utilizing solar PVs both on building roofs, on factory grounds and on parking roofs. This means that there is knowledge within the company that can facilitate further implementation of this specific technology.
As mentioned by several interviewees, expected overgeneration of on-site generated renewable electricity provides the opportunity to store it and sell it back to the grid.
It has been mentioned by multiple interviewees that transitioning from an internal combustion engine toward BEV will impact production in various ways. Batteries will have to be charged and tested and this will lead to an increase in electricity consumption which in turn leads to increased costs. In addition to this, the final assembly operations will get more complex which can result in an increased electrical consumption. Interviewee G explained that it would be beneficial for Volvo GTO to ensure that the BEV trucks are charged with 100% on-site renewable electricity before delivery. Thus, on-site renewable investments can have a great contribution to bringing down emissions.
Threats

Some aspects have been mentioned by interviewee G that can affect on-site renewable implementation. Some issues to be addressed are countries' legislations; the roof's ability to sustain the extra load; the roof's age in case it would have to be replaced or renovated; plans for future application of that specific land plot in the facility; the ownership and who is responsible to operate the equipment to mention a few. This is particularly the case for wind power, where regulations tend to be stricter in most countries.
As mentioned by several interviewees, there are disparities in the possibility for net-metering in certain regions where the facilities are located in. In some places there are regulatory constraints to sell electricity back to the grid when more is produced than used. This might increase pressure on the requirements for on-site energy storage solutions.

Feasibility: In summary, the main challenges preventing the implementation of on-site renewable energy are administrative and legal in nature. If a facility has space and is located within suitable climatic conditions, care must be taken to coordinate it with legislation and to define who will be responsible for maintaining the equipment. The investment costs tend to be paid off in a short time, but one must also recognize the limitations of getting the power supply from the site when compared to off-site. It is usually very difficult to get a large part of the energy supply from local sources, with high investment costs needed. On the other hand, the extra energy required to charge EV batteries for testing and delivery could more easily be supplied by on-site renewables. A feasibility grade of two has been assigned to this solution.

Recommendations for Volvo: On-site renewable energy should be particularly investigated for those facilities that are in places with few or no low-carbon power sources on the grid, such as the North American power plants. In such places, even powerful strategies like electrification will have no effect if the energy matrix has a strong carbon footprint. In addition to this, the organization could plan for a smart electrified infrastructure at the manufacturing sites that can charge EV batteries with renewable self-generated electricity for testing and delivery.

Table 14. SWOT analysis for off-site renewable energy.

Off-site renewable energy
Strengths
There are several ways for companies to source renewable electricity. One way is to purchase electricity from an independent green power producer with so-called power purchase agreements (PPAs). Renewable electricity can also be obtained by purchasing green tariffs from ordinary companies through a contract. Lastly, one may continue to consume average electricity but purchase renewable energy certificates such as renewable energy certificates (RECS) and guarantees of origin (GOs) (Renewable Energy Agency, 2018).
Weaknesses
Off-site renewable electricity in the form of PPAs or power purchase agreements might not always be available for Volvo GTO to be acquired.
Opportunities

In case renewable energy is not available in the local grid, interviewee O mentioned that RECs can be obtained. These certificates act as an alternative way to achieve carbon neutrality that compensates for the lack of direct renewable electricity possibilities in the local grid.
All the automotive companies listed include renewable energy supply as their main strategy for obtaining energy.
Threats
The supply of renewable energy is not the same at the different locations where Volvo GTOs facilities are found at. Some facilities will benefit because they are located in countries that have more availability of this resource, but others will have to pay more for acquiring compensation certificates.
Although purchasing credits for offsetting emissions is considered a common procedure, it does not change the fact that facilities contribute to the emissions of carbon dioxide (Doleski et al., 2022)
Some locations and energy suppliers still lag behind when it comes to certifying green energy. According to interviewee C, 99.6% of Volvo Curitiba CVA's electricity comes from renewable sources. However, the company's official data is stated at a much lower figure. This is because the local energy supplier does not provide the necessary documentation to account for the green energy produced. Thus, the national grid emission factor had to be used which accounted for a large part of the Scope 2 emissions. For the year 2021, there was not much rainfall in certain regions, leading to a national decrease in the availability of hydropower. This in turn resulted in the increase of emissions from electricity production.

Feasibility: Renewable energy is becoming increasingly cheaper over time and even if it is not available everywhere, it can still be purchased through RECs or GO procurement. RECs are not free from criticism. Some entities claim that purchased certificates can be misused and that it is not an ideal way to deal with emissions, but overall, their market has been growing at a fast pace with increasing international recognition. Based on the interviewee's responses, screening is a necessary method for collecting information on renewable energy suppliers and Volvo GTO has worked to expand its knowledge of it, as well as for the national grids of the locations it operates. One problem is the extensive number and wide range of energy contracts within the company, which makes it complicated to determine future steps and opportunities for collaboration. Nevertheless, once this is achieved, various benefits will be obtained.

All things considered, off-site renewable energy is the only way to achieve substantial carbon reduction. Efficiency gains will always have a limit. Also, processes can be electrified, but this has no effect if the energy used has a high carbon footprint. Thus, a maximum grade of 3 has been assigned to its feasibility.

Recommendations for Volvo: Even if RECs and GOs provide an accessible way for offsetting emissions. Volvo should avoid regarding the purchase of RECs and GOs as the priority and only utilize them if no other option is available. The priority should be to move away from multiple energy providers and initiate more long-sighted agreements with trusted and more established actors. However, for short term solutions, RECs should be considered. A suggested application of certificates would be for the Wacol facility in Australia, which has high emissions arising from energy purchases. In this case, the certificates would have to be sourced from the national system.

4.5.3 Carbon capture

The solutions considered for carbon capture are three: CCS; CCU; and DAC (Figure 10). The feasibility has been ranked unfeasible for all of them. In addition, none of the solutions has been implemented at Volvo GTO even though CCS and CCU have been considered.

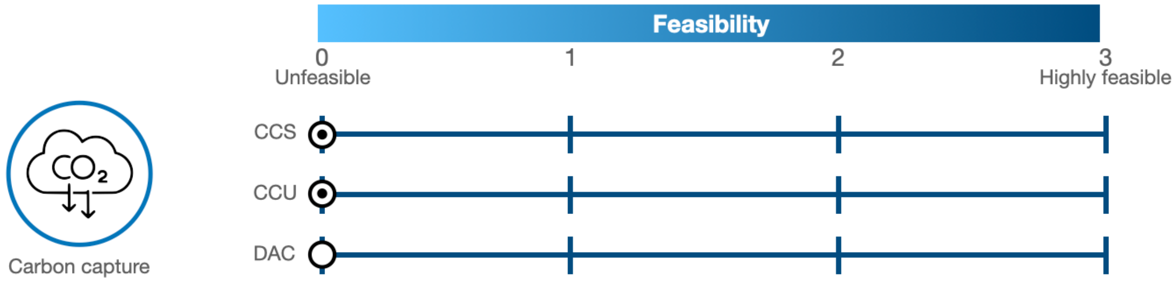

Figure 10. Feasibility for solutions under carbon capture strategy.

Table 15. SWOT analysis for carbon capture and storage

Carbon Capture and Storage (CCS)
Strengths
No need to retrofit, replace or restructure manufacturing processes or systems since it is an end of pipe solution (Rootzén, 2015).
Current measures to reduce carbon emissions will not suffice to meet climate targets, creating a need for negative emission technologies (Bauer et al., 2022). Moreover, 100% efficiency in eliminating carbon emissions is impossible to achieve within the industry and CCS can cover for the residual emissions (Fitzpatrick & Dooley, 2017).
Weaknesses
The foundry at the Skövde facility is GTO's largest CO_2 point source emission but it contributes to less than 30 000 tons CO_2 per year according to interviewee E. This lies behind what Interviewee D advised to be the techno-economic margin for making CCS economically feasible, about 100 000 tons CO_2 a year.
A requirement to implement CCS is a high enough CO_2 concentration in flue gases (Leeson et al., 2017). Even if the scale of emissions is in line with what interviewee D pointed as an optimal amount, there could still be limitations for Volvo GTO to implement if the CO_2 concentration is too low.
In addition to cost issues, interviewee D stressed that the captured carbon would need to be stored somewhere and large storage possibilities are yet to be developed in most part of the world.
According to the Volvo GTO mitigation strategy for GHG emissions, offsetting methods and technologies have the lowest priority.
Need to combine flue gas streams that have different properties (Leeson et al., 2017). This could decrease the economic feasibility of the technology.
Multiple interviewees have stated that they are interested in such technology. However, Volvo GTO lacks the expertise and experience in the field. Moreover, CCS equipment such as chemical absorption plants require space for construction and personnel dedicated for the operational phase.
Opportunities

When it comes to the automotive industry, Toyota for instance has also shown interest in developing CCS and CCU solutions for their plants (Toyota Motor Corporation, 2022). This demonstrates that this technology is attractive for other companies in the field. Since the technology finds itself in its early stages, there is an opportunity for Volvo GTO to invest in it and become a pioneer in adopting carbon capture technologies for its own facilities.

Threats

Lastly, offsetting solutions alone do not lead to a carbon-free society since it does not get rid of carbon in the production cycle, which is one of the goals of manufacturing decarbonization. Other automotive companies are thus, moving away from it and has even been considered "very critical and no longer acceptable" (MAN SE, 2022).

Feasibility: Although CCS offer multiple opportunities, the major weakness is the low emissions rate of the facilities within Volvo GTO which makes the alternative not economically feasible. In addition to this, CCS does not require the discontinuation of utilizing fossil-based material which is prioritized in front of different offsetting technologies by the Volvo GTO mitigation strategy. Therefore, the weaknesses and threats identified are more substantial than the opportunities this technology contributes with. Moreover, no strengths were identified. Thus, CCS was deemed unfeasible.

CCU: CCU follows the same SWOT logic as for CCS. However, it is not subjected to the weakness of permanent storage which is still not available for large scale applications. As mentioned by interviewee E, CCU was considered for the foundry at the Skövde facility with the implementation of biomass production through algae cultivation. Low economic margins and the large area needed for algae cultivation resulted in low feasibility for this technology and the project was discontinued.

DAC: Interviewee D mentioned that DAC could be an interesting alternative to CCS for Volvo GTO in the long run for lowering emission that are hard to abate. In addition to this, it could pose an opportunity if Volvo GTO will be forced to partake in ETS (Emission Trading System) schemes and for future carbon tax regulations. However, this technology is currently not available at a large scale which is reflected on the price per amount captured carbon (IEA, 2021a). Therefore, DAC was deemed unfeasible.

Recommendation for Volvo: Carbon capture technologies could be interesting in the long run for Volvo GTO. However, currently they are not a priority and other strategies should be prioritized.

4.5.4 Process efficiency

The only solution included under process efficiency is continuous improvements. Overall, continuous improvements can contribute to higher process efficiency both in terms of energy and material. In Figure 11, one can see that it is assigned the second grade. It has been assigned as a solution that has already been implemented at Volvo because the company has included optimization in its environmental strategy.

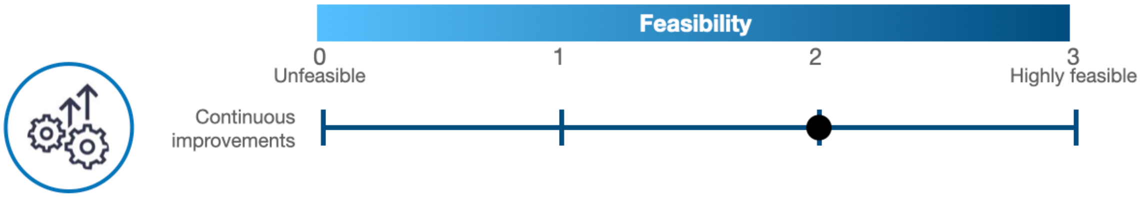

Figure 11. Feasibility for solution under process efficiency strategy.

Table 16. SWOT analysis for efficiency improvements

Continuous improvements
Strengths
As stated by the interviewees, making small changes and fixes on existing equipment does not require any substantial capital investment. In addition to this, the activity of improving efficiency can be integrated in daily routines and activities.
Efficiency improvements can be made for both production and building related matters which makes this strategy versatile. It can be achieved by replacing appliances with newer versions or prolonging the lifetime of current ones
By maintaining and improving existing equipment it prolongs the lifetime of the machines and appliances. This avoids the need for new investments and decreases the material usage of the company.
As mentioned by interviewee A, efficiency improvements are not confined by geography which means that different measures can be implemented in. Therefore, it creates a good opportunity for knowledge sharing.
Weaknesses
As explained by interviewee A, most of the activities associated with efficiency improvements require both time and personal. Therefore, some improvements could be left out due to time constraints.
At a certain point, the efficiency improvements for a certain machine or appliance will run out and only marginal improvements can be made. In this case, there is the option of replacing the current machines or appliances with newer iterations or completely replacing them with other technologies.
Opportunities
As mentioned by interviewee B, environmental consciousness and ecological mindset are important qualities for employees to have. This further helps to realize that energy efficiency results in many ways such as decreased carbon emissions, Therefore, providing additional training and courses could be seen as a good opportunity to minimize energy losses.
Digitalization is a trend that according to interviewee G, can contribute to efficiency gains. This is done by consolidating information and resources into a suite of tools that enables automation, real-time visibility of remote workforce and management and enhanced collaboration. According to interviewee J, when working with energy efficiency it is important to have information on consumption patterns and the status of different appliances. Manual readings have been utilized to a large extent up till 2022 at the Lyon site which has made it difficult to measure progress. In this case, automatic reading equipment is the preferred alternative if the information is presented in a clear and structural way.

Energy mapping is an activity that is mandated by several governments where the facilities are located. The mapping is conducted at different time intervals depending on the laws and requirements. This activity provides a good opportunity for efficiency improvements and provides support for decisions regarding whether something must be improved, modified, or completely replaced.
Threats
The effort for decarbonization has had to slow down to directly related issues pertaining to COVID-19 and much focus is now on making sure that the supply chain is running at full capacity.
As explained by interviewee O, for the foremost strength of the North American facilities is the knowledge in energy efficiency which has helped the facilities make considerable gains. However, the interviewee stated, “We are currently running out of opportunity there because it has been a priority since 2009 and the major gains have already been achieved”. The interviews mentioned several examples related to efficiency improvements. For example, replacing LED-lights with newer iterations of LED-lights will not lead to the same level of energy savings. In turn, this means more costs for less energy savings. Therefore, to achieve additional improvements in certain areas, technological replacement becomes the most relevant strategy.
Certain efficiency improvements can contribute to the extended reliance on fossil fuels. For example, replacing old boilers with modern boilers. In this case, modern boilers can increase energy efficiency by about 20-30%. If upscaled, they can reduce a substantial amount of fuel needed. However, upgrading natural gas-powered boilers could have the possibility to create and extended reliance on fossil fuels.

Feasibility: The major benefit of continuous improvement is that it only requires minor changes in comparison to other solutions that revolve around more complex alterations. Volvo GTO has extensive knowledge and has had success in implementing efficiency improvements. This is also a reason for why many facilities have already reaped the most benefits from this measure and thus, have reached a very high potential for both energy consumption and emissions. A major weakness of efficiency improvements is that it requires personnel and is a time-intensive activity. However, there are certain opportunities that can increase the significance of these types of measures. One way of doing so is to educate the employees on how to integrate efficiency practices into their daily routines so that unnecessary losses can be avoided. Another opportunity is the increased digitalization which if implemented in the right way can reduce time and streamline decision making. Thus, this solution has been given a feasibility degree of two.

Recommendation for Volvo: Digitalization is a major tool to reach further efficiency gains, particularly because other kinds of improvements have been achieved in most cases. Investments in this area are necessary to keep the organization ahead of competitors. Also, digitalization can bring efficiency gains in other areas such as time savings.

4.5.5 Technological replacement

Two solutions are listed as technological replacement. District heating can support building heating and provide processes with thermal energy, being able to replace other more emitting technologies. It has been assigned a grade of two and marked as an already implemented technology within the organization. Second, paint shop solutions involve some interesting new technologies that might not have been implemented. It has also been assigned a grade of two.

For the paint shop solutions, no emphasis was given to any specific technology or painting method due to the lack of information in the interviews. Therefore, the numerous technologies were considered as a common solution as part of one of the most intensive production processes.

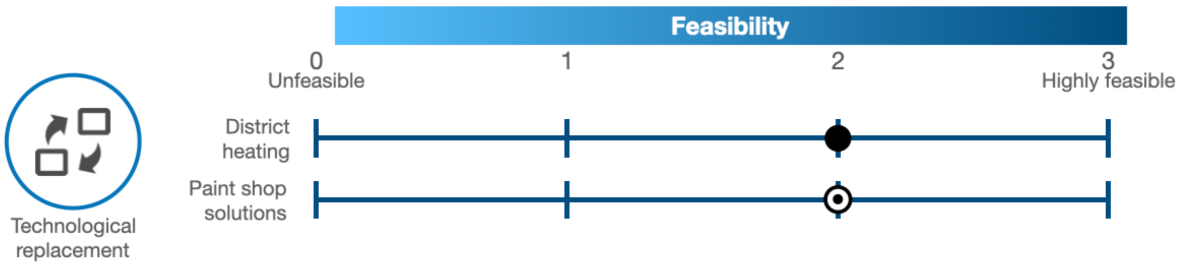

Figure 12. Feasibility for solutions under technological replacement strategy.

Table 17. SWOT analysis for district heating.

District heating
Strengths
There are several advantages with district heating such as it is usually cheaper than the price for electricity (Swedish Energy Agency, 2015).
For industrial applications, it is possible to be used for building heating and certain production processes that require heat to a certain temperature. Therefore, it minimizes the needs for electricity which can be favorable in locations with a strained electricity grid.
As mentioned by interviewee A, district heating has helped the Tuve plant to lower its emissions considerably due to it having a high quota of low carbon energy sources. In addition to this, it has proven to be energy efficient during high heating demand periods such as winter. Thus, making it interesting for the French facilities that consumes high amount of natural gas during winters.
Weaknesses
As seen for the Swedish district heating system, even with a high share of renewables, there are still CO_2 emission due to the burning of plastic waste (Fossil free Sweden, 2021). Therefore, they count as Scope 2 emission for Volvo GTO.
Approximately 90% of the world's district heating systems are powered by fossil fuels, while for Europe it is approximately 70% (Werner, 2017), making most of the district heating that is available not environmentally friendly.
Opportunities
Volvo GTO can influence the energy providers to increase its sustainable practices at a faster rate. This in turn helps the residential sector to lower its emissions which can be seen as Volvo contributing to the decarbonization of society.

For the Lyon based facilities, according to interviewee J, the district heating available in the area has a renewable energy input of about 65%. Making it an interesting alternative to replace natural gas with for certain heating and process purposes.
There are multiple opportunities for district heating to integrate sustainable technologies (IEA, 2021b).
District heating can become a negative emission energy source by e.g., implementing CCS (Fossil free Sweden, 2021). This creates an opportunity for Volvo GTO to source heat while having negative emissions.
District heating helps relieve the strain on the power grid, since it does not run on electricity.
Threats
The price for district heating changes with geographical area and by suppliers, making it difficult for Volvo GTO to decide upon this technology for all its locations.
Moreover, there is no opportunity of choosing suppliers and district heating is only available in locations where it already exists (Swedish Energy Markets Inspectorate, 2021). This means that there are limited possibilities for the GTO facilities to source district heating, especially in countries where there is a lack of infrastructure.

Feasibility: District heating offers advantages such as being an energy efficient source with cheaper prices in certain settings compared to other alternatives such as electricity. In addition to this, it provides Volvo GTO the opportunity to be part of the societal infrastructure where they can assist it and help it toward the sustainable transition. The biggest weaknesses are that it is not completely emission free, and that it is globally mostly produced from fossil fuels. Meanwhile, the biggest threats are that there is no choice of suppliers which forces the facilities to be depended on external factors and that district heating is not available in most parts of the Volvo GTO network. However, district heating has good opportunities for being integrated with sustainable technologies making it in the long run a low emission energy source. To conclude, district heating mostly provides benefits where it is possible to utilize. Therefore, it is given has been given the second highest feasibility degree.

Recommendation for Volvo: Continue to source district heating from reliable energy providers and further strengthen the possibilities of collaboration which could benefit the local communities. This is the case for the Skövde, Umeå and the Köping facility. Furthermore, it is worth evaluating the possibilities for the facilities located in France to use district heating.

Table 18. SWOT analysis for paint shop solutions.

Paint shop solutions
Strengths

While in other areas there seems to be a lack of alternatives, when it comes to the paint shop, there are several recent technologies employed to reduce emissions while conserving quality. The solutions also range in structure and nature. An example is the three-wet painting technique used by Mazda, which requires only one drying process to finish, decreasing CO_2 emissions down by more than 15% compared to conventional painting processes. Another is the aqua-tech paint system, also developed and used by Mazda, that relies on two instead of three types of coat paint and an optimized air-conditioning of the paint booth. Emission reductions in the order of 15 and 34% compared to conventional water-based paint booths have been remarked respectively.

Weaknesses

Reformulating the paint composition to lower CO_2 emissions has a major bottleneck. A preference is given to paints that present low VOC emission, which is usually the case for water-based paints compared to solvent-based ones. However, water as a diluent must be evaporated through a drying process that consumes copious amounts of energy (Giampieri et al., 2020). Balancing VOC and CO_2 emissions can be delicate, but solutions like the ones listed above can guarantee optimal results.

Opportunities

There are technologies available to also harness heat from within the facilities and further contribute to decarbonize the paint shop. An example is CHP technologies to warm up air and water. Recovering the thermal energy that would have otherwise been wasted from e.g., the paint booth exhaust air and recirculate it to heat up air and water could be beneficial in terms of curtailing natural gas requirements (Giampieri et al., 2020).

There is potential to reduce emissions in the drying phase of the paint shop using alternative curing techniques, such as infrared and ultraviolet curing. These could substitute conventional techniques and reduce energy consumption due to the lower temperature and time required by the process (Giampieri et al., 2020). However, the paint used must be curable with these specific techniques.

There are several initiates within the automotive industry for reducing the emissions from the painting process. The Toyota motor company is looking into airless paint atomizer that promotes energy saving through static electricity. CNH industrial has implemented nanotechnologies in their painting processes in the pretreatment of surfaces. This method has several benefits due to the process taking place in spaces with room temperature. Thus, there is no need for heating which saves energy requirements. The different initiatives show that there are technological replacements taking place within the industry that make it possible for Volvo GTO to reduce the dependency in processes that demand heat such as ovens.

Threats

The energy consumption for painting processes is remarkably high. Thus, it is an extra challenge to supply the whole paint shop with other types of energy than gas.

Interviewee L mentioned that the NRV facility has made major investments in the paint shop to upgrade the ovens for efficiency gains. However, these high investments have been made in natural gas technology, meaning that it will take time until the facilities can consider renovating or even replacing the upgraded ovens.

Feasibility: A challenging issue about painting processes is its high energy usage, but this also means that for the company, this is where plenty of potential lies. There are many solutions that can be used in the paint shop that have been identified as currently available and employed in other automotive manufacturers. The solutions range both in terms of complexity and maturity but overall, it seems like Volvo GTO will not run out of options available. As seen in the interviews, Volvo GTO is currently considering landfill gas for the ovens at the NRV facility and electric ovens for the Umeå facility. It is important to note that the NRV solution falls under the strategy of fuel shift and Umeå solution falls under the strategy of structural change. Therefore, they were not included in this evaluation.

A major treat that has been identified is the recent investments in the paint shops that complicate initiatives that involve major changes in the technologies. However, there are multiple solutions available and in operation that decrease emissions in the several production steps within the paint shops. Thus, due to the availability of solutions a maximum feasibility grade of two has been assigned.

Recommendation for Volvo: The solutions mentioned are proven methods for lowering the emissions of paint operations and should be reviewed when considering technological replacements in the paint shop.

4.5.6 Circularity

Heat recovery and sector coupling are the two solutions identified within circularity. Heat recovery recirculates heat and it has been assigned a high feasibility and it is a solution already implemented in many of the organization's facilities. Sector coupling has been considered a circular measure since it contributes to a well-integrated energy system making use of circular technics. Some of these technologies are already implanted while others are currently under trial. For it, a grade of two has been assigned.

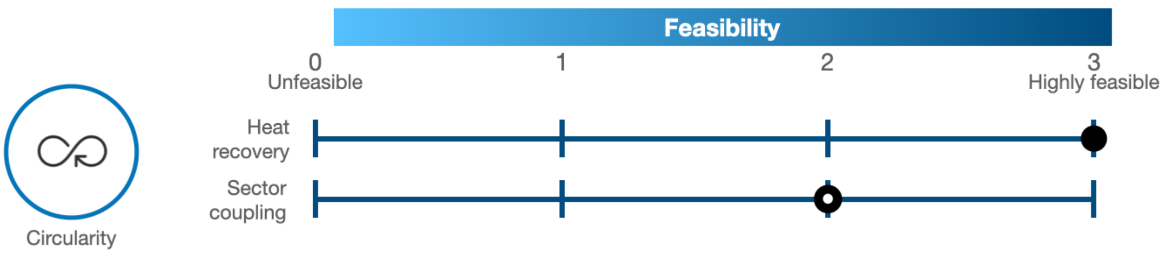

Figure 13. Feasibility for solutions under circularity strategy.

Table 19. SWOT analysis for heat recovery.

Heat recovery
Strengths
Implementing a waste heat recovery system is a straightforward way to save money on a facility by lowering the necessity for heat production. As mentioned by interviewee O, heat recovery from RTO hot chambers with elimination of air fans has shown good results in reducing the need of electricity in paint operations in the NRV facility.

There will not be an exhaustion of heat recovery technologies that can be used in automobile manufacturing. These can all be used for specific applications depending on the temperature range, the intended application (cooling or heating) and the required working fluid. Some examples are recuperative and regenerative heat exchangers, passive heat preheaters and heat pumps (Giampieri et al., 2020). At the Skövde facility for instance, interviewee P mentioned that heat recovery has been implemented in all the ventilation systems, for engine testing activities, for the cutting fluids in machining and for the cupola in the foundry.
Weaknesses
Heat recovery strategy is proven as economically advantageous in the design phase of a new paint shop. However, the investment capital cost of retrofitting tends to limit the economic benefits of the process (Giampieri et al., 2020).
Opportunities
From the thermal oxidizers, compressors, ovens, and dryers from the paint shop, thermal energy can be recovered and used for heating up water, which could then be employed for space or processes heating. For that purpose, heat pumps are a usual technology used. Potential natural gas use reduction has been reported from 10 up to 45% in some processes (Giampieri et al., 2020).
In Lyon, heat recovery from industrial processes is soon to be implemented to supply heat for the buildings but under high costs. However, French governmental entities will subsidize about half of the project's cost once it classifies as an energy efficient project as mentioned by interviewee J.
As mentioned by interviewee J, heat recovery is being applied for stamping processes at the Lyon site where it will be connected to the adjacent facilities to supply them with surplus heat. In addition to this, this project will facilitate heat recovery from other processes in adjacent buildings such as heat recovery from compressed air systems and engine testing.
Threats
When working with heat recovery, two or more different processes might have to be integrated. Different processes can work at different rates and in that case, it is not guaranteed whether it is possible to completely synchronize, shut down or alternate the operating pace of heating, ventilation, and air conditioning of different processes to match heat recovery strategies (Mohammadpour & Hane, 2020). Equipment designs are process-specific and must be adapted to the needs of a given process (U.S. Department of Energy, 2008).
At Volvo GTO, when it comes to space heating through heat recovery, the manufacturing division and the real estate organization must collaborate closely to achieve optimal results, as mentioned by interviewee G.
Contaminated exhaust streams pose a major challenge for heat recovery. Sometimes, flue gases or liquids must be depolluted before becoming suitable for heat recovery strategies. This requires further investments in filters and clean-up solutions (Giampieri et al., 2020).
Heat recovery is largely dependent on economy- of -scale.- Equipment costs favor large -scale heat recovery systems and create challenges for small-scale operations (U.S. Department of Energy, 2008).

Feasibility: Heat recovery is a versatile solution that can be applied in multiple production processes which decreases both energy consumption and costs when implemented. In addition to this, Volvo GTO has vast experience in implementing this at multiple locations. Moreover, by being classified as an energy efficient measure by certain countries, there are good financing opportunities. However, the cost of heat recovery solution can increase if applied to small-scale operations and/or applied in situations where retrofitting is needed. Therefore, due to the advantages of lowering energy consumption and cost coupled with the funding opportunities, heat recovery is given the highest feasibility degree.

Recommendation for Volvo: Facilitate collaboration between manufacturing departments and the real estate department at the different sites in order to guarantee further implementation of heat recovery solutions.

Table 20. SWOT analysis for sector coupling.

Sector coupling
Strengths
According to interviewee Q, sector coupling can reduce the costs of decarbonization in the long run through efficiency gains.
Sector coupling can be developed with already existing technologies such as electrical equipment and boilers, heat pumps and electrolysis for hydrogen production (Doleski et al., 2022). This means that it is possible to integrate with existing infrastructure and that high-cost investments are not always required.
Weaknesses
Sector coupling tends to relate to higher electricity demand, and consequently the need for more renewable electricity generation. According to the literature, a fully decarbonized energy system will require more electricity than today's electricity consumption (Kerstine Appun, 2018). This will require more output from an already strained electricity infrastructure where multiple GTO facilities are in operation.
Opportunities
A more interconnected energy system enables overall more flexibility once it provides more options for storage and demand response access (Kerstine Appun, 2018). As previously mentioned, interviewees expressed interest in a smart planning infrastructure for charging BEV at different sites.
Threats
Before developing sector coupling, the interactions across the system must be understood, and a more integrated approach to energy systems planning is needed. This requires a whole new perspective and level of understanding on the energy end-users and producers, information that might not always be easily available or collectible. In addition to this, several sites are in regions that have an underdeveloped infrastructure for net-metering which further decreases the possibility of sector coupling.

Feasibility: Sector coupling comes along with great efficiency gains but also with great challenges. In the case of Volvo GTO, as a first step, a comprehensive model will be required to be created representing the company's whole energy system. Sector coupling could be hindered by countries with low transparency that disclose faulty information or do not disclose information at all. This solution will also require a higher electricity demand at the expense of decreased fuel use, which will put increased strain on electricity infrastructure and system operation. However, it is an interesting solution that can contribute to an increased circular society. Thus, giving Volvo the opportunity to contribute toward a more circular society. A feasibility of two has been assigned to it.

Recommendation for Volvo*:* Volvo GTO is currently evaluating their supply chains and their energy providers. It would be interesting for Volvo GTO to include this perspective in their evaluations and elaborate a sector coupling strategy which is something that seems to be missing within the studied facilities and the organization. This should be considered before most of the decisions are made.

5. Discussion

In this section, the discussion is presented in two parts. Firstly, the results are interpreted and placed in context with their significance in relation to previous literature. Lastly, a discussion on the limitation is presented.

5.1 Interpretation of results

The first research question of this study concerns the recurring decarbonization strategies and solutions being considered for industry according to the literature. When examining studies that address carbon reduction in the industry, it was identified that most authors adopted a homogenous definition of decarbonization. This translates into the fact that the solutions they mentioned were oriented toward the same goal, which allows the studies to be comparable to each other. Also, many authors categorized the solutions by strategic areas, such as efficiency gains and circularity. This also allowed for comparisons.

The second research question addressed how the above strategies are applied and how they can be grouped into a new framework to make them applicable to the Volvo GTO. Most of the decarbonization pathways identified in the literature were recurrent among existing frameworks, which facilitated the selection of strategies for the framework developed for this study. However, the level of aggregation in the frameworks varies and there is little attempt to clarify how strategies are differentiated from one another. This study provides an elaborated framework with six different strategies that are collectively exhaustive but not mutually exclusive, and it acknowledges and further examines how these relate and differentiate from each other. By making this differentiation clear, this study focus rather on the strategies than on the solutions themselves. In doing so, it provides a framework that can help Volvo GTO define a set of good practices that can be used consistently within that organization. Finally, when analyzing other companies in the automotive sector, it was observed that several organizations in this sector adopt the six strategies when implementing their decarbonization measures in one way or another. When analyzing the framework with Volvo GTO's current strategies, a strong correlation was found.

The third research question aimed to answer what the feasibility of the identified decarbonization solutions is based on their strengths, weaknesses, opportunities, and threats. The results reveal that feasibility varies intensely depending on the strategy and solution investigated and that Volvo GTO is on a good path to reduce its emissions and move toward carbon neutral manufacturing. Most decarbonization strategies and solutions have already been implemented at Volvo GTO facilities, which means that the results of this study reflect the most contemporary solutions being evaluated. In turn, this explains why certain solutions are more explored than others. Since a large share of data was collected from the organization's employees, it is logical that more information is gathered in these specific areas.

The framework was used as a guiding tool to understand, conceptualize, and structure measures that can contribute to decarbonization. An effort was made to categorize the different solutions in a way that increases the singularity for each of the strategies. However, as previously mentioned, certain decarbonization strategies overlap which is also the case for the different solutions. Therefore, this must be taken into consideration when applying this framework.

When it comes to the fuel shift strategy, there are several solutions that the different Volvo GTO facilities are considering and have considered for lowering the CO_2 emissions. Most of the biobased solutions are a result of facility-based initiatives involving local suppliers. Replacing fossil fuels with low emitting or renewable fuels is a versatile way of decreasing emissions, especially for combustion processes. A major structural change has already taken place at Volvo GTO. Most of the assembly, machining, stamping, internal transportation, and welding operations have been electrified with certain exceptions. There are a few processes left such as the casting and painting processes that are yet to be electrified. Moreover, several heating systems still operate on combustion technologies. This strategy offers a major advantage if paired with renewable electricity to decouple emissions from increased production. However, electrification of highly energy-intensive processes such as the melting process of the foundry requires increased attention to how the electricity will be provided. This strategy helps to identify changes that will require an increased power capacity and increased electricity consumption. The term structural change was not coined by the study, the need for extended installed power capacity and increased electricity consumption has been further problematized and evidenced. Thus, providing an additional contribution to the field.

As seen in the framework development carbon capture is mentioned by each of the listed authors. Therefore, making it an essential tool for decarbonization. One could argue that carbon capture has a broad meaning and there are multiple solutions attributed to this strategy. However, in this project the more technically and economically demanding methods such as CSS, CCU and DAC were evaluated and given low feasibility. This does not mean that carbon capture is not an interesting strategy for the automotive industry, but rather that they are currently not the most feasible alternative for Volvo GTO for lowering CO_2 emissions.

Process efficiency is identified as the most recurring strategy in the literature review which can be explained by the numerous solutions that can be implemented to achieve it. As seen in the results, process efficiency has been employed in multiple different ways within the company. The different measures were grouped in one single solution to facilitate the SWOT analysis. It seems that most of the efficiency gains associated with low-hanging fruit have been solved. However, process efficiency has been a tenant in the company's environmental strategy for a long time and specific examples/details on how the different solutions have decreased emissions were difficult to enquire in an interview format.

Classifying technological replacement as a strategy is beneficial since it points out how a technological change, big or small, can decrease CO_2 emissions. As seen in the results, most changes at Volvo GTO are either related to fuel shift or structural change. However, there are several technological replacements available for the paint shop that have shown promise in the industry. In addition, there are several technological replacements required when the production shifts toward electric vehicles. By being new technologies, few have been adopted and even fewer have been extensively reviewed. It was difficult in an interview format to inquiry information about technologies that had not been previously considered. Moreover, it is unclear how certain technologies that have not yet been extensively implemented will affect CO_2 emissions.

5.2 Limitations

The foremost limitation of the study is the exclusion of facilities that are less carbon emitting but still account for emissions within Volvo GTO. This means that sites which have either already achieved a high target of decarbonization or that have small operations are not concerned. Moreover, within the lower emitting sites, there are operational activities such as remanufacturing and refurbishment that can be considered circular solutions. Therefore, several solutions that could be considered under the decarbonization strategies are left out.

An additional significant limitation is the focus on Scope 1 and Scope 2 emission. This means that most of the solutions in the result are directly linked to activities that reduce emissions. Therefore, solutions that indirectly contribute to reducing carbon emissions could have been left out. Another consequence of this is the lack of solutions and connection of how material efficiency reduces carbon emissions. In turn, this can be seen as a weakness of the study since material efficiency is an important part of the process efficiency strategy. An important aspect to consider in the results is the different level of aggregation of the solutions. Certain solutions that are closely related were aggregated due to lack of specific details, e.g., biogas which included biomethane and landfill gas. This means that the level of feasibility of different solutions becomes less comparable.

When it comes to the SWOT analysis, the feasibility assessment of the solutions was complex to determine. Firstly, there are inconsistencies in the level of detail of the solutions as mentioned beforehand. Issues such as technological novelty, lack of experience within the company and lack of specific knowledge of the interviewees made the information uneven. Second, the study was conducted with an international perspective. This includes continent, country or region-specific aspects that decrease or increase the feasibility of implementation of the solutions. Both international and local dimensions are included in the feasibility assessment. That said, Volvo GTO operates in a global context and must consider that feasibility is not a singular matter.

Most of the interviewees are employed as environmental managers for the manufacturing or the real estate division. These employees work with projects that target efficiency and decarbonization. This means that most of the results reflect their experience. Certain important interviews were cancelled. One of them should have been with an employee with a global function and coordination role for the paint shops within the organization. This interview could have provided valuable insights regarding paint shop solutions as well as technical and environmental aspects to consider. An additional interview that never took place should have been with an environmental representative for Wacol in Australia. This resulted in a lack of data for that specific facility. In addition, due to the large number of facilities included, there are inconsistencies in the level of detail in the results for each. However, this study was able to generate valuable results and reflections for the most carbon emitting activities within the organization.

Finally, it is worth mentioning that the answers given by the interviewees could have been biased due to their opinions rather than factual matters. The tone and level of engagement of the interviewees was not captured in the results. For example, certain interviewees were more passionate about certain issues and have even shown PowerPoint presentations during the meetings. In addition, certain interviewees were more open to email exchanges for clarification questions. These factors and conditions could have influence what was included in the report.

6. Conclusion

This study provides two major outcomes. First, it delivers a decarbonization framework that can be applied to the automotive sector and for Volvo GTO to define a set of good practices that can be used consistently within the organization. The framework reflects Volvo GTO's environmental strategies to reduce emissions and it contemplates the measures that other automotive companies are implementing, investing in, or considering. Secondly, it provides the feasibility of the solutions identified within this framework for the organization. Most decarbonization solutions have already occurred within Volvo GTO and multiple solutions are on the verge to be implemented.

This study concludes that decarbonization at the facility level is achieved through multiple strategies and solutions that must be placed in the context of the local community to help the transition toward a more sustainable society. Decarbonization is a product of its surrounding, that depends on the local infrastructure. If local infrastructure is not available, then it is up to each facility to initiate and create it. Most of the solutions that have been implemented revolve around structural change. Therefore, attention must be placed on how to provide renewable electricity without increasing the strain on the power grid. In addition, there are emerging solutions such as sector coupling and digitalization that can further increase the effectiveness of decarbonization.

The developed framework has been applied to solutions that could be identified in the literature and the interviews. Some solutions were identified in the literature but not included in the report because of time constraints. This leaves room for continuous application of the framework and evaluation of solutions that can further contribute to the decarbonization of Volvo GTO.

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Appendix

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Summary of transcripts

Interviewee A

Interviewee A mentioned several plans to address the overall natural gas usage and the diesel used in engine testing. The effort for decarbonization has had to slow down to directly related issues about COVID-19 and much focus is now on making sure that the supply chain is running at full capacity. In addition to this, quality operations in some ways take focus from sustainability-related issues. The interviewee also mentioned that time is the main challenge in achieving the carbon reduction targets. Most measures to reduce carbon are known, but time hinders them from being in place at the right moment. Money is not always the problem, but time must be set aside for employees to make these changes. The interviewee also mentioned that the time variable also represents a challenge due to certain legislations that can be implemented that require the company to progress at a faster rate than planned. Therefore, legislation can be seen as a challenge.

Interviewee A mentioned that the strength of a circular economy is that it has been in implementation in multiple forms for many years. It encompasses the complete waste stream such as packaging, reassembly, and scrap while considering the role of the suppliers. All areas of Volvo Group are working toward circularity and have been doing it for many years. Programs like the Green New Deal further collaborate with suppliers and can help to achieve decarbonization within the company in a long run. The Interviewee mentioned that the Best available technologies (BAT) are always considered but they pose a challenge due to several cost factors and they usually create difficulties in how they can be implemented in existing infrastructures. When it comes to the consequences of BEVs on Scope 1 and Scope 2 emissions electrical trucks are currently at the prototype stage. When it will be scaled up to production quantities there are most certainly several challenges that will arise.

The interviewee stated that it is important to address emissions that arise from several different areas, such as the use of natural gas in several European facilities. This has been given more attention due to the Ukrainian war that is putting pressure on the availability of natural gas. An important issue to solve is how natural gas can be reduced and replaced. This is very dependent on what country the factories are in and how the national governments choose to address the usage of natural gas. Therefore, it is not only up to Volvo Group how to address this problem. It has been easier to address in Sweden due to the priorities set by the Swedish government compared to how it is addressed in France. Further, the interviewee adds that it is a complicated subject that cannot be answered with one reply. When it comes to district heating, the interviewee mentioned that the Tuve plant uses district heating that is considered highly renewable which is particularly beneficial when heating the building during winter. However, in France, natural gas is used for heating the buildings during winter which contributes to emissions. In addition to this, the ventilation system requires high energy demands during these periods.

Regarding assembly related activities, interviewee A stated that there are certain easy fixes that could be done if there was more time set aside for them. For example, long lines of pneumatic torque machines are used for cab and vehicle assembly which can be susceptible to leakages. This could be addressed by replacing the torque machines that have leakages which has shown to save copious amounts of energy. Moreover, the interviewee states that these types of measures are not confined to geography. There are skilled people with right competences within the factories that have knowledge on how to implement these measures. When it comes to the painting and surface treatment, the painting processes are a problem due to the elevated temperatures required for drying the paint. It would take approximately three times longer for the vehicles to dry in room temperature and for that additional space would be required. Therefore, energy mapping has also been applied to processes surrounding the painting. It helps to determine first and foremost if the process need to be improved or if the fuel needs to be changed.

It was stated by the interviewee that the primary measure that has been employed to determine where most energy has been consumed is energy mapping. This activity has been conducted by external actors that are knowledgeable in this kind of activity. For example, energy mapping helps to determine the efficiency of pumps and air fans which supports the decision making that determines if they need to be replaced. In turn, it helps to prioritize investments. Interviewee A stated: "Energy usage is directly connected to the reduction of emissions, the better we are at reducing the energy usage and still be able to run the factories as they should is a benefit on both reducing energy usage and emissions".

Interviewee B

According to interviewee B, the reported emissions in 2021 did not show a strong enough reduction in GHG emissions. It is important to work with emission decrease from different perspectives. A key factor is environmental consciousness. For example, it is important to understand that energy efficiency reduces emissions. Therefore, it is important to help people think more ecologically. There are several challenges in achieving this. For example, one challenge is overcoming cultural barriers that could hinder how environmental practices can be integrated throughout the facilities and into the daily routines of the employees. Another challenge is the age of the employees, the younger employees usually have an easier time understanding environmental issues and accepting the required solutions. An additional challenge is prioritizing which emissions to reduce depending on the geographical locations. In several countries, certain emissions and material usage are more acute to solve. Regarding time as a challenge, there are several factors that further delay decarbonization in diverse ways. The interviewee mentioned that most of the measures already should have been implemented. In addition to this, it takes time to validate the effectiveness of the newly implemented solutions. Moreover, it is challenging for Volvo GTO to move interesting pilot technologies to maturity levels so that they can be utilized.

Interviewee B explained that sustainable development within the GTO organization does not follow a top-down structure, the facilities initiate the programs themselves. This was uplifted as strength due to the possibility for the facilities to find the best local solutions available. When it comes to fuels, natural gas and fossil fuels are the biggest production challenges. If the production is mainly fossil powered, it means that increased production will result in increased emissions. Therefore, the challenge is to disconnect emissions with increased production. The Gent site was one of the sites in the GTO organization to achieve CO_2 neutrality. The reason for this was that it had an advantageous geographical location with plentiful wind resources and that most of the processes inside the facility were electrically powered. Due to the renewable electricity use, increased production volume did not equate to increased emissions. When asked about circularity, the interviewee mentioned that the connection between circularity and the decrease of Scope 1 and Scope 2 emissions is not straightforward. Therefore, circular measures are not always prioritized when implementing measures that are directly aimed at lowering emissions.

Regarding heating, interviewee B explained that it can be very difficult and costly to improve the energy efficiency in old buildings. At a certain point, there are no further improvements possible to make. For example, the Lyon CDL warehouse is mainly powered by natural gas for heating purposes. Due to the building being old, there is energy lost due to poor insulation capacity. There are several investigations for replacing natural gas for heating, some facilities are looking into biogas. For example, the Gent site is utilizing bio-propane partly for the heating systems. In addition to this, the Gent plant is looking at wood pallets as a power source. However, there are ethical concerns when considering biofuels due to the land competition dilemma. Moreover, the criteria for biogas approval from the real estate organization is strict where the biomass must be sustainably grown, and that the gasification process must be powered from renewable fuels. There are additional concerns regarding the high price levels and that the market is not mature enough as well as that there is a lack of certification schemes.

Lastly, interviewee B mentioned that the biggest challenge with the battery electric vehicles is going to be the life cycle of the batteries and did not see any specific connection with Scope 1 and Scope 2 emissions.

Interviewee C

The electricity used in the Curitiba CVA facility is used in multiple processes. Following the information provided by the interviewee, 99.6% of this electricity originates from renewable sources, despite official data stating a much lower value for the renewable electricity utilized. This is because the energy supplier does not provide the necessary documentation to account for green energy. Thus, the national grid emission factor has been considered instead. For that particular year, there was not much rain in certain regions, leading to a national decrease in hydropower availability. Therefore, the emissions associated with electrical use have seen an increase. There were plans on investing in dedicated solar farms for Volvo do Brazil to further reduce scope 2 emissions, however, it did not get approved due to contractual obligations. Proceeding, the Curitiba plant (Both Curitiba CVA and Curitiba Engine) is interested in purchasing I-RECs for offsetting emissions.

When it comes to scope 1 emissions, the Curitiba CVA plant uses much of its natural gas consumption for the paint shop, which according to interviewee C, does not differ much from how this process happens across multiple Volvo facilities. The employees in manufacturing are working to find solutions to reduce gas consumption by increasing the efficiency in the process. LPG in the Curitiba CVA plant is used in the showers, changing rooms, and cafeteria to provide heat. Moreover, it is used for forklifts, which are currently being replaced by electrical ones with lithium batteries.

In Curitiba CVA, diesel is largely used. One example is for transporting parts and vehicles to and from the production line and the C3 plant, the local logistics site. Some investigation on how to reduce and phase out diesel consumption has been ongoing. One idea that has been on the radar, according to interviewee C, is to invest in biodiesel, which is a local viable alternative to fossil fuel. Initial research on employing biodiesel is ongoing. However, it is believed that the fuel will start to be supplied by the government-owned gas company Petrobras from 2025 only, posing a major challenge for Volvo GTO in Brazil to implement it. When asked about weaknesses identified within the organization at Volvo do Brazil, the interviewee mentioned a lack of cross-functional work and an ownership deficit. Interviewee C explained that instead of reporting environmental work to environmental managers, other managers should be active in the environmental role while having guidance from environmental specialists.

Interviewee D

Interviewee D explained that the implementation of CCS comes down to two predominant factors which are the scale of the emissions and the concentration of CO_2. These two factors regulate the price and energy consumption of running the chemical absorption facility that would be required for capturing CO_2. This type of plant would be built close to the point source of emissions and would require heat and electricity. The interviewee mentioned that the current techno-economic limit for operating a chemical absorption plant is equivalent to an input of 100 000 tons CO_2/year. However, the interviewee mentioned that there is no hard limit and that it is an experienced based value where anything below 100 000 tons CO_2/year would equate to unproportionate costs per captured CO_2. The interviewee stressed the viability of CCS depends also on the company's willingness to pay and the alternatives at hand. In addition to this, the captured carbon would have to be stored. By 2025, carbon storage will be available in the sub seabed outside of Norway, Netherlands, Denmark and UK.

Other alternatives to CCS that were mentioned by interviewee D were DAC and DACCS as future alternatives for emissions that are hard to abate. Furthermore, the interviewee mentioned that questions such as “What is the cost of emitting CO_2?” and “What will the future cost of emitting CO_2 be?” should be asked when considering such alternatives. When asked about replacing coke with bio-coke for foundries, interviewee D expressed concerns. Specifically, the biggest challenges with alternatives such as bio-coke would be to secure reliable supply chains, ensure that it has the right composition and properties as well as to at what extent the fossil coke can be replaced. On a brief note about hydrogen, interviewee D mentioned that while it does not produce CO_2 when combusted, it still produces nitrogen oxide emissions that would need to be remediated.

Interviewee E

Employee E was interviewed two times and most of the answered revolved around the foundry process. One thing mentioned was that Volvo Group is not taking part in the emission trading system (ETS). However, the interviewee expects that the company will be part of it in the future. Currently, the company is working with an internal ETS system. Therefore, the company has gained knowledge and practice which will make it easy to adjust for an ETS which can be seen as a strength.

Within the foundry process at the Skövde facility, the cupola furnace stands for 79% of the emissions. The preheating process powered by LPG stands for about 9% of the emissions. About 10% of the cast iron is produced by electric CIF furnaces. Regarding the emissions, the melting process that takes place in the cupola furnace is the highest direct emission source within the Volvo GTO facilities. The main contributor is the fossil coke that is used for powering the melting. It was pointed out that the cupola furnace has several benefits including the ability to produce high-quality iron at a low cost and the furnace has low maintainability compared to other alternatives. In addition, environmental advantages are that one can use a lower grade of raw material that enables the use of external scrap, and it makes it possible to recycle the scrap in production. The cast iron that is melted in the copula furnace is entirely derived from external scrap. Therefore, there is an internal interest from the foundry employees to not replace the cupola. However, projects such as HYBRIT (A massive project for Swedish fossil free steel production that involves several stakeholders such as SSAB and Volvo AB) pose a threat to the current foundry process. This is due to the steel industry's intention to start utilizing scrap at higher rates which could create a scrap shortage.

There have been several attempts to reduce and eliminate the use of coke in the foundry. Firstly, the amount of coke need for production has been optimized as much as possible to 10% (10 kg coke for 100 kg cast iron) in comparison to 30% in other foundries around the world. Other attempts have been to exchange the tuyeres (Lower pipes at the bottom of the cupola that ignites the coke) with plasma burners. However, the cost was too high and technically advanced. Another attempt was made to replace 10-20% of the coke with biogas, but it turned out to give multiple disadvantages. It possible to replace 100% of the coke with biogas. However, it would require extensive modifications such as integration of a water-cooling system. In addition to this, large quantities of biogas would have been required which would have been primarily unfeasible from a financial perspective. Sewer material was even considered to be used as replacement for 10% of the coke, but it did not yield good results. Another thing that was mentioned was CCS and CCU. These two alternatives had been considered for alleviating emissions from the foundry. CCU was looked in to, more specifically algae production out of the coast of Gothenburg. The appeal for this alternative was that possibility to utilize carbon emission in the algae production in order to produce biomaterial that could be used in several manufacturing processes. Thus, creating a closed loop cycle. However, the cultivation area needed would have been as big as half the municipality of Gothenburg. Furthermore, the carbon capture was not deemed interesting due to the relatively low CO_2 emissions from the foundry process in comparisons to the economically beneficial margins.

As explained by the interviewee, an alternative for replacing fossil coke that has showed promising results is conglomerated biochar, more specifically bio-coke. This is a pioneer project that the interviewee is spearheading since this product is not available in the market. It is being manufactured trough cooperation between Volvo and a German and Swedish suppliers. However, there are no certainties on who or where bio-coke is going to be produced. This project is divided into smaller projects eloping simultaneously, where one of the projects has partially funded by a governmental entity. One type of biochar that has showed great results is biochar manufactured with HTC (Hydrothermal carbonization) process. This process is emission friendly and biobased materials with high renewability can be used such as leaves.

The goal is to replace 100% of the fossil coke with HTC bio-coke. Currently, 40% of the fossil coke has been replaced with bio-coke in lab scale tests. However, there are several challenges with this. Firstly, it is only up to the interviewee and his research collaborations to ensure success in the endeavor. Secondly, a challenge is the energy density and carbon content per volume unit. As of now, the carbon content in the developed bio-coke has a 70% fixed carbon composition compared to 89% in fossil coke, which is a noticeable difference. Thirdly, bio-coke must be manufactured with a certain diameter to sustain permeability in the melting process. Even if the diameter is correct, there are challenges regarding how to enable the bio-coke to sustain itself in 2000 degrees Celsius and how to sustain it from pressure caused by tons of overlaying material. The goal is by 2023 to reduce 10% of the emissions from the cupola which means that 10% of the fossil coke will have to successfully be replaced with 10% bio-coke.

As previously mentioned, the foundry produces 10% of its cast iron with electric CIFs. Interviewee E stated that this is a failsafe procedure in case the bio-coke alternative would not turn out to be successful. Which in turn means, that the melting process would be 100% replaced with electric CIFs. However, there are certain drawbacks with CIFs. Firstly, this type of furnace requires more expensive materials which are harder to source. For example, the CIFs require high quality scrap that is scarcer on the market and is sold at a higher cost. Secondly, the possibility of recycling the scrap will be reduced due to lower quality in the metallurgical waste from the process. Moreover, the foundry personnel will be increased with approximately 15 employees and there will be high investment costs involved. There has been dialogue with the energy provider regarding the increased installed power capacity (40 MW) and the increased electricity consumption this project would require. Despite this, the interviewee is not certain if CIFs would be a good addition and impact the electrical grid in southern Sweden that has had heavy price fluctuations in the recent years. Another point that was mentioned by the interviewee is that if 100% electrification of the melting process would happen, renewable energy solutions would be preferred such as wind power with hydrogen storage. However, from the corporate perspective, investing in CIF is the preferred option compared to other alternatives. There are employees inside corporate who are working with securing government funding that stretches up to 30% of the investment cost.

Another emission source from the foundry process is the preheating of ladles that is required in order to facilitate the melting. For the preheating of ladles, LPG gas is used as the primary fuel. There are plans to replace the LPG with biomethane that is sourced locally. The interviewee is leading this project which will be implemented within a year. However, disadvantages were expressed regarding the choice of biomethane. The biggest disadvantage that was mentioned is that biomethane is not emission free. Certain modification will be required to accommodate the fuel change such as replacing old burners, changing nozzles and constructing a new piping infrastructure due to the lower energy content in biomethane compared to LPG. To bypass the Seveso laws (Swedish laws that regulate and prevents chemical accidents), the fueling station will be constructed outside the facilities boundaries. The fueling station will be connected to the facility with pipelines and at the same time serving as a refueling station for freight trucks to help the trucking companies on their way toward the green transition. The new piping system will make up approximately half of the costs for this project.

Biomethane will be transported in liquid format which is beneficial due to it having beneficial properties in a liquified state in addition to lowering the number of transports. In this case, the cost for biomethane is not expected to exceed the cost of LPG. Even if this project has been selected as the way to decarbonize this process, a point that was made was that hydrogen would have preferred instead of biomethane due to it being CO_2 emission-free and little to no retrofitting would have been needed to accommodate it. However, the hydrogen alternative was appointed low feasibility and the idea was discontinued.

When asked about how the foundry will have to accommodate the increased of BEV in manufacturing. The interviewee replied that they will pose an existential challenge to the foundry process. As previously explained, the foundry produces cylinder blocks and cylinder hats, which are components that are not present in BEVs due to the electrical vehicle motors are made of aluminum and copper. Therefore, the only way for the foundry to continue running in the long run is if they start casting other applications such as axels and brake components. In addition to this, the type of iron will have to be changed. However, the change of casting products and iron will not change the melting process, only the pre-handling activities will have to be changed. The interviewee further asserted that even if those factors will not have a large impact on the melting process, these factors make it hard for decision making and to decide the best way forward.

Interviewee F

Interviewee F mentioned that coordinating projects that involve multiple facilities is difficult. Therefore, the coordination process of investment decisions is handled independently by each facility. For example, even if ovens are similar in certain facilities there are process and structural differences which makes it hard to align what type of items that needs to be purchased and at what point it should be purchased. This makes it hard to have a common strategy. However, there are several global coordinating functions that try to spread knowledge to create a common view on what direction investment should move toward. A weakness that was mentioned was that for most decisions it always comes down to cost. However, the environmental targets are very important and should not come at the expense of cost. A point that was underlined by the interviewee was that Volvo GTO needs to find solutions to help the local communities close to the different facilities. On way of doing that is to reduce the facilities need of energy and to do what is possible to decrease CO_2 emissions.

The interviewee mentioned several attempts that the Umeå site has attempted to decarbonize the different operations. For the welding operations, most of the activities are completely electrified. In addition to this, the consumption of electricity for welding operations is relatively low. For example, for the BIW (Body in white) process there is good and energy efficient equipment but some of it will need replacement in the future. When it comes to energy demands, a factor that determines what equipment is needed and how much power it demands is the thickness of the steel. Therefore, it was mentioned that the electricity consumption for welding equipment could vary in other Volvo GTO facilities depending on the thickness of the steel.

Another decarbonization attempt is the ongoing project to replace LPG driven ovens in the painting process with electrical ovens. This is seen as the best alternative due high share of renewable energy in the area. However, the replacement of LPG ovens with electrical ovens will require a substantial increase in installed power capacity and the facility will increase its electricity consumption. An additional attempt that was made was the HVO (Hydrogenated vegetable oil) 100 which replaced the previous fossil driven vehicles used for internal transports. However, the HVO 100 powered vehicles will be replaced with electrically driven ones in the long run. The reason for this is that the HVO 100 is not 100% emission free which is not what is advertised by most suppliers. However, the switch to electrical vehicles will increase the power demand for the charging needs. In addition to this, additional transformers might need to be purchased and installed.

When asked about circularity, Interviewee F motioned the stamping process at the Umeå facility. The stamping process consists of two press lines that utilize the hydraulic pressing method (Cold pressing). The press lines are constantly running due to multiple shifts and are always consuming electricity in idle mode. However, the electrical consumption is considered relatively low, and the electricity utilized is completely emission free. The sheet metal used in the presses are bought as steel coils from suppliers and they weigh 10 tons each. The interviewee mentioned that it would have been more environmentally friendly to purchase heavier steel coils due to decreased transportation needs. However, there is no capacity for handling heavier steel coils in production which makes that alternative not feasible. There have been ongoing projects to reduce transport and scrap production by internalizing various activities. One project was aimed toward internalizing the scrap recycling which is currently outsourced to a recycling company. This project would have required the purchase of additional machines and an increase in material handling activities. Therefore, this project was deemed both economically and technically demanding and discontinued.

When asked about how the Umeå facility will have to accommodate the increased BEV in manufacturing. According to the interviewee, it will not require any major changes, especially in the stamping process. However, it was stated that for other facilities that assemble chassis there will be an increase of models to assemble which will change the structure and layout of the activity.

Interviewee G

Interviewee G mentioned that extensive number and broad range of energy contracts within Volvo GTO makes it difficult to answer the following questions: Which are the next steps that can be taken? Can we have more collaboration with the energy providers? Can they lend us equipment or invest in projects with us? The interviewee said that they “need to be better at ensuring that everybody is up to date with information so that we don’t need to investigate certain things all over again which can turn out to be costly”. To turn this weakness into a strength projects that help educate and update employees on how to think regarding considering alternatives for climate change is required. When asked about opportunities, it was said that French regulation is very firm positive, and it will push the implementation and changes for lowering both energy use and emissions. Moreover, it was stated that new business relationships with energy providers need to be created so that the company can move away from multiple small different energy providers to larger ones to secure more reliable and prospective contracts. This will help to secure the reliability of the energy supply to counter the fluctuations in price of the energy system. With the big supplies it easy to have dialogue and find out future investment plans. Reliable partnerships are important. As a threat, interviewee G mentioned that the Ukrainian war has impacted the availability and price levels of fuels, especially for natural gas. The interviewee mentioned that the war is an overall threat to human beings and has had devastating consequences. Therefore, the company should realize that it needs to move away from natural gas in general, especially in Europe.

According to interviewee G, by the middle of 2022, all global real estate divisions are supposed to have delivered roadmaps for achieving the 50% CO_2 reduction target of 2030 that has been set by the real estate division. These roadmaps will include feasibility studies on the alternatives available for sourcing renewable electricity. It will include mappings of both local and national energy providers. Almost every project regarding on site renewable electricity that has been implemented is solar energy. Facilities in France have covered parking roofs with solar panels and at the Skövde facility, 0,3% of their electricity comes from solar panels located on the roof of the buildings. Questions to be asked when implementing solar panels at different facilities while ensuring that the process is handled in the right are: What are the countries legislations? Can the roof sustain the extra load? Is the roof up to date so it does not have to be replaced after installation of solar power? If it is off site, what are the future for that land area? Who owns and operate it? If owned by Volvo, will the company need that extra space in the future? Regarding wind power, environmental permits are hard to acquire, and it is especially the case in Sweden. For example, the Tuve facility tried to acquire environmental permits for windmills, but the request got rejected in the final stages of the legal process. There are societal safety concerns regarding wind power, and it usually require land that Volvo usually does not have. Therefore, partnerships with energy companies for offsite construction of wind power facilities are especially interesting.

Digitalized systems are being implemented for energy optimization in several facilities. In addition to this, there are several plans for increasing and implementing heat recovery solutions according to the interviewee. For example, heat recovery is going to be integrated with the compressed air solutions. More specifically, it is going to be integrated in the Lyon location. The Lyon location has several facilities that extend outside of the Volvo GTO network. Therefore, the air compressor machined have been installed in the same building. This means that it has good possibilities for and effective heat recovery. This can be challenging due to the real estate organization has to collaborate with manufacturing which requires experience and common projects. However, this heat recovery project has been deemed as a cost-effective solution.

When it comes to heating and cooling, interviewee G mentioned that several boilers for natural gas systems in France have been replaced by modern boilers that have increased the energy efficiency of 20-30%. However, the interviewee mentioned that there is a danger in updating and investing in modern fossil fuel driven equipment due to it creating an extended reliance of fossil fuels. Natural gas is one of the most important issues to address. The strategy adopted by the real estate organization is to firstly to reduce the heating demand as much as possible, then go for electric solutions such as heat pumps. Heat pumps are viewed as viable alternatives. However, their feasibility can be lowered depending on the size of the facility due to large sized facilities requiring larger and more numerous pumps. In addition to this, the cost can be substantial if the heat pumps are used for replacing natural gas-powered burner systems instead of boiler heated systems. The high cost is attributed to the need for installing new heat driven water systems. Within the facilities, the interviewee stressed that cooling is mostly driven by electricity. However, the cooling solutions have started to create different problems due to the increased temperature in several parts of the worlds. Therefore, they need to be optimized with the increased temperature levels.

Interviewee G explained that Volvo Group needs to be a part of society and show that it supports the overall green transition. This means for example, ensuring that the BEV trucks destined for delivery are charged with 100% on-site renewable electricity.

Interviewee H and I

Interviewee H mentioned that when it comes to decarbonization, the focus has been on the product and not on production. In addition, it was said that electrification could be a solution for production, but there are also bottlenecks here. In Sweden, electrification is an option for decarbonization. It might not be applicable in all processes, but hydrogen closes the gap and fills in the requirements not provided by electricity alone. Moreover, digitalization can be implemented to increase efficiency and reduce energy requirements. However, hydrogen is still surrounded by political and technical issues. Interviewee H also mentions that one strategy for companies using a lot of electricity is investing in their own power plants, otherwise they will strictly be depending on the societal infrastructure for electricity. Interviewee I mentioned that much of the initiative to make processes greener comes from the industry itself and that that even if it does not make it more profitable now, in the longer run it will.

Interviewee I said that carbon-free steel presents a major step toward achieving zero emissions in Scope 3 emissions. The mindset about decarbonization necessity is considered widespread and has become the goal of the industry. When it comes to biofuels, it will be impossible to replace all fossil fuels with it or the simple fact that there is not enough biomass for that. Thus, other solutions must be taken. Lastly, it was said by interviewee I, that solutions that take local aspects into consideration are key to reduce emissions. As an example, if a facility has access to locally sourced biogas, then it should absolutely make use of that instead of electrifying.

Interviewee J

As explained by interviewee J, the Lyon site is composed of multiple adjacent buildings where different activities belonging to different Volvo organizations take place. There are both air and water heating systems present on the facility grounds. The buildings with water heating systems have high feasibility for implementation of solutions such as heat recovery, district heating and heat pump. Heat recovery is going to be integrated in the stamping processes where the heat is going to be utilized for heating the building, decreasing the need for natural gas. This project involves high costs. However, the French governmental entities are subsidizing half of the projects cost since it is categorized as an energy efficient project. The heat recovery in the stamping process will be connected to adjacent facilities to supply them with heating when there is surplus heating available. In addition to this, this project will facilitate heat recovery from other processes in adjacent buildings such as heat recovery from compressed air systems and engine testing.

According to interviewee J, when working with energy efficiency it is important to have information on consumption patterns and the status of different appliances. Manual readings have been utilized to a large extent up till 2022 at the Lyon site which has made it difficult to measure progress, particularly for following short term actions that must be audited by the French governmental agencies. In this case, automatic reading equipment is the preferred alternative. Digitalized equipment is connected to the servers where the data is organized in a smart way to read data. However, in some cases automatic reading equipment demand time for the employees to understand, analyze, and use it for decision making. Automatic reading equipment in combination with a digitalization strategy could help improve energy efficiency related issues. Sensors that have been connected to automatic reading equipment in certain parts of the Lyon facility have shown good results. When asked about the energy supply, the interviewee said that the French facilities source renewable energy with contracts of guarantees of origin. For the Bourg En Bresse facility, the renewable electricity is sourced in the form of guarantees of origin from a local hydraulic production site.

Most of the CO_2 emissions generated from the GTO facilities at the Lyon site (Vénissieux Engine facility, St. Priest axel facility and Lyon CDL warehouse) are derived from heating, ovens and product testing. Most of the buildings at the Lyon facility are almost 100 years old and have poor insulation. In addition, heating pumps becomes an expensive solution since electricity costs almost three times more than natural gas. There are no short-term plans for eliminating natural gas completely. After the heat recovery project has been implemented, there will be more focus on researching alternatives for natural gas. The interviewee mentioned, “Biogas is a solution; from my point of view, it will not be sufficient and not interesting to use for heating purposes. It would be interesting in certain production processes”. Other alternatives that were mentioned is heating with wood pellets. District heating for the before mentioned facilities could be a solution according to the interviewee. However, these alternatives would have to be studied as business cases and usually flexibility and low cost are preferred attributes.

Regarding the Lyon CDL warehouse, interviewee J said that it is currently the oldest building on factory grounds completely heated by an air heating system powered by natural gas burners. It has one of the highest energy consumptions in the facility. However, this warehouse building will be demolished and replaced with a modern construction where the heating is derived from an electrical heating system or by the district heating system. For the Bourge En Bresse facility, there are plans to further expand the heat pump solution to decrease the need for natural gas.

Interviewee L

In late 2020, Volvo Group North America decided to publish a sustainability strategy. According to Interviewee L, the personal at quality and engineering started to reflect on how to support the whole organization to drive environmental targets for 2025, 2040 and 2050. Some goals mentioned were about becoming 100% landfill free by 2025 and have 30% CO_2 emissions reductions by 2025 in scope 1 & 2 emissions. The first step in the first quarter of 2021 was to educate the organization. To approach this topic as one GTO in North America, they created the GTO north America Sustainability Network. For that, there is a meeting every quarter of the GTO top management for North America. This improved the company’s division coordination to achieve environmental targets. The interviewee said that by joining “Better Climate challenge” deal, Volvo at North America aims to reduce 50% of its emissions by 2031 while getting aid from the US government in form of technical, research and development support.

The interviewee mentioned that work has been done in 2021 to start offsetting North American plants’ electricity emissions. With renewable energy credits, Lehigh valley technically already achieved 100% renewables from off-site production followed by the NRV plant, which has also some in-house generation. Power companies have provided renewable energy credits. Another think that was mentioned was that there are state legislative constraints regarding what type of electricity that can be sourced and on the ability of net metering which is factors that must to be considered when decision making. Regarding engine testing, the interviewee stated that diesel, mostly used in engine testing and trucks tank filling for customer delivery, contributes second to emissions at the NRV facility. However, this only represents about 6% of the emissions. The challenge is to find a fuel that runs on Volvo engines, without modification since they are already validated according to EPA and Euro 6 standards. HVO100 (hydrogenated vegetable oil 100%) has been considered a potential alternative. However, it has not yet been approved on the east coast and Volvo has been active in advocating for approval.

When it comes to the paintshop, interviewee L said that the NRV plant has an ongoing investigation to identify an alternative to natural gas used in the paint shop. Electrifying has not been considered a short-term solution since the paint shop at the North American location has been refurnished with new gas-driven equipment as part of massive investment, putting Volvo at the tail end of one of the company's industrial investments. Part of the investigation is identifying fuel suppliers. The alternatives presented are two: Purified methane from landfills and biogas. Biogas has been growing at a faster pace than landfill gas around the US, but landfill was decided upon due to their lower prices. Landfill methane costs about five to six times more than natural, while biogas costs more than ten times what natural gas does. The next step is to investigate the logistics behind the gas supply, where pipelines have presented major advantages. The process is now transitioning from an investigation to an industrial project. In the first phase, 60% of gas will have landfill origin by 2024 and then 100% by sometime between 2026 and 2029, when all gas emissions will be offset.

Interviewees M and N

Interviewee M stated that the North American long-term energy efficiency history starting in the NRV plant, which was the first site in the US to become certified, presents a solid ground for new developments toward sustainability. However, a big constraint regarding electrification is that in some American states, electricity is strictly regulated, and buyers cannot select supply and do not get any credit for the overgeneration of renewables. This hinders Hagerstown's effort to get renewable energy supply. Also, the interviewee stated that there is a lack of alternatives when it comes to renewable energy sourcing. Nevertheless, Hagerstown operates in theory 100% on renewable energy. This is achieved through the two solar panel systems present in the facility, which provide about 11% of the electricity usage cells or through renewable energy credits.

Interviewee N stated that Hagerstown has been ISO 50001 certified starting in 2014 and they have gone through two iterations of recertification since then. They have become SVP certified which is stands for superior Energy program or performance. But now, after major improvements have been made, it is not so obvious what can be done to reduce energy consumption. In the areas of heating and cooling, interviewee M mentioned that they have been working with companies to build a facility that will start to source landfill gas in order to substitute the natural gas mostly used in heating processes. The question is how many places they can help fund and where would be the most strategic place to invest in. When it comes to machining, roughcasting is taken and turned into finished products that go into the engines. Lastly, interviewee M mentioned that much effort is being put to investigate the use of HVO100 as an alternative to diesel at the Hagerstown facility.

Interviewee O

Interviewee O said that, regarding the North American facilities, the foremost strength knowledge is energy efficiency. The NRV facility was the first facility in the USA to achieve the ISO 50001 certification. However, when asked about weaknesses, the lack of renewable energy alternatives in the regions where the facilities are located was stressed. As explained by interviewee O, the North American facilities need to continue working with energy efficiency as much as possible. However, the interviewee stated, "We are currently running out of opportunity there because it has been a priority since 2009 and the major gains have already been achieved". For the North American facilities (NRV, Hagerstown, Lehigh Valley), interviewee O mentioned that most of the renewable electricity share is from RECs. They act as a substitutive alternative for reaching carbon neutrality that compensates for the lack of direct renewable electricity possibilities in the local grid. As of 2021, Hagerstown had 11% of its electricity consumption covered by on-site solar PVs. Moreover, NRV is currently sourcing a small share of their electricity locally from landfill gas generators with a partnership with a local college. When asked about the impact that vehicles electrification will have, it was said that there have been internal reports within Volvo Group regarding the increased electricity bills due to the charging activities. This was the case for facilities in North America that are manufacturing electrical busses.

When it comes to hydrogen, the Lehigh Valley facility has been looking into a case for hydrogen for industrial applications according to interviewee O. The hydrogen solution was intended for fuel cell powered forklifts. However, the facility decided to invest in lithium-ion battery driven forklifts instead. The interviewee mentioned that hydrogen for industrial application has not been discussed in the networks. Talking about the paint-shop, the interviewee said that the ovens and the emission control equipment such as RTOs are the biggest user of natural gas at the NRV facility. In order to solve this challenge, Volvo has worked with the US department of energy to increase energy efficiency. Electrification was looked at as the primary alternative. However, the infrastructure for electrification would have required extensive capital investment and there is not enough renewable energy capacity in the state of Virginia to sustain the capacity needed for electrifying the paint shop. There were several energy-efficient solutions implemented, a measure that showed good results and good emission reduction was the utilization of natural gas injections in the RTOs. Moreover, heat recovery from RTO hot chambers prior to air dilution and reductions in the air handling units (Elimination of air fans) have reaped good results in reducing the need for electricity in paint operations.

Interviewee P

According to interviewee P, the internal GTO targets have helped to effective the environmental work for decreasing CO_2 emissions. This have further emphasized the need for multiple teams within several divisions to start working on and developing approaches of how environmental routines can be integrated into their daily work. However, the interviewee mentioned that in many cases the different facilitates work separately on the same issues and that can be seen as a weakness. Therefore, improved knowledge and a more structured way for sharing information would be valued. One example that was mentioned was that it would be beneficial for facility environmental managers and engineers to have more knowledge about the energy system.

As mentioned by Interviewee P, there are opportunities for the company to share success and failures with the industry to show that things are possible to achieve. This will equate in Volvo contributing to helping society with the green transition. Nevertheless, the Swedish authorities are constantly learning and evaluating how to handle questions regarding batteries. This usually results in longer handling time for certain requests that include battery related questions. Which further puts strain on the short time scope for action. Electrification is increasing in society, which in total puts stress on the capacity of the energy providers to deliver renewable and stable electricity supply. Especially where there are already unstable grid conditions. Therefore, it is crucial from Volvos side to implement solutions regarding smart energy management that can cope with peak demand fluctuations. Interviewee P mentioned that the renewable electricity purchased at the Skövde facility is in the form of certificates guaranteeing that the electricity is produced from renewables. In this case, hydropower.

When asked about the Skövde facility, interviewee P said that heat recovery has been implemented in all the ventilation systems, engine testing activities, cutting fluids in machining and for the cupola in the foundry. This means that heat recovery has been achieved in all the places. Regarding engine testing, there are ongoing projects to decrease the number of engines that are tested and to increase the cold testing which is an environmentally friendly testing method. The site is currently testing different fuels, especially biobased ones such as B100 (Biodiesel100) and HVO100. The biggest issues with biobased diesels are that the demand is rapidly increasing which could surpass the available quantities on the market. Due to the increased demand, prices for biobased fuels have been increasing. The internal transports are partly electrified at the Skövde facility, and the share is expected to increase. However, there are challenges when electrifying internal transports due to extensive planning regarding where to safely install charging stations and how to safely handle batteries.

According to interviewee P, continuous improvements is the primary strategy implemented in multiple projects to reduce energy usage for the assembly related activities at the Skövde facility. In addition to this, energy mapping is conducted every fourth year to optimize the energy use. This activity is conducted in conjunction with Swedish governmental agencies and external environmental consultants. The interviewee mentioned that after every energy mapping, the lower hanging fruits are almost always prioritized. In addition to these activities, the maintenance staff is tasked to make incremental improvements in energy efficiency whenever they conduct maintenance operations. When asked about the impact of BEVs on manufacturing, the interviewee said that the batteries in the assembled trucks will eventually have to charged and tested. These changes will lead to an increase in electricity use, handling of different materials, and new waste streams. These activities will eventually impact Scope 3 emissions.

Interviewee Q

According to Q, fossil-free Sweden has made 22 roadmaps to guide different business organizations including what state support is available. Interviewee Q stated that some aspects of the Swedish government approach could be applicable at such big company like Volvo Group such as setting defined goals and rewarding based on environmental performance rather than only on financial. The interviewee mentioned that it usually pays off to be an early mover when it comes to green solutions adoption by companies, particularly in Europe and hopefully worldwide according to interviewee Q. Even if legislation does not follow up immediately, it will eventually. Volvo, as part of the Swedish society, has the power to push legislation with its actions, and so does it for other locations as well where Volvo has big operations.

When it comes to hydrogen, interviewee Q mentioned that it requires great infrastructure investment such as routes in strategic locations. There have been some considerations of including blue hydrogen into the roadmap but at least for Sweden, the focus has been on green hydrogen only when it comes to industry. Another aspect mentioned is sector coupling, which plays a big part of a more integrated and sustainable energy system. When it comes to circularity, once low hanging fruits are gone, the next step in terms of energy efficiency would be to connect with neighboring industries. Maybe there is waste heat that can be used. When asked about biofuels, the interviewee mentioned that there is a problem with bioresources availability in Sweden. The country must import residues for the production of biofuel and prices will increase. Lastly, the interviewee said that district heating is moving toward bio-CCS with the potential to buy certificates to offset the carbon.

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