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Decarbonisation of manufacturing operations: a case study in automotive manufacturing

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ABSTRACT

In response to the climate crisis, companies are increasingly committed to lowering their emissions. Previous studies have investigated climate mitigation strategies in carbon-intensive industries. However, emissions from less carbon-intensive sectors must also be addressed to reach net-zero goals. This study focuses on manufacturing operations and proposes a three-step approach to initiate industrial decarbonisation activities. Technological solutions across six strategies were investigated: fuel shift, electrification, carbon capture, process efficiency, technology substitution, and circularity. An in-depth case study at a multinational automotive manufacturing company was conducted with 16 semi-structured interviews to qualitatively evaluate technological solutions, highlighting implementation challenges from the case company's perspective. While there is no universal set of priorities for decarbonisation, the proposed three-step approach can help companies organise their decarbonisation activities more effectively. Finally, we suggest further work to tackle current and emerging challenges potentially hindering decarbonisation efforts in less carbon-intensive sectors.

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SUSTAINABLE DEVELOPMENTS GOALS
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1. Introduction

In a recent report, the United Nations Environment Program warned that atmospheric concentrations of greenhouse gases (GHG) are still increasing and global warming is likely to exceed 1.5°C if rapid, large-scale actions are not taken immediately (United Nations Environment Programme, 2023). Climate change is imposing patterns of extreme weather events putting pressure on society to commit to environmental practices. International programmes, such as the Paris Agreement (United Nations, 2015) and European Green Deal (European Commission, 2019), provide a vision towards climate neutrality and a circular economy. Global initiatives, such as the Greenhouse Gas Protocol and the Science Based Targets initiative (SBTi), are developing standards, tools and guidance for companies to set targets and monitor their GHG emissions, aiming to reach net zero by 2050 (CDP, 2025; SBTi, 2024; WRI and WBCSD, 2004).

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However, researchers have warned about alarming inconsistencies between the science-based targets and national commitments, calling for clear and long-term roadmaps to guide the planning and execution of mitigation and adaptation measures in line with the Paris Agreement (Rockström et al., 2017).

The term *decarbonization* represents different approaches to reduce GHG emissions (Andersson, 2020; De La Peña et al., 2022; Doleski et al., 2022; Nakićenović, 1996). Decarbonisation can be expressed as a product of two factors (Nakićenović, 1996): (1) carbon intensity – also called supply-side measures to reduce emissions per unit energy (Davis et al., 2018; Goh et al., 2018) and (2) energy intensity – demand-side measures about energy requirements per unit of value added (Mundaca et al., 2019). This study adopts the following definition of decarbonisation: 'The process by which countries, individuals or other entities aim to achieve zero fossil carbon existence. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport' (IPCC, 2018). A total of 36.8 Gt of carbon dioxide (CO_2) was emitted globally in 2022. With power generation, industry accounting and transport for 14.65 Gt CO_2 (42%), 9.15 Gt CO_2 (26%) and 7.98 Gt CO_2 (23%), respectively (IEA, 2023a), it is critical to advance decarbonisation practices in these sectors to address climate change. While electrification in the power and transport sectors can significantly reduce emissions during the use phase, producing the technology to support electrification is also expected; e.g. manufacturing and end-of-life handling of electric vehicles have higher environmental impacts compared to conventional vehicles (Koroma et al., 2022). Accordingly, this paper focuses on industrial decarbonisation opportunities in manufacturing operations.

Some have argued that industrial climate action is often opportunistic with ad-hoc solutions and blind spots, potentially leaving important areas of improvement unaddressed (Horan, 2019; Mundaca et al., 2019; Napp et al., 2014). An example is the installation of solar panels for on-site electricity generation, while most of the GHGs are emitted from burning fossil fuels in processes unaffected by the renewable electricity produced. To avoid such misguided investments and efforts, systematic methodologies and pathways have been proposed (Bauer et al., 2022; Mundaca et al., 2019; Rissman et al., 2020; Rockström et al., 2017). While they provide support and direction for change, they can be difficult to translate into company-level guidance for climate action.

In addition, multinational corporations (MNCs) need to build from where they are, given the company history. The case company selected for this study is a global vehicle manufacturer which has grown by acquiring different brands with existing plants across the world, resulting in today's manufacturing footprint. The plants' operating context varies widely in terms of manufacturing processes, volumes and energy sources. The objective of this study was to support their journey towards fossil-free production by getting an overview of the problems and potential solutions, providing a basis for a manufacturing technology roadmap. The CO_2 data used in this study is from 2021. Even though CO_2 reduction measures have been taken since then, the technical challenges connected to the specific manufacturing processes and the regional energy supply availabilities remain almost the same today. More importantly, however, this article focuses on a pragmatic approach to make a roadmap for decarbonisation for a large manufacturing MNC. As such, the results of the study are more relevant than ever.

To assist manufacturing companies organise their climate action more effectively, this study proposes a three-step approach for industrial decarbonisation to identify, evaluate and prioritise technological solutions to identify opportunities which the company has the most direct control on (Scope 1 and Scope 2 emissions). This approach builds on previous work done for primary sectors (e.g. Bauer et al., 2022; van Sluisveld et al., 2021) but focuses on the secondary sector with vehicle manufacturing, which is a smaller contributor to global emissions but still important to reach global emission targets. The guiding research question was: *What decarbonisation strategies and technological solutions can be applied in the automotive manufacturing industry?* The academic and grey literature were surveyed to identify existing decarbonisation strategies, technologies and practices proposed by researchers and implemented by leading manufacturing companies. This literature review formed the foundations for the proposed industrial decarbonisation approach. A case study at a case company was used to test the approach by evaluating various technological solutions for each strategy and indicate the conditions under which they can deliver a significant impact for the company's industrial decarbonisation.

2. Methods

The work presented in this paper is based on a project conducted in 2022. It started with an integrative review of the academic and grey literature on industrial decarbonisation (Torraco, 2005) leading to the development of a three-step approach applied in a case study in an automotive manufacturing MNC. The grey literature initially included the companies' latest annual sustainability reports available (dated 2021 or 2022 at the time of the original grey literature review). The academic literature was also used as secondary data to complement the primary data collected from experts during the case study to provide additional details about specific technology solutions under the decarbonisation strategies discussed during the interviews. Another round of literature review was performed to complement the initial review with more recent publications, including industrial practices from the new sustainability reports (dated 2023 to 2025 depending on the latest version published on the companies' webpage). No new decarbonisation strategies could be found when reviewing additional publications, indicating that saturation was reached and the list of strategies sufficiently comprehensive.

The in-depth case study was carried out at Volvo Group Trucks Operations, an MNC operating with 40 production plants in 18 countries and 75 logistics sites across 32 countries (Volvo Group, 2022), including cab and vehicle assembly, powertrain production, production logistics services, parts distribution, and remanufacturing. To focus on the largest improvement opportunities which the case company has the most direct control on, the 13 sites with the highest CO_2 emissions (Scope 1 and Scope 2) were selected, as presented in Table 1 with their profile, location and production volume, as well as in Figure 1 for the sites' annual emissions and emission sources. Additional details about the facilities and their energy profile can be found in Appendix (Table A1). The emissions for different fuel types were calculated based on conversion factors from the British Department for Business, Energy & Industrial Strategy (BEIS, 2021). For electricity and district heating, the emission conversion factors from the energy supplier were used. When supplier information was unavailable, the local energy mix was used. When the exact energy mix was unknown, such as for the Brazilian sites (WPA1 and PMA4), the national average was used.

Table 1. List of facilities included in the study with production volumes (proportion of total production at the case company) and annual emissions based on data from 2021.

Site and location	production volume
Cabs and Vehicles Assembly plants	
• Plant CVA1, Australia	2% of complete trucks
• Plant CVA2, U.S.A.	15% of complete trucks
• Plant CVA3, France	15% of complete trucks
Cabs and Vehicles Welding, Painting & Assembly	
• Plant WPA1, Brazil	10% of cabs and complete trucks
• Plant WPA2, U.S.A.	20% of cabs and complete trucks
Cabs and Vehicles Stamping, Welding & Painting	
• Plant SWP1, Sweden	40% of cabs
Powertrain Assembly	
• Plant PA1, France	20% of engines
Powertrain Machining & Assembly	
• Plant PMA1, Sweden	60% of transmissions
• Plant PMA2, France	15% of axles
• Plant PMA3, U.S.A.	10% of engines; 10% of transmissions
• Plant PMA4, Brazil	10% of engines; 15% of transmissions
Powertrain Foundry, Machining & Assembly	
• Plant PFMA1, Sweden	100% of casted iron cores and cylinder heads; 50% of engines
Logistics	
• Warehouse W1, France	No production

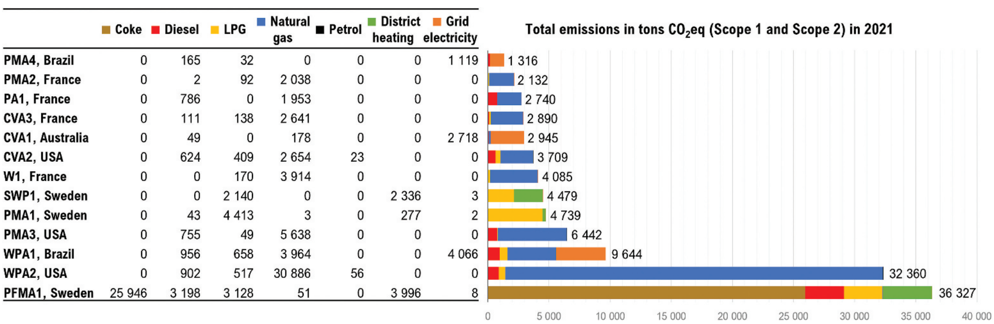

Figure 1. Scope 1 and Scope 2 emissions by source for selected facilities.

Semi-structured interviews were conducted in Spring 2022 with 16 experts, of which twelve from the case company (Table 2) and four from other Swedish organisations (Table 3). The second set of experts was included to include an external perspective to the case company as well as cover important contextual aspects related to the state of knowledge and national policies for industrial decarbonisation. The interview protocol was designed to enable a SWOT analysis (Strengths, Weaknesses, Opportunities, and Threats) to qualitatively evaluate the internal and external factors of the solution areas for the case company across its manufacturing sites. The structure of the questionnaire and a sample of questions are shown in Appendix (Table A2). The interviews were conducted, transcribed and analysed by two researchers, with insights from the interviews organised according to the SWOT categories. The SWOT tables for each solution area can be found in the Appendix (Tables A3 to A15).

Table 2. List of experts interviewed at Volvo group.

	Position, department	Role description/expertise
A	Quality & environmental manager, Europe and Brazil Manufacturing (regional)	• Sustainability coordinator for manufacturing facilities in Europe & Brazil for 2 years (4 years of prior experience at Volvo Bus) • Specialised knowledge about site CVA3, WPA1 and SWP1
B	Head of environmental sustainability, Quality and Engineering (global)	• Coordination and support for the environmental community within GTO with 11 years of experience in environmental management and strategy
C	Environmental manager, Powertrain (regional)	• Overview of several powertrain facilities • 17 years of experience in environmental engineering and management, specialised knowledge about site PMA4
E	Process engineer, Powertrain (local)	• Over 30 years of experience in the foundry PFMA1 • R&D on biocoke and CO_2 emissions reduction
F	Technology investment strategy coordinator (local)	• Plan and prioritise technology investments at site SWP1 • 9 years of experience with investments and projects
G	Sustainability manager, Real Estate (global)	• Sustainability projects in real estate and property management • Specialised knowledge about energy sourcing based on 18 years of experience at the company
J	Property project manager, Real Estate (regional)	• Regional project manager for real estate, including W1 and other facilities (production and offices) • Specialised knowledge about energy infrastructure
L	Quality director, Assembly (regional)	• Responsible for quality and environment at WPA2 and CVA2 • Specialised knowledge about environmental management and ISO 14,001 auditor based on 23 years at Volvo Group in the U.S.A.
M	Environmental manager, Powertrain (local)	• Environmental regulations and improvements at PMA3 for 10 years
N	Energy specialist, Powertrain (local)	• Environmental engineering at PMA3 for 4 years
O	Health, Safety and Environment advisor	• Advisory role for over 30 years • 10 years of experience with energy decarbonisation issues • Overview of energy systems in North America
P	Environmental engineer, Powertrain, (local)	• Management of environmental projects at PFMA1 for 6 years

Table 3. List of external experts interviewed at various Swedish organisations.

	Position, organisation	Role description/expertise
D	Doctoral student, Chalmers University of Technology	• Specialised knowledge about carbon capture and storage (CCS) and energy technology in industry
H	Program manager, Vinnova (Sweden's innovation agency)	• Research expertise in production engineering and sustainable industry
I	Program manager and deputy director, Vinnova (Sweden's innovation agency)	• Responsible for the national research program on sustainable industry • Research expertise in production engineering and green transitions in industry
Q	Project manager, Fossil Free Sweden (national programme)	• Specialised knowledge about decarbonisation measures in Sweden

Based on the SWOT analysis, a value between 0 and 3 was assigned to represent the solution areas' *implementation priority score*. A score of 0 stands for a solution area deemed as lowest priority due to weaknesses and threats posing major setbacks which cannot be balanced by strengths and opportunities. Scores of 1 and 2 stand for low and medium priority, respectively, reflecting either minor weaknesses and threats or limited strength and opportunities. More specifically, a score of 1 stands for a solution area presenting some benefits while having setbacks such as little organisational know-how or costs considered disproportionately high for the case company. A solution area with a score of 2 offers major strength and opportunities in comparison to weaknesses and threats but not considered as generally or easily applicable. Finally, a score of 3 means that the solution area should be prioritised as it offers high chances of impact and success. The results are presented in this paper, as shown in Figure 2, and also were presented at the case company to support the discussion and planning of their climate actions at different manufacturing sites.

3. Literature review and proposed approach

This section reviews the academic and grey literature to identify relevant strategies, practices and technological solution areas to decarbonise manufacturing operations.

3.1. Strategies in the literature

Looking at industrialisation as a historical phenomenon leading to environmental concerns, the fact that terrestrial carbon cycle cannot maintain a balanced atmospheric concentration has been recognised for many decades (Frosch & Gallopoulos, 1989; Keeling, 1973; Socolow et al., 1994). Early efforts focused on low carbon steel and the primary energy source substitution from coal to oil to natural gas (Nakićenović, 1996). Technological measures were proposed as necessary but not sufficient in isolation (Grübler & Nakićenović, 1996).

In recent years, the topic of decarbonisation has grown rapidly with proposed decarbonisation pathways (Bauer et al., 2022; Horan, 2019; Rissman et al., 2020; Sachs et al., 2015). Prominent studies focused on megatrends and future projections presenting desirable trajectories for emissions reduction over time. For example, Rockström et al. (2017) proposed a decade-by-decade roadmap to achieve the Paris Agreement's goals (science-based targets) and Rissman et al. (2020) also proposed a framework for complete decarbonisation of global industry with three timeframes between 2020 and 2070. Both papers identify actions for near- and long-term impacts, thereby creating a basis for

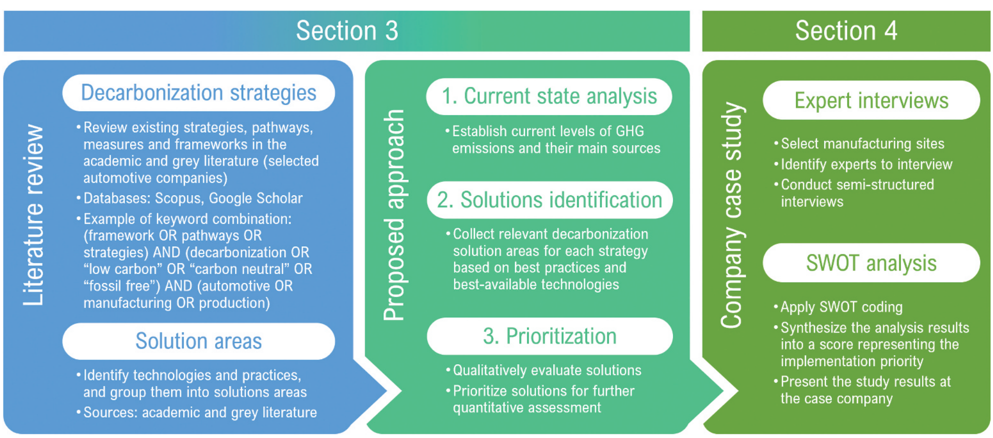

Figure 2. Overview of the study and paper structure.

national and international climate strategies. While 2017–2020 focused on policy instruments, such as carbon tax schemes and cap-and-trade systems (Rockström et al., 2017), the current decade shall increase dramatically energy efficiency, phase out coal in the global energy mix, phase out internal combustion engines in new cars, and achieve fossil-fuel free transport through renewables, electrification, and shifting from air to rail transport (Rissman et al., 2020; Rockström et al., 2017).

The next decades between 2030 and 2050 are projected to achieve many breakthroughs with complete electrification in some countries, the phase out of oil on the global energy mix, the development of alternative materials and hydrogen-based processes to achieve carbon neutrality in the most polluting sectors, such as construction and cement. Pathways typically combine supply-side interventions for materials, carbon capture and energy (hydrogen, electrification, efficiency), as well as demand-side interventions (product and material use; additive manufacturing; material substitution; circular economy) supported by various policy interventions and sociological considerations (Bataille, 2020; Grübler & Nakićenović, 1996; Kumar et al., 2025; Rissman et al., 2020; Sachs et al., 2015). Finally, the lessons learnt from successes in emissions-free countries will enable the faster transition of other countries with the help of CCS to compensate for the remaining unavoidable emissions.

Focusing on industrial decarbonisation, various studies defined key strategies – sometimes called scenarios, pathways, measures, interventions, etc.—at a global or national level (Brown et al., 2012; Dai et al., 2024; Evro et al., 2024; Swedish Ministry of the Environment, 2020; Tan et al., 2025), sectoral level (Bataille, 2020; Bataille et al., 2018; Bauer et al., 2022; Brown et al., 2012; Dai et al., 2024; Lane, 2019; van Sluisveld et al., 2021), and company level (Bataille et al., 2018; Doleski et al., 2022; Fitzpatrick & Dooley, 2017). These publications listed and summarised in Table 4 were used as foundations to synthesise six decarbonisation strategies used in the proposed approach for industrial decarbonisation (Section 3.3).

While the list of publications in Table 4 is illustrative of the current state of knowledge, it is non-exhaustive as there is an increasing number of scientific articles and reports being published to propose industry-specific roadmaps and actions. Besides articles in scientific journals, some of the most notable reports include the IPCC Synthesis Report of the Sixth Assessment Report (IPCC, 2023) and the IEA Net Zero Roadmap (IEA, 2023b) amongst others. These publications cover similar decarbonisation strategies, often focused on technological solutions but also including policy recommendations, green finances and innovation capabilities (Bataille, 2020; IEA, 2025; Kumar et al., 2025; Malehmirchegini & Chapman, 2025). This paper focuses on technological solutions, hence these non-technological measures are not included in the case study. Geoengineering solutions aiming at altering the earth's radiation balance are excluded from this study but are also possible decarbonisation strategies (Fawzy et al., 2020).

3.2. Practices in automotive manufacturing

Looking into decarbonisation practices adopted by world-leading automotive manufacturers, this section describes the current decarbonisation state-of-the-art in the automotive industry, focusing on factory-level practices (as opposed to product-oriented decarbonisation). The information was gathered from company websites and annual

Table 4. Overview of strategies identified in the literature.

Source title (reference)	Decarbonisation strategies	Level
Reducing CO_2 emissions from heavy industry: a review of technologies and considerations for policy makers Brown et al., (2012)	• Maximise energy efficiency potential through process-specific and industry-wide energy-efficient technologies (replace older, inefficient processes) • Fuel and raw material switching to low carbon energy sources • Accelerate research and investments in industrial CCS plants and other novel technologies • Alter product design and waste protocols (life cycle changes) for reuse and recycling aim to close the materials loop	Global
Pathways to deep decarbonisation of carbon-intensive industry in the European Union Rootzén, (2015)	• Improved energy efficiency • Fuel shift • CCS • Structural change • New steelmaking processes	Not specified
Holistic view of CO_2 reduction potential from energy use by an individual processing company Fitzpatrick & Dooley, (2017)	• Energy generation approaches to reduce CO_2 emissions • Improving energy efficiency • Carbon capture and storage • Cleaner product technology	Company
Assessment of the Broader Impacts of Decarbonisation Lane, (2019)	• Technological replacement • Process improvement • Demand management • Circular economy	Sectoral
Physical and policy pathways to net-zero emissions industry Bataille, (2020)	• Decarbonising production (near zero and zero emissions technologies for different sectors) • Decarbonising demand: Material efficiency and circular economy	Sectoral
Sweden's long-term strategy for reducing greenhouse gas emissions Swedish Ministry of the Environment, (2020)	• Transition from fossil to renewable raw materials and energy carriers • Improve process and material efficiency • Replace the basic process entirely; e.g. through electrification • Introduce technologies for CCS, capable of reducing both fuel-related and process-related emissions	National
Assessing the position of heavy industry in a global net-zero CO_2 emissions context van Sluisveld et al., (2021)	• Energy and carbon efficiency • Fuel switching • Technological choices	Sectoral
Assessing the feasibility of archetypal transition pathways towards carbon neutrality Bauer et al., (2022)	• Production and end-use optimisation • Electrification with carbon capture and utilisation (CCU) • CCS • Circular material flows • Diversification of bio-feedstock use	Sectoral
Digital Decarbonisation Doleski et al., (2022)	Established measures: • 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 Complementary measures: • Increase in energy efficiency • Improvement of energy conversion • Optimisation of existing plant facilities • Avoidance of process-related emissions	Company

(*Continued*)

Table 4. (Continued).

Source title (reference)	Decarbonisation strategies	Level
Country-specific net-zero strategies of the pulp and paper industry Dai et al., (2024)	• Wood harvest practices • Energy mix • Specific energy consumption (efficiency) • Waste disposal mix • Methane capture rate • Recycling rate	National and sectoral
Twelve pathways of carbon neutrality for industrial parks Sun et al., (2024)	• Carbon capture and utilisation • Substitution of raw materials • Cleaner production • Consumption waste recycling • Product and waste infrastructure (industrial product and waste exchange) • Energy infrastructure (energy exchange) • Water infrastructure (water exchange) • Waste-water-energy nexus • Buildings and transportation • Service infrastructure (carbon reduction by management) • Land use change • Carbon storage	Cross-sectoral and regional
Strategies for achieving carbon neutrality within the chemical industry Malehmirchegini & Chapman, (2025)	• Process technology innovations • Energy transition • Carbon capture, utilisation and storage technologies • Circular economy • Green chemistry	Sectoral
Recent trends in optimisation models for industrial decarbonisation Tan et al., (2025)	• Shift to renewable energy and hydrogen • CCS and carbon dioxide removal (CDR) • Alternative heating technologies (incl. electrification) • Interim decarbonisation measures such as process efficiency and purchasing CDR credits	Sectoral
Towards a Net Zero Cement: Strategic Policies and Systems Thinking for a Low-Carbon Future Kumar et al., (2025)	Production solutions: • Mineralisation • Carbon capture, utilisation, and storage • Supplementary cementitious materials • Electrification • Alternative fuelsUse-phase solutions: • Optimised use • Sustainable practices • Biobased materials	Sectoral

sustainability reports. The companies reviewed included Toyota Motor Corporation, Volkswagen Group, MAN Truck & Bus, Scania, Ford Motor Company, CNH Industrial, and Daimler AG. The practices at Volvo GTO (the case company) are presented in more depth in the next section.

Toyota Motor Corporation places a strong emphasis on environmental leadership and provides rich reporting material on their environmental strategy and plans (Toyota Motor Corporation, 2025). The company is expanding the use of renewable energy, innovative technologies, and hydrogen, including the construction of a hydrogen plant at one of its manufacturing plants. Daily Kaizen activities (from the Japanese term Kaizen 改善, the practice of making continuous, small improvements in work processes) aim to reduce energy consumption per vehicle by over 1% annually. At the facility level, the company is replacing natural gas with biogas and introducing wind and solar power. In production processes, airless and steamless painting technologies and light-emitting diode (LED) lighting promote further energy savings. Energy monitoring and best practice are shared across plants and suppliers. Toyota also plans CCS and CCU projects to address residual emissions, targeting carbon neutrality in plants by 2035 and zero emissions by 2050.

The Volkswagen Group holds many brands endorsing green practices (Volkswagen, 2024). European sites today use 100% renewable electricity, and biogas is used at Porsche sites, while other plants are transitioning from coal and gas. Combined heat and power (CHP) systems, such as the one at Zwickau, support low-carbon heat. Process efficiency measures include over 9,000 actions since 2018 to cut energy use by 3.5 million MWh, including optimised thermal afterburning, air compressors, smarter fans, and digital monitoring. Painting shops have adopted low-solvent technologies and airless processes. To boost circularity, Volkswagen is increasing the use of secondary materials and closing several material loops, such as aluminium scrap from the press delivered back to the original supplier.

MAN Truck & Bus, a subsidiary of the Traton Group, is implementing ambitious measures to decarbonise its manufacturing operations (MAN Truck & Bus, 2023). The company is systematically replacing fossil fuels with renewable electricity at all production sites and aims for CO_2-neutral production by 2030. District heating is sourced for Nuremberg, and Pinetown will rely fully on solar energy. Diesel use in engine testing is being eliminated. Process innovations include new paint concepts and expanded reuse of metals in foundries to promote circularity. Unavoidable emissions are offset, with a maximum 5% compensation allowance.

Scania continues to prioritise sourcing fossil-free electricity across all its production sites (Scania, 2024). Facilities operate with nearly 100% fossil-free electricity, and targeted energy efficiency programs are in place to reduce energy use and eliminate waste. In Oskarshamn, paint shop ovens are powered by renewable rapeseed oil-based fuels. Heating, lighting, and ventilation systems are optimised, including the replacement of gas boilers with heat pumps. Circularity efforts focus on material reuse, especially metals, and reducing virgin resource dependency to decouple growth from resource use.

Ford Motor Company aims to use 100% locally sourced, carbon-free electricity at all manufacturing sites by 2035 (Ford Motor Company, 2024). Solar energy projects, such as a 13.5 MW installation in South Africa, support this target. Manufacturing CO_2 emissions have been reduced by 49% from 2017 levels. Efficiency improvements focus on compressed air systems, fans, pumps, motors and heating. Ford is piloting 3D printing for commercial vehicle parts to advance circularity and operates a closed-loop aluminium recycling system. Waste reduction activities also aim for true zero waste to landfill across global plants.

CNH Industrial is actively reducing fossil fuel use by sourcing renewable electricity, optimising energy consumption, and investing in heating and compressed air system upgrades CNH Industrial (2024). At the Lecce site, 7,110 solar panels supply over one-third of the plant's needs. Energy efficiency projects across plants, reduced emissions by 4,100 tons in 2023. In manufacturing, nanotechnology in painting processes minimises heating needs and volatile organic compound (VOC) emissions. Circularity efforts include a 95% waste recovery rate and expanded metal recycling. Composting initiatives and oil recovery projects also support broader eco-efficiency.

The Daimler AG, through Mercedes-Benz Group, pursues its 'Ambition 2039' goal, targeting carbon-neutral production at all European plants and carbon-neutral energy supply globally by 2039 (Mercedes-Benz Group, 2024). Their strategy includes a strong expansion of renewable electricity sourcing, such as onsite photovoltaic systems at multiple production locations and power purchase agreements (PPAs) with wind farms. Biomass, geothermal energy, and district heating with renewable components are utilised to decarbonise heat supply. Investments are being made in the electrification of production processes and the deployment of heat pumps powered by green electricity at sites like Kecskemét and Tuscaloosa. Energy efficiency efforts include upgrading to more efficient building and production technologies, real-time energy monitoring, heat recovery systems in ventilation, and data-driven optimisation of energy-intensive processes. Remaining emissions from natural gas-based combined heat and power plants are offset through CO_2 mitigation projects.

3.3. Proposed approach for industrial decarbonisation

Based on the academic and grey literature, categories of practices and technologies were identified (thereafter called *strategies*). The six strategies described in this section aim to be exhaustive and complementary to ensure that all relevant solutions from the literature reviewed are covered. Systematic reviews of decarbonisation strategies were used to cross-check this list and ensure its completeness (see list of references in Table 23). Figure 3 shows the academic and grey literature mapped against the six strategies.

Process efficiency encompasses efficiency gains through resource management (energy and materials) with or without technological change. When major alterations to the process or resource flows are required, the solutions will overlap with other strategies, such as technology substitution, fuel shift or circularity. Incremental, continuous improvements without major alterations to processes (also known as kaizen) are a central part of Lean production to increase quality, efficiency and productivity. While all studies and companies reviewed considered energy efficiency, only a subset of them also considered material efficiency (Bauer et al., 2022; Doleski et al., 2022; Lane, 2019; van Sluisveld et al., 2021).

Fuel shift entails a shift from fossil energy carriers to less polluting alternatives or, ideally, renewable fuels without the need to replace the technology in place. Therefore, it is less disruptive and gives the possibility to continue manufacturing operations with less or no emissions. All studies and companies reviewed considered this strategy. However, companies accustomed to fossil resources tend to be cautious towards bio-based resources due to its low carbon density, seasonal availability, and variable quality. In addition, biofuels present other challenges related to land use, competing for space with food production as well as rural and urban development. The use of waste and agricultural residues reduces concerns regarding land use; for example, co-firing of biomass and waste could significantly reduce fossil fuel use and, unlike biofuels, does not require to grow crops.

Electrification refers to structural changes to the manufacturing systems' infrastructure and equipment, and how the electricity is provided. Under this strategy, fossil-driven technologies are replaced with electrical ones. This strategy relies on an increased power capacity and renewable electricity availability at low costs. Electrification in manufacturing can entail major operational changes; e.g. replacing the gas oven with an infrared

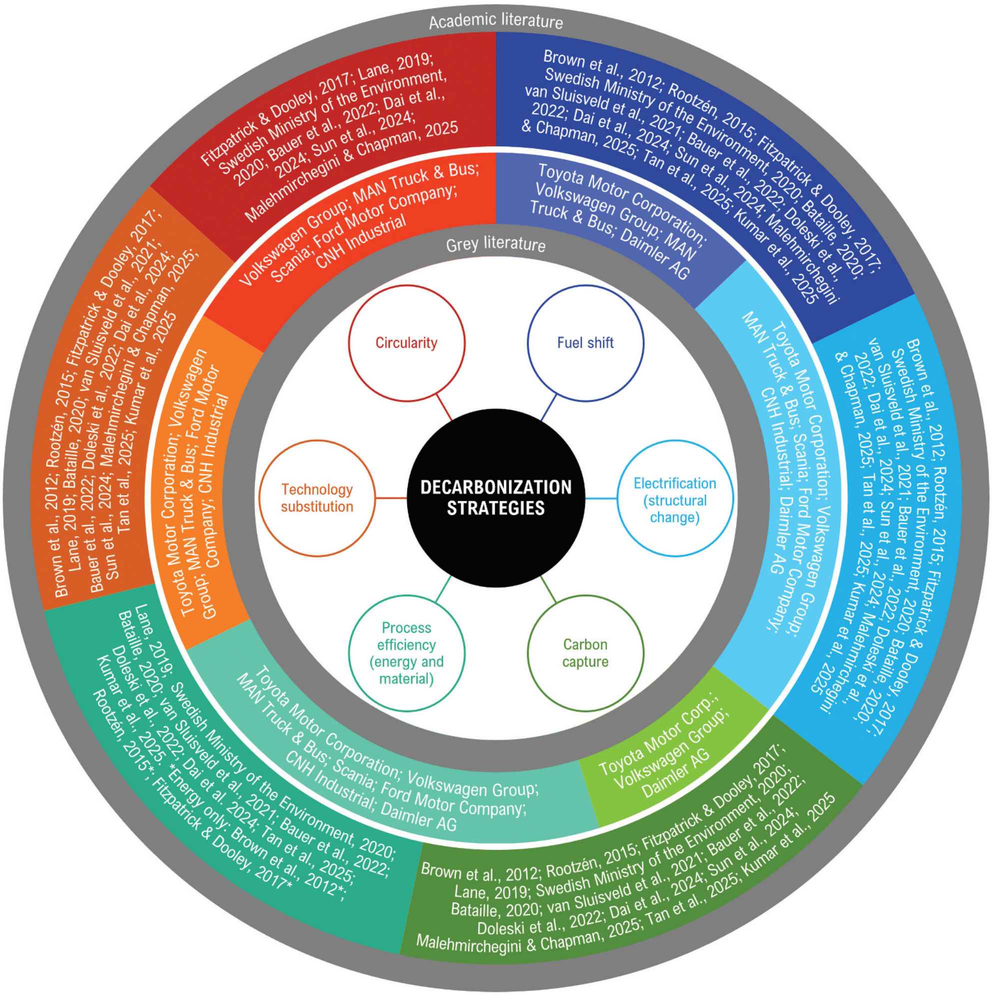

Figure 3. Mapping the reviewed literature against the decarbonisation strategies; the outer donut diagram captures cited articles from the academic literature and inner donut diagram industrial practices from selected multinational automotive manufacturing companies.

oven. When energy is produced from renewable sources, the challenge is to cope with supply fluctuations and to counter electricity cost variation (Wei et al., 2019), which can partly be mitigated by adapting the manufacturing operations, such as batch sizing and scheduling forklift charging. The technologies and solutions are mature, but they need to be implemented at a larger scale (Bauer et al., 2022). Also, structural change for electrification often requires major investments and long-term planning, which may not align with desired decarbonisation schedules.

Carbon capture, also called carbon sequestration, is the process of (re)capturing CO_2 emissions before (or after) they enter the atmosphere and encompasses two processes currently used at an industrial scale (Doleski et al., 2022): CCS involves storage of carbon dioxide in geological structures, and CCU of sequestered CO_2. The IPCC states that current measures to reduce emissions will not be sufficient to meet climate targets and therefore carbon capture technologies are needed. While Lane (2019) considers CCU to be a circular economy strategy and CCS as part of process improvement, Bauer et al. (2022) considers CCU as part of their electrification strategy, and van Sluisveld et al. (2021) considers it to complement various energy solutions under their proposed strategy called technological choice.

Technology substitution is about the best available technologies and innovation. It concerns the shift of current production systems by alternative ones with the implementation of new technologies replacing more polluting ones. New technologies might have high market entry barriers which have limited testing and find themselves in pilot or demonstration phase (Lane, 2019). Thus, technology substitution may be considered a longer-term strategy as such changes require new knowledge and time to mature.

Circularity is a broad strategy ranging from circular product design to closed-loop production systems to shift from linear resource use to a more integrated approach for product and material value retention and to reduce the use for virgin resources. Circularity can be considered the most systemic decarbonisation strategy.

To identify and evaluate relevant technologies and practices (thereafter called *solution areas*) for each decarbonisation strategy, the proposed three-step approach shown in Figure 4 corresponds to the workflow applied at the case company. A SWOT analysis was performed to qualitatively evaluate promising solutions for the case company across its manufacturing operations globally. This is an important step to prioritise and scope potential decarbonisation projects before a more in-depth quantitative analysis is performed to evaluate more accurately implementation costs and expected impacts for specific solutions at specific sites.

4. Case study

The proposed approach aims to guide companies through a simple and structured workflow to cover comprehensively relevant strategies and prioritise solutions areas to support effective industrial decarbonisation of their manufacturing operations. This section presents its application at a case company.

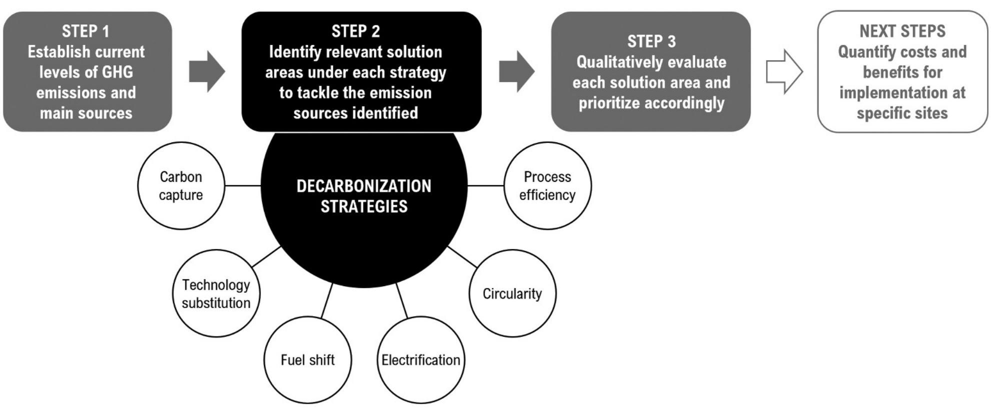

Figure 4. Proposed three-step approach and decarbonisation strategies.

To focus on the largest improvement opportunities within the case company (step 1), the Scope 1 and Scope 2 CO_2 emissions were quantified by site and by source (see Figure 1). The combined emissions for the 13 selected sites represent over 83% of the company's global emissions; the other sites are mostly logistics services, thus lower energy and carbon intensity. Since the carbon intensity is highly dependent on the regional energy mix, the country in which the facilities are located was also specified in Table 1.

For each strategy, different solution areas were identified (step 2) to define relevant types of solutions which can encompass more than one technology. Each solution area was evaluated with a SWOT analysis (step 3) considering on the present conditions at the case company across its manufacturing operations globally. A total of 13 solution areas were investigated based on the literature review (Section 3.1 and 3.2) and expert interviews, focusing on solutions relevant to the case company, targeting the sources and facilities with the highest CO_2 emissions. Since the interviews were the primary source of information, solution areas in which the interviewees had good expertise were selected.

Figure 5 shows how the evaluation results were presented to the case company with a scale from 0 to 3 representing the implementation priority score based on the SWOT analysis. The details of the interview data and SWOT analysis for each solution area can be found in Appendix (Table A3 and Table A15) and in the project report (Serino Olander & Albuquerque Wolf, 2022). To capture the case company's current activities related to each solution area, the score marker also shows the current state of planning or implementation. The full black dot indicates that technologies under a specific solution area have already implemented in their global operations. The hollow black dot means that small-scale pilots or trial projects were initiated at specific facilities. The last two white dots indicate whether the solution areas have been considered or not by the case company.

4.1. Process efficiency

The solution area included under process efficiency is continuous improvements (Figure 6. Implementation priority score for a solution under the process efficiency strategy). Many solution areas can also contribute to higher energy and material efficiency but have been classified under other strategies depending on the type of system change they entail. The details of the SWOT analysis can be found in Appendix (Table A3).

Several interviewees describe **continuous improvements** as small changes and fixes to existing equipment which do not require substantial capital investments and can be integrated in daily routines. The case company has extensive experience in successfully

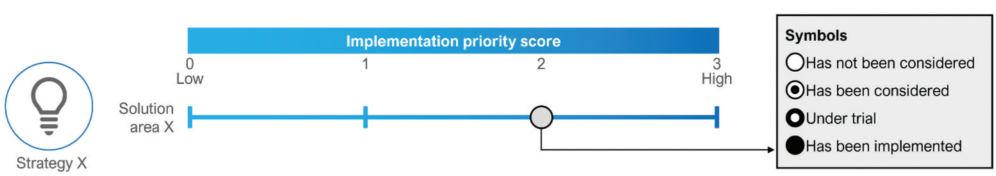

Figure 5. Visualisation of evaluation results (implementation priority score) for different decarbonisation strategies and solution areas.

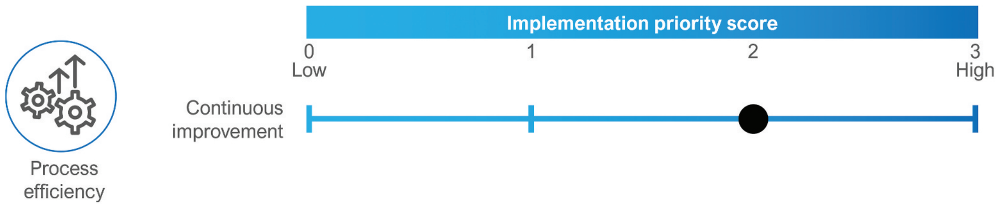

Figure 6. Implementation priority score for a solution under the process efficiency strategy.

implementing continuous improvements for eco-efficiency (reduce energy and material consumption, reduce waste and emissions) across multiple facilities, especially at CVA2, WPA2 and PMA3. Interviewee O stated that the case company has implemented continuous improvement programmes for a long time as part in its environmental strategy, thus low-hanging fruits and quick wins have already been completed. Even though industrial digitalisation presents good opportunities, it has its own set of challenges but also presents new opportunities to streamline information flows, enhance collaboration, enable automation and real-time performance visualisation, and support more complex continuous improvements (process optimisation). This solution has been given a medium implementation priority score.

4.2. Fuel shift

As shown in Figure 1, fossil-based coke and natural gas are the two largest emission sources at the case company and fossil-based diesel accounts for a large share of emissions at multiple facilities. Accordingly, four solutions areas were considered for the fuel shift strategy (Figure 7) due to their ability to be integrated in the existing infrastructure: biodiesel, hydrogenated vegetable oil 100 (HVO 100), biogas, hydrothermal carbonised bio-coke (HTC bio-coke) and hydrogen. The technology readiness level (TRL) of such alternative fuels for machinery can range broadly and depend on the technology provider and contextual factors; for example, TRL5–7 for biofuels, TRL1–5 for biogas, and TRL2–6 for hydrogen depending on the sector of application (Pesonen et al., 2025). While the first three solution areas do not require major technological change (technology substitution), hydrogen is an energy carrier that can be used in combustion processes or in fuel cells to operate, but otherwise compatible with the energy infrastructure installed. The SWOT analysis for these four solutions can be found in Appendix (Tables A4–A7).

Biofuels such as **biodiesel and HVO 100** have the possibility to be either utilised purely or be blended with fossil fuels for a wide range of different applications at manufacturing companies. The foremost advantage of these biomass-based fuels is that they do not require modifications to the engines (Verger et al., 2022). Diesel is utilised at various processes such as engine testing, truck tank filling and internal logistics. Therefore, biodiesel and HVO 100 provide an opportunity for the case company to lower emissions across multiple facilities. According to the IEA, biofuels have already reached a great market development in the United States, Brazil, Central Europe, and Sweden (IEA, 2020). These countries represent the sites where the case company has operations with the largest share of emissions. Interviewee L mentioned that HVO

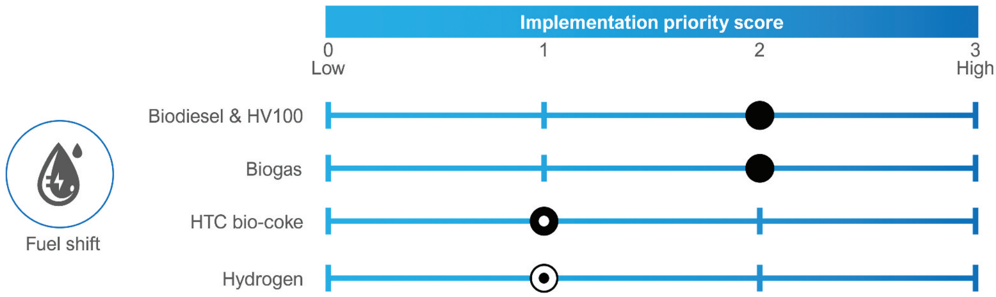

Figure 7. Implementation priority score for solutions under the fuel shift strategy.

100 has been difficult to get approved on the East Coast of the United States, which means that there are legislative barriers impeding the adoption of biomass-based fuels for CVA2 and WPA2, amongst other sites. While not applicable globally, this solution was deemed relevant for many facilities located in geographical areas where there is large potential for market growth. Therefore, biodiesel and HVO 100 were given a medium implementation priority score.

Biogas is already being explored in various automotive companies and includes several gases produced from bio-based sources, such as raw biogas, compressed biomethane, liquefied biomethane and landfill gas. Two issues raised by multiple interviewees are the cost differences between natural gas and biogas, as well as the limited availability of biogas in certain regions. Both biomethane and landfill gas are viable alternatives at some of the facilities for heat generation in e.g. specific boilers, or it can be used in modified natural gas boilers (some modifications required to specific technical requirements on existing equipment to accommodate for the use of biogas) (Abanades et al., 2022). When electrification is too expensive or other alternatives are not suitable to implement, biogas can offer a fast and more economic bridging solution towards decarbonisation. For the North American facilities, the projected landfill gas pipeline will reduce the emissions from the use of natural gas at the WPA2 and CVA2. Therefore, biogas will enable lower emissions in the second most CO_2-emitting facility within the case company and was given a medium implementation priority score.

Coke is used at PFMA1 to power the melting process in a cupola furnace where cast iron is produced. This foundry has the capacity to produce high-quality low-cost iron and has a high maintainability potential compared to other alternatives. In addition, the use of a lower grade of raw material (external scrap and recycling scrap from production) provides environmental advantages. **HTC bio-coke** is the only promising alternative to replace fossil-based coke while keeping the cupola furnace in operation. According to Interviewee E, who has an extensive expertise on foundry processes, lab-scale test has successfully replaced 40% of the coke with bio-coke in a project partially funded by the Swedish government. However, the HTC bio-coke is not ready to be deployed to replace fossil coke completely and several chemical and physical properties need further development. Furthermore, there were no suppliers available in the point in time when this study was conducted. Therefore, HTC bio-coke has been given a low implementation priority score and is currently under trial.

According to Rissman et al. (2020), **hydrogen** solutions offer several opportunities and benefits due to its inherent properties and applications to store energy (IEA, 2019). Today, hydrogen is almost entirely supplied from fossil fuels. Therefore, hydrogen production is responsible for over 1Gt of CO_2-eq per year (IEA, 2024). Other important factors are the high costs associated with in-house production, storage, and distribution due to electricity price, capital cost of electrolysers, and their utilised capacity (Longden et al., 2022). The case company is subject to different legislations in the countries it operates, which hinders large-scale implementation of hydrogen. According to Interviewee O, fuel cell powered forklifts were considered at CVA2 to reduce emissions from internal logistics but not implemented as the costs for such a project were deemed unsustainable. The lack of know-how, experience and practice across the studied facilities also decreased the implementation priority of this solution area.

4.3. Electrification

Four solution areas were identified for electrification (Figure 8): coreless induction furnace (CIF), heat pumps, on-site and off-site renewable energy. While these technologies are largely mature (TRL8–9), continuous technology developments are ongoing to improve their efficiency and innovate with new ways to harvest renewable energy sources (Pérez Caballero et al., 2023). All four areas have a medium or high implementation priority and have already been implemented to some extent at the case company. The SWOT analysis for these four solutions can be found in Appendix (Tables A8–A11).

CIF is a technology that eliminates the need of fossil coke or other fossil fuels for the melting processes in a foundry. In the case of PFMA1, this technology could eliminate the emissions produced from fossil coke at the foundry, which is the company's single largest source of CO_2, putting them on track to reduce its total emissions by 30% by 2025. According to Interviewee E, about 10% of the cast iron at PFMA1 is produced by electric CIFs. The knowledge for this technology inside of the company already exists, creating opportunities to scale up. However, replacing the cupola furnace with CIFs also presents trade-offs. The material quality requirements are higher, and the circularity of the melting process is decreased. In addition, Interviewee E stated that the complete replacement of the cupola furnace with CIFs will require a considerable increase in installed power capacity that will have to be accommodated by the local energy supplier. Therefore, CIFs were given a medium implementation priority score due to the identified trade-offs.

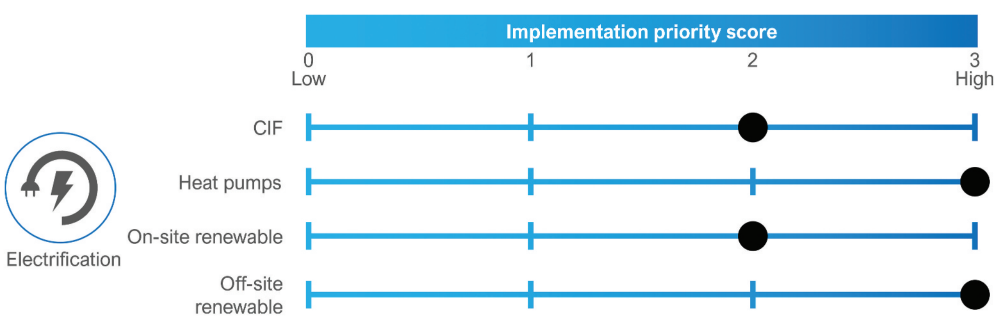

Figure 8. Implementation priority score for solutions under the electrification strategy.

Heat pumps are overall more efficient than conventional heating systems, thus producing lower emissions due to reduced energy consumption (IEA, 2022b). While this technology has the potential to be a carbon-free alternative, a low renewable electricity mix could be a threat to successful decarbonisation using heat pumps (Ahmed et al., 2022). A large-scale deployment can strain the electrical grid which can be problematic in locations where the grid is unreliable and electricity prices are also volatile. Finally, heat pumps can also enable heat recovery which has major potential in curtailing emissions. Thus, heat pumps received a high implementation priority score.

On-site renewable energy and **off-site renewable electricity** are both forms of sourcing climate-neutral electricity (Ahmed et al., 2022). Different from other solutions highlighted in this study, these are not technologies *per se* but rather enablers of electrification. A clear example of the former is to harness energy through photovoltaic panels installed on the facility premises, while the latter can be provided by a third party in various contractual forms. There are limitations in generating sufficient to cover any substantial portion of a facility total energy demand, putting increased pressure on sourcing off-site renewable power. Hence, a medium and high implementation priority score was assigned to on- and off-site renewable electricity accordingly (International Renewable Energy Agency, 2018).

4.4. Carbon capture

Carbon capture options are diverse (pre-/post-combustion, oxyfuel, chemical looping, etc.), and their maturity can range broadly, covering the entire TRL scale (Bukar & Asif, 2024). For example, depending on the separation method (membrane, solvent or sorbent) and the technology developer or provider, pre- and post-combustion technologies typically range from TRL3–9 (Bukar & Asif, 2024; Hekmatmehr et al., 2024). Post-combustion capture technologies are more extensively researched, and consequently more mature solutions are commercially available. Direct air capture only recently benefitted from more attention and is of relatively lower maturity; however, some promising technologies are already at TRL 7 and above (Bisotti et al., 2024). Industrial large-scale solutions exist to capture carbon directly from the ambient air with **direct air capture (DAC)** technologies, or through end-of-pipe technologies from point sources of CO_2 emissions with **CCS** and **CCU** (Hawken, 2017). All three solution areas were deemed as less desirable and/or economically unfeasible by the experts interviewed even though CCS and CCU have been considered (Figure 9). The SWOT analysis for these solutions can be found in Appendix (Table A12).

A major issue preventing end-of-pipe solutions from being widely used in industry is their techno-economic feasibility. Current solutions are limited to large point sources and not scalable for smaller facilities and for emissions of lower-carbon intensity. Interviewee D pointed that the foundry at PFMA1 is the case company's largest source of CO_2 emissions but it is a small point source in relation to the techno-economic margin for current technologies. In addition, CCS does not require the discontinuation of fossil-based resource which is prioritised over offsetting technologies by the case company. The weaknesses and threats identified were more substantial than the opportunities offered by this technology, and no strengths were identified by experts. CCU follows the same

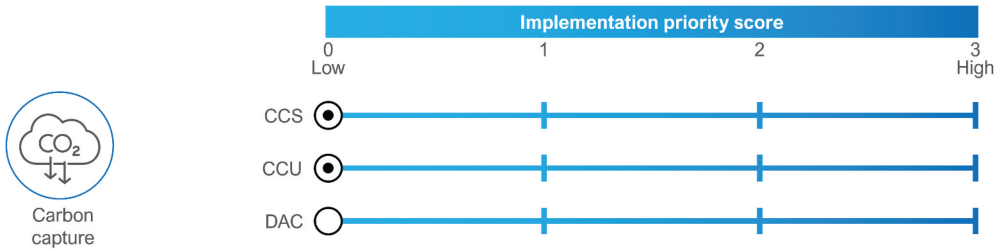

Figure 9. Implementation priority score for solutions under the carbon capture strategy.

SWOT logic as CCS. However, it is not subjected to the weakness of permanent storage of the captured carbon.

Interviewee D mentioned that DAC could be an interesting solution to offset hard-to-abate emissions. In addition, it is an opportunity for the case company to partake in Emission Trading System (ETS) schemes and to avoid future costs under upcoming carbon tax regulations. However, this technology has too high costs per amount of captured CO_2 compared to the current carbon price to be profitable (IEA, 2022a).

4.5. Technology substitution

While there are numerous technologies available for this strategy, district heating and alternative paint shop solutions were investigated to tackle the largest sources of CO_2 emission at the case company's manufacturing sites (Figure 10). The SWOT analysis for these two solutions can be found in Appendix (Table A13 and A14).

In select regions, **district heating** offers a low-carbon alternative for thermal energy needs in buildings and processes, currently utilised in SWP1, PMA1, and PFMA1. Despite its potential to reduce CO_2 emissions, most district heating systems globally still rely on fossil fuels, hence many providers are transitioning to renewable energy sources to mitigate emissions (Werner, 2017). Recognised for its efficiency and cost-effectiveness, district heating is increasingly adopted worldwide, aiding societal decarbonisation (Swedish Energy Agency, 2015). However, its availability is limited at the case company's sites, with external control over heating sources posing dependence risks, resulting in a medium implementation priority.

Paint shop solutions are required to tackle one of the most energy intensive processes at the case company Paint deposition and curing processes involve many steps consuming significant amounts of electricity, natural gas or other heating energy sources, hot and cooling water, chemicals, and compressed air in pre-treatment and cleaning baths, air supply systems, paint spray booth, and curing ovens (Giampieri et al., 2020). A three-wet painting technique requires only one drying process and has the potential to decrease CO_2 emissions by 15%. Another technique, the aqua-tech paint system uses two instead of three types of coats and an optimised air-conditioning paint booth reducing emissions by 15 up to 34% compared to conventional water-based paint booths (Mazda, 2024). Painting activities at WPA1, WPA2 and SWP1 are powered by natural gas for the most part, thus contributing to a large share of emissions at the case company (Figure 1). A major threat for this solution area is potential conflicts with recent investments made

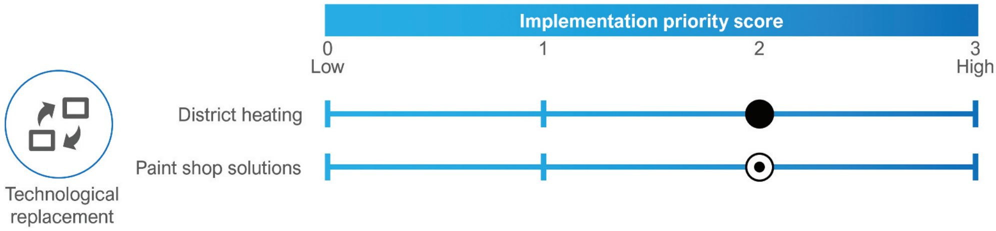

Figure 10. Implementation priority score for solutions under the technology substitution strategy.

in the paint shops at multiple facilities, complicating initiatives that involve major changes in the technologies newly installed. Thus, a medium implementation priority score was assigned to this broad solution area.

4.6. Circularity

Heat recovery was investigated under the circularity strategy (Figure 11). The SWOT analysis for this solution can be found in Appendix (Table A15).

Heat recovery is a versatile solution to recirculate waste heat and can be applied in various processes to reduce energy consumption and costs. Thermal waste energy can be recovered from ovens and dryers in the paint shop using heat exchangers to be used in space heating or (pre)heating processes. The case company has implemented heat recovery in several facilities, such as PFMA1, PMA2 and CVA3. Interviewee O pointed that waste heat recovery is a straightforward way to decrease the need for heat production and associated facility costs. However, Interviewee G recognised that the cost of heat recovery can increase if applied to small-scale operations and/or applied in situations where retrofitting is needed. Given the numerous advantages and many potential applications of heat recovery, this solution area should be highly prioritised.

4.7. Summary and lessons learnt from the case study

The proposed approach guided the exploration of six decarbonisation strategies in a simple and structured way to identify and prioritise solution areas given current conditions at the case company. The highest scores were obtained for the strategies Electrification and Circularity. The other solution areas also scored relatively high, except for carbon capture which was considered the least desirable solution area according to the experts interviewed.

The first lesson learnt was that the strategies are complementary, and it is not possible to define a predefined order of preference for their effectiveness (for example, as the

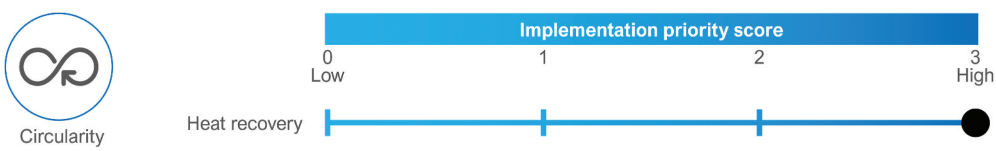

Figure 11. Implementation priority score for solutions under the circularity strategy.

waste hierarchy does). Since the target is to achieve zero emissions in a short period of time, all strategies should be employed in combination to tackle both demand- and supply-side emissions simultaneously. This is especially important to consider when there may be trade-offs or rebound effects when applying a single strategy in isolation.

The second lesson learnt was that existing knowledge and experience within the company is a critical factor to determine the implementation priority of solution areas. Existing capabilities can be transferred across manufacturing sites through the companies' internal mechanism to disseminate best practices. While the literature review provided both industry-specific and more general information to contextualise the interviews, the interviewees' responses provided tacit knowledge based on their hands-on experience and insights specific to the case company culture and personal values. Although efforts were made to mitigate bias and subjectivity when evaluating solutions, it remains an influencing factor when prioritising investment decisions.

Finally, the third lesson learnt was that the solution areas' desirability and potential impact can change over time and across manufacturing sites. The SWOT analysis was performed across manufacturing operations globally (rather than on a site-by-site basis) and focused on a snapshot of the situation today based on technical requirements, estimated costs, current capabilities, and potential environmental benefits for the case company. Therefore, it is essential to differentiate the manufacturing sites' specific conditions to account for the national and regional legislation, and local opportunities and incentives (including actual costs and benefits). Such an in-depth analysis should be carried as part of the next steps before implementation (step 4 in Figure 4).

5. Discussion

This study investigated strategies and technological solutions to decarbonise manufacturing operations and this section discusses broader implications, pointing to potential avenues for further work.

The strategies and solution areas in the proposed approach aligned with the definition of decarbonisation – reduce carbon intensity on the supply side (Davis et al., 2018; Goh et al., 2018) and reduce energy intensity on the demand side (Mundaca et al., 2019). These two aspects allow for good coherence in their corresponding research and policy efforts as demand- and supply-side measures have different requirements (Liu et al., 2022; Rissman et al., 2020; Sachs et al., 2015). This is especially critical to address the urgency of climate change, requiring immediate and impactful actions to stay within 1.5°C global warming (Paris Agreement).

At a micro and meso level, acting fast must be done with careful planning to ensure that the measures implemented lead to effective and efficient emissions reductions (Davis et al., 2018). For the case company in this study, many of these quick wins were already done, thus the efficiency improvements are more advanced and more difficult to identify. The fuel shift strategy holds great potential for quick action towards phasing out fossil fuel by increasing the share of low-carbon and renewable resources without major changes to the production systems. These actions can readily be taken, thus addressing the need to a rapid response to reduce emissions.

Since the target is carbon neutrality, all areas of emissions must be tackled eventually. Different decarbonisation strategies can be combined. For example, the quick wins and largest emission sources can be tackled first, and other processes with lower emissions can be investigated later on or in parallel. Long-term action plans typically include larger systems change (circularity and electrification) and technology innovation (technology substitution, such as novel processes using electricity or hydrogen to replace fossil-fuelled processes), addressing the need for impactful actions to deliver zero or positive carbon footprints. Therefore, a non-hierarchical approach is needed to emphasise solution areas that are more appropriate depending on the manufacturing processes taking place and geographical location of the studied facility.

Companies must often deal with the dilemma to balance short-term profitability and long-term sustainability goals, accounting for the short-term successes that will make possible the long-term ones (Despeisse et al., 2022). On the one hand, remaining competitive is critical to stay in the game and contribute to the increase sustainability of the manufacturing industry. On the other hand, climate action is becoming a prerequisite to be competitive in today's market under the European Green Deal and Paris Agreement. Bridging technologies or low-carbon technologies (i.e. not sufficient to achieve carbon neutrality) for short- to mid-term action should consider potential lock-in effects to understand the long-term consequence and avoid undesirable outcomes. This is especially critical when decarbonisation solutions are competing or incompatible, whereby investment in one direction reduces the incentive to invest in other decarbonisation strategies (e.g. electrification vs. fuel shift). In addition, low TRL solutions may be the most advantageous and companies need to decide whether to take the risk of being early adopters (pioneers) or to reduce risk by waiting for proven solutions to be more mature. Thus, careful considerations for different scenarios are essential to fully comprehend the consequences of different decarbonisation pathways.

Novel indicators can help quantify impacts as well as indicate improvements, accounting both for relative improvements (per unit) and absolute (total emissions). Absolute sustainability KPIs need to be further developed, especially to help translate planetary boundaries into metrics usable at a local or company level (Hjalsted et al., 2021). Such absolute sustainability indicators are necessary to highlight potential rebound effects and to avoid the environmental burden shifting to other parts of the systems (Brown et al., 2012; Fitzpatrick & Dooley, 2017; Sachs et al., 2019). For example, more efficient and low-cost energy systems leading to increased usage compensating for the initial efficiency savings, or technological change to improve process emission locally but generate additional emissions up- and downstream. Another example is electrification in regions with carbon-intensive electricity mixes (reducing Scope 1 emissions while increasing Scope 2 emissions) or the additional environmental impact related to the extraction of raw materials and production of renewable energy technologies, batteries and other required infrastructure to support decarbonisation through electrification.

Various strategies can be combined to achieve manufacturing decarbonisation, each offering multiple-solution areas. Prioritisation is based on contemporary solutions from the literature and interviews. However, solutions vary depending on organisational experience, processes, and locations. All strategies remain valid, but their effectiveness may differ based on local conditions, such as technological expertise and renewable energy availability. While CCS and CCU were not prioritised by the case company, supply-side interventions can reduce carbon intensity, with CCS and CCU addressing so-called unavoidable emissions.

Regarding geo-political and regulatory issues, national or regional programmes in place and upcoming are encouraging green investments (policy instruments), especially when current market forces are not steering in a sustainable direction. Energy-economy models, such as MARKAL (market allocation) (Fishbone & Abilock, 1981), can help evaluate economic benefits and optimise investments in energy systems accounting for multi-objectives, including decarbonisation (Rafaj & Kypreos, 2007). In some cases, the political context and local regulations may hinder the implementation of some decarbonisation solutions perceived as high risk or not considered as sustainable, such as CCS and nuclear power. Other local initiatives and bottom-up solutions with the local community can deliver powerful examples further inspiring new initiatives and, when possible, scaling up of these local solutions; for example, the pipeline project to supply biogas from landfill to the case company's facilities located in the northeast of the US.

6. Conclusion

This study aimed to provide a simple approach as a quick starting point for companies to initiate decarbonisation activities. First, decarbonisation strategies and solutions were reviewed based on the academic and grey literature. The proposed three-step approach is as follows: (1) map emissions, (2) identify potential solutions, and (3) perform a SWOT analysis. The second step includes six decarbonisation strategies: process efficiency, fuel shift, electrification, carbon capture, technology substitution, and circularity. Suggested next steps include quantifying costs and benefits (business case) for implementation at specific sites. Additional aspects to be considered for further work were also made in the discussion section, such as alignment with climate policies, and balancing short- vs. long-term efforts to avoid lock-in effects. Moreover, we suggest integrating novel sustainability indicators to support decisions in line with the science-based targets, manage potential trade-offs, and monitor progress towards absolute sustainability.

The proposed approach was tested in MNC manufacturing vehicles to obtain the implementation priority score through semi-structured interviews for different solutions areas under each of the six decarbonisation strategies. The results and proposed approach were helpful to understand what can be dealt with locally and in which regions to prioritise investments to get the most impact. The lessons learnt from this case study were reported and discussed to highlight a broad set of factors to be considered when selecting and implementing technological solutions, going beyond the technical and economic feasibility of individual technologies. There is no one-size-fits-all when it comes to selecting solution areas for decarbonising manufacturing operations. The most appropriate solutions can only be identified by considering the specific conditions and resources available to the focal company, and doing so in collaboration with their employees and the local community. The proposed industrial decarbonisation approach provides a structured way to harmonise efforts and start a learning curve towards more advanced capabilities to decarbonise manufacturing operations effectively.

Disclosure statement

Lena Moestam is employed at Volvo Truck Corporation. The authors have no other competing interests to declare for this article.

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Appendix

Table A1. Facilities overview and energy profiles.

Facility	Energy profile
CVA1, Australia. It has 600 employees and is a cabs and vehicle assembly plant for both the case company's 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.
CVA2, USA. It has 2975 employees and covers approximately 230 Ha. Cabs and vehicle assembly plant where case company's trucks and multi-brand cabs are produced. The main activities are assembly, machining, and foundry. 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.
CVA3, France. Cabs and vehicle assembly 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.
WPA1, Brazil. Cabs and vehicle assembly plant that assembles case company's 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.
WPA2, USA. It 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.	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.
SWP1, Sweden. With 1450 employees, cabs and vehicle assembly plant which produces 75 000 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.
PA1, France. It employs 750 employees to produce annually around 5000 engines of three different types for all applications at the case company (trucks, buses, construction equipment, etc.). The facilities are relatively new and modern.	Natural gas is used for cooling and heating. Diesel is used for production (engine testing and internal logistics). Similar to the other French site, electricity is sourced from renewables.
PMA1, Sweden. 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.	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.
PMA2, France. Currently part of Cabs and vehicle assembly. However, there are plans for categorizing this plant as powertrain due to the activities of machining & assembly to produce axles. 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.

(*Continued*)

Table A1. (Continued).

PMA3, USA. With 1300 employees, it is part of powertrain production where both engines and transmission equipment are produced. The main processes that take place are machining and assembly.	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.
PMA4, Brazil. Powertrain production for 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.
PFMA1, 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.
W1, France. The warehouse is positioned to supply several facilities both outside and inside the case company.	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.

Table A2. Interview questionnaire structure and example of questions asked.

Introductory questions

1. Could you please tell me about yourself, your role in the company, and which manufacturing facilities you work with?
2. Are you currently working on any sustainability-related project toward decarbonization?
3. What are your thoughts on the company's progress to decrease CO_2 emissions?

Company-specific questions

4. In your opinion, what is the most important decarbonization issue to address at the company?
5. Most of the CO_2 emissions come from these sources *[list emission sources collected from the company's databank relevant to the site(s) for the expert interviewed]*. What are the processes contributing to them?
6. What measures is the company taking to decarbonize manufacturing? What kind of actions are required to reach the targets?

SWOT-related questions

7. Focusing on internal aspects within the company's industrial facilities that you work with, what are the main challenges and opportunities for the company to achieve the emissions targets in manufacturing? (strengths and weaknesses)
8. Accounting for what is happening outside the company boundaries in an increasingly connected world with complex interactions, what are the main opportunities and challenges to decarbonize the manufacturing facilities? (opportunities and threats)

Framework questions

9. Given your expertise on *[specific strategies from the framework]*, how and to what extent can they contribute to the goal of reducing carbon emissions?

Closing questions

10. Based on your previous answers, what do you think are the more urgent issues?
11. How do you think the manufacturing of electric vehicles will affect carbon emissions? Will it require changes in the manufacturing? If so, what changes?
12. Are there further issues you want to discuss that you feel we have missed

Table A3. SWOT analysis for efficiency improvements

Continuous improvements
Strengths
Small changes and fixes on existing equipment do not require substantial capital investment.
Efficiency improvements can be integrated into daily routines and activities.
Versatile strategy applicable to both production and building-related matters.
Prolong the lifetime of machines and appliances, reducing the need for new investments.
Not confined by geography, allowing for knowledge sharing.
Weaknesses
Require both time and personnel, leading to potential time constraints.
Marginal improvements after a certain point, necessitating replacement or new technologies.
Opportunities
Environmental consciousness and ecological mindset among employees.
Digitalization can contribute to efficiency gains through automation and real-time visibility.
Energy mapping mandated by governments provides opportunities for efficiency improvements.
Threats
Decarbonization efforts slowed due to COVID-19, focusing on supply chain capacity.
Running out of opportunities for efficiency improvements in North American facilities.
Extended reliance on fossil fuels through certain efficiency improvements.

Table A4. SWOT analysis for Biodiesel (B100) & HVO100.

Biodiesel (B100) & HVO100
Strengths
Can be utilised at 100% concentration or blended with fossil fuels.
Do not damage or require modifications to engines.
Validated according to EPA and Euro 6 standards.
Weaknesses
Contribute to air pollution when combusted.
Require fertilizers connected to emissions, not entirely carbon-free.
Compete over land with biodiversity and contribute to soil erosion.
Large spread in GHG emissions and production costs.
Opportunities
Lower emissions at multiple facilities of the case company.
Great market development in the United States, Brazil, Central Europe, and Sweden.
Threats
Market price fluctuation due to extreme weather.
Difficulty in approval on the East Coast of the United States.
Rapidly increasing demand surpassing market availability.

Table A5. SWOT analysis for Biogas.

Biogas
Strengths
Low GHG emissions, decreased nitrogen oxides and particulate matter emissions.
Can replace natural gas in processes and logistics.
Great application potential for heat generation and CHP systems.
Weaknesses
Require modifications to accommodate fuel change.
Lower energy content compared to LPG.
Opportunities
Natural gas accounts for most emissions, biogas can be a replacement.
Competitive costs due to soaring natural gas prices.
Explored in various automotive manufacturing companies, becoming more mature.
Production is expected to grow considerably with decreasing prices by 25% by 2040.
Technical, research and development support from the US government for biogas projects through the “Better Climate Challenge” deal.
Central Europe and the US have many biogas plants.
Threats
Like biodiesel and HVO100, supply chain and prices dependent on weather conditions.
Limited availability in certain regions.
Increasing demand for biogas.
Different views on biogas as a decarbonization solution.
Strict criteria for biogas to be approved by the real estate organisation within the case company due to certification requirements and further specifications.

Table A6. 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.
Good storage and transportation possibilities due to its properties.
Successful lab scale tests replacing 40% of the fossil coke with bio-coke.
High interest from external actors.
Weaknesses
Lower energy density compared to fossil coke.
Must sustain melting process under high temperatures and pressure.
Opportunities
Promising biobased alternative for replacing fossil coke.
Funded by Swedish governmental entity with interest from the steel industry.
Allows continued operation of the cupola furnace.
Threats
Multiple uncertainties in sourcing bio-coke.
Competing projects like HYBRIT pose a threat to the foundry process.

Table A7. SWOT analysis for hydrogen.

Hydrogen
Strengths
Can be produced without carbon emissions.
Promising as energy storage solution to store renewable electricity and deal with fluctuation in supply and demand.
Ability to replace LPG or natural gas with hydrogen in burners with minimal to no retrofitting (slight or no modifications).
Weaknesses
High production costs due to electricity price, the capital cost of the actual electrolysers and their utilised capacity, making it difficult to compete with natural gas.
Produces nitrogen oxide emissions when combusted with air, requiring additional investments for treatment solutions.
Logistical challenges due to cooling requirements.
Opportunities
Dropping prices in renewable energy technology.
Tested in other automotive companies.
Threats
Lack of knowledge and practice in utilising hydrogen.
Fuel cell powered forklifts were considered but battery-powered alternatives were preferred as a more straightforward solution.
Regulatory limitations in the development of a clean hydrogen industry in most places.
Today, hydrogen mostly produced from fossil fuels. If green hydrogen is to be used, in-house production is subjected to the same conditions and factors revolving around on-site energy generation, in addition to other hydrogen-specific bottlenecks.

Table A8. SWOT analysis for coreless induction furnace.

Coreless induction furnace (CIF)
Strengths
Eliminate the need for fossil coke, reducing emissions.
Existing knowledge within the case company for scaling up.
Weaknesses
High electricity consumption.
High investment costs.
Higher material quality requirements.
Lower metallurgical waste quality compared to the waste produced by the cupola furnace, resulting in decreased possibility to recycle the scrap in-house.
Opportunities
Knowledge already exists inside of the case company about electric furnace and a good opportunity to scale up.
Opportunity for heat recovery solutions.
Possibility to secure governmental funding in Sweden (up to 30% of investment cost), thus high cost is not seen as a barrier.
Threats
Increased logistical activities impacting Scope 3 emissions.
Increased installed power capacity of 40 MW which can strain on an already volatile local electrical grid.
Increased personnel costs as operations require 15 additional employees.

Table A9. SWOT analysis for heat pumps.

Heat pumps
Strengths
More efficient than conventional heating systems.
Carbon-free solution if powered by renewable electricity.
More reliable heating compared to gas boilers (susceptible to volatile prices due to geopolitics).
Several types of heat pumps for specific applications and in different climates.
Can satisfy both heating and cooling needs.
Weaknesses
High cost for replacing natural gas-powered systems.
Limited usage for processes requiring fast and high heat.
Opportunities
Cost savings relative to capital cost with higher energy (electricity and fuel) prices.
Can satisfy 90% of the global water and space heating, potentially making heat pumps one of the largest contributors to CO_2 reductions of technologies currently available on the market.
Threats
Feasibility lowered for large facilities.
Increased strain on electrical grid, especially in locations with unstable electricity grid.

Table A10. SWOT analysis for on-site renewable energy.

On-site renewable energy
Strengths
Minimised transmission and distribution losses.
Utilises unused space on facilities' site.
Weaknesses
Facilities might not be located in optimal places for renewable energy.
Intermittent energy sources requiring investments in energy storage systems.
Opportunities
Contributes to the case company's renewable energy targets.
Potential for heat generation and integration into paint shop processes with heat cascade strategy.
Several facilities within the case company use solar PVs both on building roofs, on factory grounds and on parking roofs, thus knowledge already exist within the case company and can facilitate further implementation.
Expected overgeneration provides the opportunity to store it and sell it back to the grid.
Decreased dependence on grid, especially for location with unstable electricity grid.
In line with the electrification trend and transition to electric vehicles, with opportunities to assemble electric trucks, charging and testing batteries with 100% on-site renewable electricity and achieve net zero targets.
Threats
Regulatory constraints, especially for wind power.
Disparities in net-metering and feed surplus to grid in certain regions.
Issues with roof ability to sustain extra load without replacement or renovation, and future land plot applications.

Table A11. SWOT analysis for off-site renewable energy.

Off-site renewable energy
Strengths
Multiple ways to source renewable electricity.
Possibility to purchase renewable energy from an independent green power producer with power purchase agreements (PPAs).
Possibility to purchase renewable energy certificates (RECs) and guarantees of origin (GOs).
Weaknesses
PPAs might not always be available.
Opportunities
RECs can compensate for lack of direct renewable electricity on the grid.
Common strategy among automotive companies.
RECs have an international standard (I-RECs).
ThreatsThreats
Supply of renewable energy varies by location.
Although purchasing credits to offset emissions is common practice, it does not eliminate carbon emissions.
Some locations and energy suppliers lag behind with certifying green energy

Table A12. SWOT analysis for carbon capture and storage.

Carbon Capture and Storage (CCS)
Strengths
No need to retrofit manufacturing processes.
Can cover residual emissions which currently cannot be eliminated.
Weaknesses
Economically feasible only for large-scale emissions.
Requires high CO_2 concentration in flue gases and need to combine flue gas streams that have different properties.
Lack of expertise and experience in the field as CCS equipment (such as chemical absorption plants) require space for construction and personnel dedicated for the operational phase.
Captured carbon needs large and reliable storage (yet to be developed in most parts of the world).
Offsetting methods and technologies have the lowest priority in the case company's climate mitigation strategy.
Opportunities
Deployed by other automotive companies (such as Toyota) demonstrating its potential.
Opportunity to be amongst the pioneers in adopting CCS early.
Threats
Controversial as it does not eliminate carbon emissions in the first place.

Table A13. SWOT analysis for district heating.

District heating
Strengths
Cheaper than the price for electricity (when available).
Possible to use for building heating and certain production processes requiring heat at a certain temperature.
Energy efficient during high heating demand periods (winter in northern Europe).
Weaknesses
Uncertainties regarding energy sources (fuel or waste burned in the district heating).
About 90% of the world's district heating systems powered by fossil fuels (70% in Europe), thus most district heating systems are not environmentally friendly.
Even with a high share of renewables in Sweden, burning plastic waste counts as Scope 2 emission for the case company.
Opportunities
Influence energy providers to increase sustainable practices.
In France, district heating available with 65% renewable energy input, making it an interesting alternative to replace natural gas for heating and in some processes.
Opportunities to integrate sustainable technologies (such as renewables) when shifting away from fossil fuels.
Relieve strain on the power grid since it does not run on electricity.
Threats
Price changes with geographical area and suppliers.
Limited availability due to a lack of infrastructure in certain regions.

Table A14. SWOT analysis for paint shop solutions.

Paint shop solutions
Strengths
Several technologies can reduce emissions while conserving quality.
The solutions range in structure and nature, such as three-wet painting technique and aqua-tech paint system with emission reductions of 15-34% compared to conventional water-based paint booths.
Weaknesses
Challenge in balancing VOC and CO_2 emissions when reformulating paint composition.
Opportunities
Thermal energy recovery from paint booth exhaust air and recirculate it to heat air and water, thus reduce natural gas requirements.
Potential for alternative drying and curing techniques, such as infrared and ultraviolet curing. Novel painting process technologies continuously being developed, such as Toyota's airless paint atomizer promoting energy saving through static electricity and CNH industrial implementing nanotechnologies to pretreat surfaces at room temperature.
Threats
Painting remains one of the most energy-intensive processes in automotive plants.
Major investments in natural gas technology in some facilities at the case company still require time until return on investment is reached.

Table A15. SWOT analysis for heat recovery.

Heat recovery
Strengths
Straightforward way to save money by lowering the need for heat production.
Multiple technologies available for specific applications depending on the temperature range (cooling or heating) and the required working fluid, such as recuperative and regenerative heat exchangers, passive heat preheaters and heat pumps.
Weaknesses
High investment capital cost for retrofitting.
Opportunities
Energy recovery from the thermal oxidizers, compressors, ovens, and dryers in the paint shop, potential natural gas use reduction for heating water, space and some processes in adjacent facilities.
In France, governmental subsidies for energy-efficient projects.
Threats
Integration challenges for different processes working at different rates (not synchronized).
Manufacturing division and the real estate organisation must collaborate closely to achieve optimal results for space heating through heat recovery.
Contaminated exhaust streams requiring further investments in filters and clean-up solutions to depollute gases and liquids before becoming suitable for heat recovery strategies.