Future Carbon Footprints of Heavy-duty Road Transport in Sweden

A Vehicle Fleet Simulation Capturing the Impact of Electrification and Biofuel Use

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This degree project has been carried out at the Department of Physical Resource Theory, Chalmers University of Technology.

It was carried out in collaboration with *IVL Swedish Environmental Research Institute* and within *the Mistra Carbon Exit research programme*. It was also a part of the research project *“VHGgods – var sker godstransportsektorns framtida växthusgasutsläpp?”* funded via *Triple F (Fossil Free Freight)*.

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Abstract

To reach the national climate goals, the use of fossil fuels in the Swedish transport sector needs to be phased out. This thesis estimates the effects on the carbon footprint, energy and battery demand of Swedish heavy-duty lorries between years 2025 – 2060 for electrification and biofuel use scenarios. The degree project was carried out within the Mistra Carbon Exit programme as well as the VHGgods project and in collaboration with the Swedish Environmental Research Institute. The method consists of a simulation study, where a MATLAB-model was developed to capture the turnover of the Swedish heavy-duty lorry fleet and its potential development in a set of future scenarios. Finally, prospective lifecycle assessment is used to estimate the carbon footprint of the fleet.

The results suggest that a high electrification rate, with battery electric vehicles reaching 100 % market share in new sales by 2050, has the potential to completely phase out fossil fuels around year 2056 and to reduce annual total CO_2-eq emissions by 67 – 92 % between years 2025 – 2060, depending on climate policy ambitions affecting the liquid fuel, electricity and vehicle production processes. The use of biofuels has a large impact on the CO_2-eq emissions reductions of the heavy-duty lorry fleet, especially for a case with a low electrification rate. While the total energy demand for propulsion decreases over time, a high electrification rate could yield an increase in annual electricity demand for charging from 0.7 TWh in 2025 to 4 TWh in 2060 and increase the annual demand of new battery capacity from 1.1 to 6.5 GWh between years 2025 – 2060.

Consequently, electrification of Swedish heavy-duty lorries shows a high potential to reduce the CO_2-eq emissions of the fleet. However, complementary measures such as use of biofuels, or other renewable fuels, are necessary to reduce CO_2-eq emissions in the short-term and in line with national climate goals. To achieve the investigated electrification rates, prerequisites such as infrastructure development for charging needs to be in place to support the gradual expansion, which should be investigated in future studies.

Keywords: Heavy-duty transport, Decarbonisation, Electrification, Biofuels, Prospective life cycle assessment, Carbon footprint estimation, Battery electric truck, Transport simulation

Preface

This thesis concludes five years of studies within the Environmental Engineering programme with a specialisation in Energy Systems at the Faculty of Engineering, Lund University. The degree project was conducted during the spring semester -23 at Chalmers University of Technology, by Emma Rytterdahl and Sonja Toomingas. Both authors participated equally in the work to realise this thesis.

We would like to thank our supervisors Johannes Morfeldt and Julia Hansson, for the continuous support and guidance throughout the process, as well as examiner Associate Professor Daniel Johansson for his feedback. We would also like to extend a warm thank you to Pål Börjesson, Professor of Environmental and Energy Systems Studies at Lund University, for your time and effort to act as an external examiner for us. Lastly, we would like to express our gratitude to the people at the IVL office in Malmö for the warm welcome and opportunity to work there during the semester.

Lund, June 2022

Emma Rytterdahl & Sonja Toomingas

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Acronyms, Abbreviations and Nomenclature

Acronyms & Abbreviations

GHG	Greenhouse Gas
LCA	Life Cycle Assessment
ICEV	Internal Combustion Engine Vehicle
BEV	Battery Electric Vehicle
ZLEV	Zero- and Low-Emission Vehicle
GVWR	Gross Vehicle Weight Rating
GCWR	Gross Combination Weight Rating
GVW	Gross Vehicle Weight
GCW	Gross Combined Weight
WTT	Well-To-Tank
WTW	Well-To-Wheel
Vkm	Vehicle kilometres
Tkm	Tonne kilometres

Nomenclature

Gross Vehicle Weight Rating	The maximum allowed total weight for a vehicle, including passengers, fuel, and cargo
Gross Vehicle Weight	Total weight of a vehicle and its load
Gross Combination Weight Rating	Maximum allowed total weight for a vehicle and loaded trailer, including passengers, fuel and cargo
Gross Combined Weight	The total weight of a powered unit, trailer(s) and load
Heavy-duty lorry	A lorry with a GCV/GCW over 3.5 tonnes
Rigid lorry	Lorry with fixed load on its own axels
Articulated lorry	Lorry with separated tractor and trailer sections
Vehicle Activity	Annual total distance covered by a vehicle fleet, measured in vehicle kilometres (vkm)
Road Freight Activity	Measure of freight transport covered by a vehicle fleet, measured in tonne kilometres (tkm)
Vehicle cycle emissions	Emissions linked to production, maintenance and disposal of a vehicle
Fuel cycle emissions	Emissions linked to fuel/electricity production
Tailpipe emissions	Emissions emitted during vehicle operation

1. Introduction

A transition of the Swedish transport sector is required in order to reach the overarching national target of net zero greenhouse gas (GHG) emissions by 2045. Domestic transport accounts for approximately a third of the annual territorial GHG emissions in Sweden (Swedish Environmental Protection Agency 2021b) and according to the climate goal of the sector these emissions should be reduced by 70 % by 2030 compared to the levels in 2010 (Government Offices of Sweden n.d.). Within the domestic transport sector, heavy-duty lorries contribute to approximately 21 % of the emissions (Swedish Environmental Protection Agency 2021a). This emphasises the need to understand how and when to phase out fossil fuels within the heavy-duty lorry fleet in Sweden in a sustainable, timely, and cost-effective manner.

The Government official report SOU 2021:48 *"In a changing world - Sweden without fossil fuels in 2040"* (authors' translation) published in 2021 proposes that the use of fossil fuels in the entire Swedish vehicle fleet should be phased out by 2040, and electrification has been identified as an important pathway in the transition of the heavy-duty vehicle fleet, from predominantly running on fossil fuels to utilising 100 % renewable alternatives (Government Offices of Sweden 2021a). The pace of the electrification will impact the development of lifecycle GHG emissions of the heavy-duty lorry fleet and affect the demand of biofuels and critical components (e.g., battery metals) as well as complementary energy carriers necessary to completely phase-out the use of fossil fuels, such as electro-fuels[1] and hydrogen (Government Offices of Sweden 2021a).

This thesis investigates scenarios for the electrification and biofuel use of the heavy-duty transport sector in Sweden between years 2025 – 2060 and the subsequent estimated effects on lifecycle GHG emissions as well as battery and energy demand.

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[1] Synthetic fuels produced from renewable electricity.

1.1. Aim and research questions

The aim of the thesis is to formulate and analyse scenarios of the electrification and biofuel use of the Swedish heavy-duty lorry fleet, in order to investigate the effects on the carbon footprint of the fleet as well as to provide a better understanding of shifts in energy and battery demands. This will be achieved by creating a scenario-based simulation model of the domestic heavy-duty lorry stock between years 2025 – 2060.

The research questions to be answered in this thesis are:

1. *How can long-term scenarios be formulated to describe shifts in Sweden's heavy-duty lorry fleet composition and size?*

2. *How will scenarios for the transformation of the Swedish heavy-duty lorry fleet impact its carbon footprint over time?*

3. *How will scenarios for the transformation of the Swedish heavy-duty lorry fleet impact demand of fuels, electricity for charging, and batteries over time?*

1.2. Scope and delimitations

- The study investigates the Swedish heavy-duty lorry fleet and its transports within Swedish borders. Foreign-registered lorries transporting goods within Swedish borders are not considered. The analysed system is shown in figure 1.

- The time horizon for the scenario analyses is set to years 2025 – 2060.

- The considered vehicle types in the model are limited to internal combustion engine vehicles (ICEVs) run on fossil diesel and biofuels, and battery electric vehicles (BEVs). Vehicles with other propulsion systems and ICEVs run on alternative renewable fuels are not considered.

- The analysed environmental impact is limited to GHG emissions.

- Lorry sales and purchases from the second-hand market is not accounted for in the model. All sales are assumed to be new sales, and all vehicles are assumed to exit the fleet at end-of-life (when scrapped).

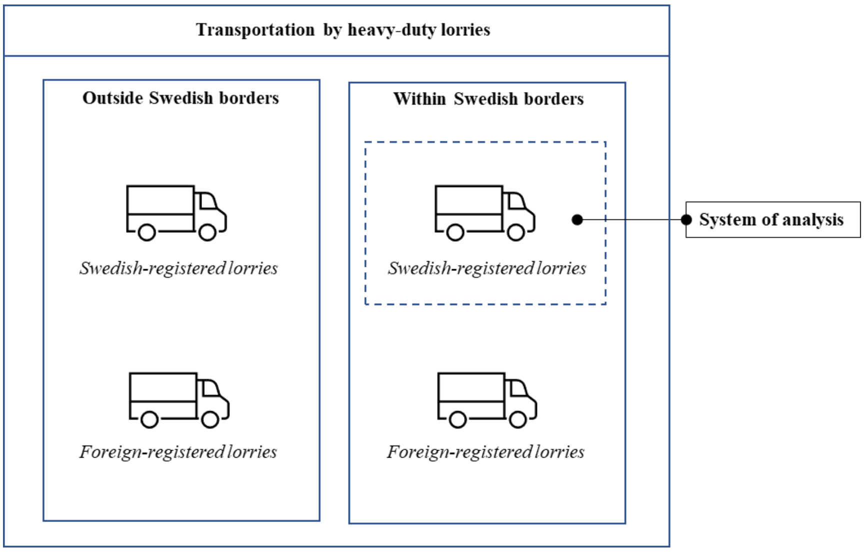

Figure 1: Study system of analysis.

1.3. Contribution to research

In a previous article within the Mistra Carbon Exit programme, Morfeldt et al. (2021) examined the potential impact on the carbon footprint of the Swedish passenger car fleet by banning sales of internal combustion engines in cars. By investigating the effects on the carbon footprint associated with electrification of the heavy-duty lorry fleet, this study extends the understanding of the impact and timing of decarbonisation measures within the Swedish transport sector.

1.4. Outline

The ensuing chapters of the report contain the following content:

2. **Methodology:** This chapters presents the theory and methods that were used to conduct the study. General assumptions for the created model are also presented and motivated.

3. **Background:** An overview of the Swedish heavy-duty lorry fleet is given, followed by powertrain and fuel technologies, current and historical transport demand, climate policies on EU and national level as well an overview on pathways to achieve a fossil free fleet.

4. **Foreground system scenario design:** Presents literature findings and model assumptions for parameters related to the foreground system[2] of the model.

5. **Background system scenario design:** Presents literature findings and model assumptions for parameters related to the background system[3] of the model.

6. **Simulation results & analysis:** Presents an overview of the selected main simulation scenarios and sensitivity analyses, followed by a presentation and analysis of the simulation results.

7. **Discussion & conclusions:** Includes a discussion of the results with regards to the research questions, followed by conclusions. Lastly, potential improvements and suggestions for future research are presented.

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[2] The foreground system model parameters include scenarios for electrification, biofuel demand and transport demand. The associated GHG emissions are tailpipe emissions.

[3] The background system model parameters include climate mitigation scenarios for the vehicle cycle and fuel cycle. The associated GHG emissions are the vehicle cycle emissions and fuel cycle emissions.

2. Methodology

This chapter provides a description of the research approach, followed by methods for scenario design, the vehicle fleet turn-over model and carbon footprint estimations. Lastly, general fleet characteristics that are independent of scenario developments are presented.

2.1. Research approach

To answer the research questions, a simulation study was conducted. The study consisted of three major parts which together create the complete study: 1) design of scenarios describing a potential evolution of the heavy-duty lorry fleet and associated life cycle emissions, 2) design of a model describing the turn-over of the heavy-duty lorry fleet, and finally 3) carbon footprint estimations.

2.1.1. Scenario design

The aim of the scenario design was to formulate scenarios between years 2025 – 2060 that capture 1) the changing demand for transport by heavy-duty lorries, the electrification rate of the fleet, as well as biofuel use, and 2) potential changes in the GHG emissions of the various life cycle stages of heavy-duty lorries, due to climate change mitigation strategies. The scenario design was based on prospective LCA methodology, which is presented in section 2.2.

2.1.2. Model design

The aim of the model design was to build a MATLAB-model capturing how the fleet changes each year during the modelled period, with regards to composition and size. This model is called the *"vehicle fleet turn-over model".* It calculates the inflows (new vehicles entering the fleet) and outflows (vehicles reaching end-of-life) based on estimated fleet characteristics (vehicle lifetime, average yearly mileages, etc.) as well as the designed scenarios for the transport demand and electrification rate. The methodology for the model is presented in section 2.3.

2.1.3. Carbon footprint estimations

The aim of the carbon footprint estimations was to estimate the annual carbon footprint of the entire fleet. Emissions within the fleet was divided into three groups which were calculated separately:

- Vehicle cycle emissions, which are connected to the annual production of new vehicles, maintenance of vehicles, and disposal of end-of-life vehicles (Morfeldt, Davidsson Kurland, and Johansson 2021).

- Fuel cycle emissions, which are connected to production and distribution of fuels and electricity for charging, also referred to as well-to-tank emissions (Morfeldt et al. 2021).
- Tailpipe emissions, emissions during the use phase, also referred to as tank-to-wheel emissions (Morfeldt et al. 2021).

The formulated scenarios and outputs from the vehicle fleet turn-over model were used to perform the emission calculations. General assumptions for the carbon footprint calculations are presented in section 2.4.

2.1.4. Study sources

Articles and other research that acted as basis for the scenario design, model design and carbon footprint calculations were acquired through the search engines Google Scholar and LUBSearch, as well as by reviewing policy documents, governmental documents, expert input and trade association documents acquired directly on relevant actors' websites.

Key sources for the prospective LCA data (development of carbon intensities over time) for the vehicle cycle and fuel cycle emissions were two articles by Morfeldt et al. (2023, 2021), and the data was acquired directly from one of the authors. This allowed the study to primarily utilise uniform and consistent assumptions for the carbon intensity development over the simulation period.

Historical and current statistics for the Swedish heavy-duty lorry fleet were key sources for estimating general fleet characteristics (average yearly mileages, lifespans etc.). These were primarily retrieved from the governmental agency *Transport Analysis's* website[4] and through direct contact (mail correspondence) with Transport Analysis.

2.1. Conceptual division of the simulation system

The simulation system was conceptually divided into two sub-systems: a foreground system and a background system, inspired by Morfeldt et al. (2021). Figure 2 displays an overview of the foreground and background systems. *Transport demand* and *transport supply* refer to the demand and supply of vehicle kilometres (vkm) from the fleet. Arrows represent inputs and outputs from the respective segments.

The foreground system captures the development of the fleet size and composition over time, which depend on scenarios regarding the evolution of the transport demand, electrification rate and biofuel usage. The background system concerns the developments connected to climate change mitigation scenarios affecting the vehicle cycle and fuel cycle. Therefore, the GHG emissions associated with the foreground system are the tailpipe emissions and the GHG emissions associated with the background system are the vehicle cycle emissions and fuel cycle emissions.

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[4] https://www.trafa.se/

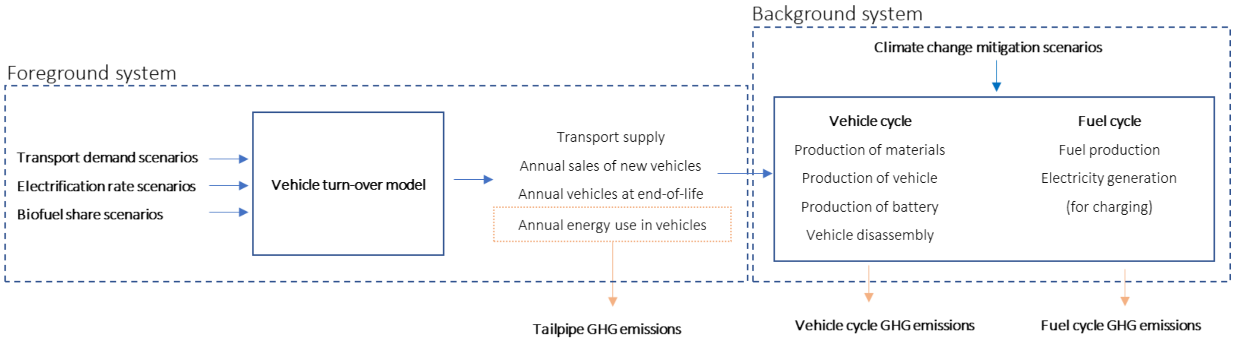

Figure 2: Overview of foreground and background systems.

2.2. Scenario design for prospective LCA

This section presents possible scenario design methodologies for prospective LCA, followed by a description of the design approach used in this study.

2.2.1. Methodology background

The use of LCA data for current product systems is of limited use when investigating the systems in the future, as these may change over time in a way that affects the environmental impact (Arvidsson et al. 2018). One example is the potential evolution of the grid mix, which has an important effect on the climate impact on BEVs (Mendoza Beltran et al. 2020). Product systems which are early in their development with regards to technology developments, production scale and market diffusion can be expected to undergo significant changes over time, where the environmental impact of the system changes as the product system becomes more mature (Mendoza Beltran et al. 2020; Morfeldt et al. 2021). This can be attributed to the influence of time and production scale on technological performance parameters (Arvidsson et al. 2018).

To deal with the system developments and the consequential effects on the environmental impact, prospective life cycle assessment can be utilised to model the system in a future, more matured phase (Arvidsson et al. 2018; Mendoza Beltran et al. 2020). This is done by applying future scenarios to the systems, which describe possible developments during the investigated timeframe based on a set of assumptions on how the system will evolve (Arvidsson et al. 2018). While not forecasts, the scenarios aim to represent possible future outcomes (Bisinella, Christensen, and Astrup 2021).

Whilst allowing for systems to be studied further ahead in time, there are inherent uncertainties associated with prospective LCA as a methodology (Arvidsson et al. 2018; Bisinella et al. 2021). Particularly regarding data scarcity and poor data quality (Arvidsson et al. 2018; Bisinella et al. 2021). For emerging products, data on what the system may look like when scaled-up, and the corresponding environmental impact at that point, may not be available (Bisinella et al. 2021). Moreover, when scaling a life cycle inventory to a point further ahead in time, the quality of the data decreases (Thonemann, Schulte, and Maga 2020). There is also no standard for prospective LCAs, unlike for conventional ones (Bisinella et al. 2021).

2.2.1. Scenario types and design process

Arvidsson et al. (2018) identifies two types of main scenario strategies for prospective LCAs: using *predictive scenarios* and using *scenario ranges*. Predictive scenarios are based on assumptions that a certain future development can be expected to occur, meaning that there is plausible evidence pointing towards that the scenario is likely to occur (Arvidsson et al. 2018). For instance, a predictive scenario can be formulated based on forecasts by authorities (Arvidsson et al. 2018). Using scenario ranges entails investigating *potential developments* and aims at including the possible range of developments (Arvidsson et al. 2018). As such, scenario ranges consider extremes, such as *high* and *low* cases, and can be useful if sound predictions on a likely future development is not available, or if it is desired to investigate the range of potential impacts (Arvidsson et al. 2018).

Similarly, Bisinella et al. (2021) presents three definitions of scenario types: *predictive*, *explorative*, and *normative*. The definition of predictive scenarios largely coincides with the definition by Arvidsson et al. (2018) and aims at investigating what *will* (likely) happen (Bisinella et al. 2021). Explorative scenarios aim at investigating possible futures and what *could* happen, whereas normative scenarios aim at investigating a preferable future (Bisinella et al. 2021). The latter can be useful for investigating how targets can be reached, through for instance backcasting or optimisation (Bisinella et al. 2021). As such, normative scenarios differ from predictive and explorative scenarios, as it originates from a desired endpoint (such as a target being reached) and identifies ways to reach this target, whereas predictive and explorative scenarios look forward into the future (Bisinella et al. 2021).

A generic approach for scenario building is presented by Bisinella et al. (2021), and consists of five iterative phases: 1) defining the goal and scope of the future scenarios, in order to identify the suitable scenario type(s) (predictive, explorative or normative), 2) Identifying key aspects of the scenarios and their future states, 3) Integrating the key aspects of the scenarios and performing consistency checks, 4) selection of scenarios for the system and 5) scenario application to the system.

2.2.2. Study approach

In this study, battery electric heavy-duty lorries were chosen as the emerging technology due to the potential of electrification to decarbonise the fleet, and due to the current limited availability and market diffusion of heavy-duty lorry BEVs (Government Offices of Sweden 2021a). As such, scenarios were formulated to capture the electrification rate of the fleet. To limit the scope of the study, plug-in hybrid electrical vehicles (PHEVs), hybrid electric vehicles (HEVs) and fuel cell electric vehicles (FCEVs) were not considered. In scenarios by Fossilfritt Sverige (2020), hybrids are assumed to contribute to under 10 % of the sales of electrified vehicles until 2030, thus constituting a small proportion. Fossilfritt Sverige (2020) also claim that calculations and predictions of future emissions for hybrid vehicles are complicated to perform. Moreover, while sales of heavy-duty BEVs are expected to take off during the coming decades, a significant expansion of corresponding FCEVs currently seem more likely to take off closer to the 2050s (Fossilfritt Sverige 2020, Nordic Energy Research 2021). Aside from electrification rate, scenarios were formulated to investigate the evolution of biofuel usage in ICEVs, transport demand, and climate change mitigation measures in the background system. See table 1 for an overview of the scenarios. The scenarios for these parameters were formulated based on findings in literature, which are predominantly presented in chapter 4 and 5. The final scenarios are presented in chapter 6.

Table 1: Scenarios influencing the foreground and background systems.

Foreground system scenarios	Background system scenarios
Electrification rate scenario Transport demand scenario Biofuel usage scenario	Climate change mitigation scenarios (influencing vehicle and fuel cycles)

The generic approach by Bisinella et al. (2021) influenced the scenario development process. The goal and scope were defined as "to investigate how the carbon footprint of the heavy-duty lorry fleet *could* potentially develop, between year 2025 and 2060". The design of the scenarios was largely based on prognoses and scenario analyses, governmental reports, expert opinions and policy. While the study aimed at providing realistic developments, there were large uncertainties attached to the scenario assumptions due to the long time horizon. Due to these uncertainties, scenario ranges and sensitivity analyses were utilised. Moreover, as the study aimed solely at investigating ICEVs and BEVs, all possible technology advancements within the fleet during the chosen time horizon were not considered. Consequently, the authors of the study claim that the chosen scenario types should not be defined as predictive, but rather as explorative. Scenarios were developed separately for the foreground and background system to avoid a temporal mismatch, and results presented both combined and separately. The latter to increase usefulness in future studies as recommended by (Arvidsson et al. 2018).

2.3. Vehicle fleet turn-over model

In this section an overview of the vehicle fleet-turn over model is provided, followed by a presentation of the governing equations in the model.

2.3.1. Overview

To create a model describing the dynamics of the evolving heavy-duty lorry fleet, a stock-flow modelling approach was utilised. This was inspired by the methodology in other articles modelling transportation systems (Morfeldt et al. 2021; Morfeldt and Johansson 2022). In a stock flow-model the "stock" is an accumulation, influenced by the flows in and out of the stock, as seen in equation (1) and figure 3 below (Shepherd 2014). Depending on the inflows and outflows, the stock may increase or decrease in size (Shepherd 2014).

$$Stock\ (t) = \int_{t_0}^{t} [inflow(s) - outflow\ (s)]ds + Stock\ (t_0) \qquad (1)$$

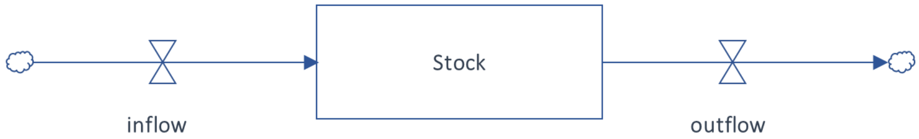

Figure 3: Overview of a simple stock-flow system.
Based on figure in (Shepherd 2014).

For a vehicle fleet the stock represents the current fleet, with sales and imports contributing to the inflows and end-of-life (scrapping), exports and deregistrations contributing to the outflows (Morfeldt et al. 2021). As such, the turn-over of the fleet can be captured over time.

The vehicle fleet-turnover model is modelled in MATLAB and extracts input data from Excel files. Based on a set of equations and corresponding data inputs, it calculates the inflows and outflows to the vehicle fleet (the stock). In this model, inflows to the stock are assumed be completely covered by new sales, and outflows by vehicles reaching end-of-life. As such, the model describes how aging vehicles exit the stock at end-of-life and are replaced by new vehicles. The number of new vehicles that enter the stock each year is dependent on the evolution of the transport demand (in vkm), the loss of supply (vkm) from the retiring vehicles, and supply from the remaining fleet. The number of new vehicles that are BEVs are dependent on the electrification rate of the fleet, and the number of ICEVs that are fuelled by biofuels by the biofuel usage share.

The main unit of the model is transport demand, reflecting the vehicle activity (in vkm), and transport supply (in vkm) from the heavy-duty lorry fleet. The choice to use vehicle activity in the model rather than freight activity (in tonne-kilometres) is due to having acquired more reliable sources regarding distances than freight weight on a fleet basis. Since the load affects the carbon footprint, average payloads were added on to the vehicle kilometres. This is explained further in sections 2.3.2 and 2.5.2. The share of biofuel usage within ICEVs was also applied to the model, which is explained in section 2.3.3.

A simple figure showing the stock-flow concept applied to the vehicle fleet is shown in figure 4 below. The parameters influencing the sales are the supply from the current stock, the transport demand, and the electrification rate (here defined as the share of sold vehicles that are fully electrified). The parameters influencing the vehicles leaving the stock are the vehicle ages within the fleet and corresponding survival probabilities at that age.

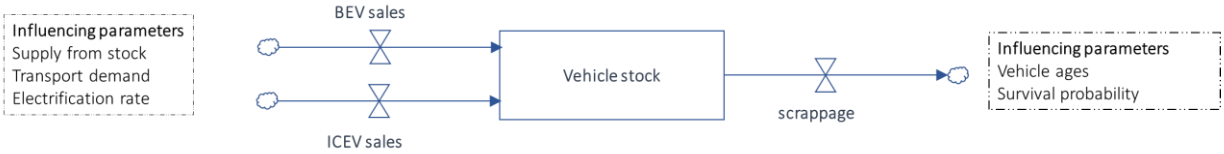

Figure 4: The stock-flow model concept applied to the vehicle fleet.

The figure only shows the parameters influencing the inflows and outflows of the stock. Not displayed is the supply (vkm) from the current stock. This supply is dependent on the number of vehicles within the stock and the supply from each vehicle.

2.3.1. Main stock equations

The parameters used in the main stock equations describing the fleet evolution are summarised in table 2, followed by a presentation and explanation of the equations.

Table 2: Parameters for calculation of the main stock.

Parameter denotation	Description	Unit
D	Transport demand	Vkm
S	Supply from the current fleet	Vkm
S*	Current supply from the remaining stock from the previous year	Vkm
N	New sales	Number of vehicles
m	Average yearly mileage	Vkm
ε_e	Share of engine type *e*	Percentage
φ	Survival probability	Percentage

Equation (2) to (6) below describe the major equations governing the vehicle fleet turnover model. These were inspired by the equation system by Morfeldt et al. (2021) describing the evolution of the Swedish passenger car fleet, but adjusted and further developed for the purpose of this study.

The supply (vkm) from the heavy-duty lorry fleet at year *t*, $S(t)$ match the traffic demand, $D\ (t)$, at all times as displayed in equation (2) below.

$$D\ (t) = S(t) \tag{2}$$

The total supply from the heavy-duty lorry fleet at year *t* is equal to the sum of the supply from vehicles with the respective engine type *e*, as displayed in equation (3). In this report internal combustion engines and electric engines, here denoted ICE and EE respectively, are considered.

$$S(t) = S(t, e_{ICE}) + S(t, e_{EE}) \tag{3}$$

The supply from vehicles with engine type *e* at year *t* is described by equation (4). It is equal to the sum of the current supply from the remaining ("surviving") stock from the previous year, $S^*(t,e)$ and the supply from the new sales at year *t*, $N(t,e) \cdot m(0,e)$, where $N(t,e)$ represents the number of new vehicles and $m(0,e)$ represents the average yearly mileage of a new vehicle (age 0).

$$S(t,e) = S^*(t,e) + N(t,e) \cdot m(0,e) \tag{4}$$

The number of new sales of a certain engine type at year *t* is given by equation (5). The total necessary number of new vehicles across all engine types is equal to the difference between the total demand at year *t* and the and the supply from the remaining stock from the previous year, divided by the average yearly mileage of a new vehicle. The number of new vehicles with an engine *e* is then acquired by multiplication with the share of the sales of the specific engine type at year *t*. This share depends on the electrification rate.

$$N(t,e) = \frac{\left(D(t) - S^*(t)\right)}{m(0,e)} \cdot \varepsilon_e(t,e) \tag{5}$$

The supply at year *t* from the remaining stock from the previous year is calculated as the sum of the contributions from each age group of the stock, see equation (6). Parameter *a* represents the age of a group at year current year *t*. The supply at year *t* for a specific age group is acquired by multiplying the number of surviving (i.e., not scrapped) vehicles from the previous year with the average mileage per vehicle at age a, $m(a,e)$. The number of surviving vehicles in the age group is acquired by multiplying the number of cars in the age group at year *t-1* with the probability for survival for vehicles of age a, $\varphi(a,e)$. The survival probability function is presented in section 2.5.1. The parameter $S_a(t-1,e)$ represents the supply from age group *a* at the previous year, and $m(a-1,e)$ the average yearly mileage of age group *a* the previous year. Dividing the supply by the mileage consequently yields the number of vehicles in the age group for the previous year.

$$S^*(t,e) = \sum_{a=1}^{age_{max}} \frac{S_a(t-1,e)}{m(a-1,e)} \cdot \varphi(a,e) \cdot m(a,e) \tag{6}$$

To achieve a stock matching the current one, the model was initiated at year 2000 by setting the supply of the stock equal to statistics on the demand at this year. An initial age distribution was created and applied to the stock by using available statistics on supply contributions for different age groups[5]. The model was then run and results verified by comparing to statistics, which can be seen in appendix F.

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[5] Mean values found in statistics for 2010 and 2011 were used to obtain the supply contribution (in %) for each age group (Transport Analysis 2022b).

2.3.2. Weight class equations

To divide the fleet into weight classes, a share for weight classes w_c is used in the model as presented in table 3. The parameter $\mathrm{w_c}$ describes the share of the total fleet supply (vkm) that is supplied by a specific weight class. In total, four weight classes were assumed in the model. These details of the weight classes and the assumed distribution are presented in section 2.5.3 and 2.5.4. The purpose of dividing the fleet into weight classes is to 1) account for varying energy consumption per km depending on weight and 2) to account for varying material demands in production of new vehicles.

Table 3: Parameters for calculation of weight classes.

Parameter denotation	Description	Unit
w_c	Share of total vehicle activity (vkm) supplied by weight class *c*	Percentage

The number of new sales in a weight class N_{w_c} is acquired by multiplying the number of new sales of year *t* of engine type *e* with the weight class share w_c, as described in equation (7).

$$N_{w_c}(t,e) = N(t,e) \cdot w_c \qquad (7)$$

To acquire the supply S_{w_c} at year *t* from engine type *e* of vehicle age a for a certain weight class w_c, the supply at year *t* from engine type *e* of vehicle age *a* is multiplied with the weight class share w_c, as described in equation (8).

$$S_{w_c}(t,e,a,w_c\,) = S(t,e,a) \cdot w_c \qquad (8)$$

In the model, the yearly mileages are assumed equal for all weight classes, which is explained further in section 2.5.1. Therefore, the same shares can be used for dividing both number of vehicles and supply (vkm) into weight classes.

2.3.3. Energy consumption equations

The model calculates the energy consumption of the stock each year, which is then used as input for the tailpipe and fuel cycle emission calculations. Aside from the distances driven, the energy consumption in the model depends on the engine type (ICE or electric), production year of vehicle and gross vehicle weight. Therefore, the calculations are based on the supply at year *t* from engine type *e* of vehicle age a for a certain weight class w_c as described in equation (8). The parameters required for the energy consumption calculations are presented in table 4.

Table 4: Parameters for calculation of energy consumption.

Parameter denotation	**Description**	**Unit**
λ	Share of loaded operation	Percentage
E	Energy consumption	kWh
э	Specific energy consumption	kWh/km
b	Share of biofuel	Percentage

The energy consumption also differs depending on loaded versus unloaded (empty) operation, which is represented by a share of loaded operation λ in the model. Due to the previous mentioned factors influencing the energy consumption, a specific energy consumption э is applied for each baseline vehicle for loaded and empty operation and varies with production year.

To calculate the supply S_L at year *t* from engine type *e* of vehicle age *a* from weight class w_c at loaded operation, the supply at year *t* from engine type *e* of vehicle age *a* from weight class w_c is multiplied with the share of loaded operation λ, as described in equation (9). For empty operation the λ is replaced by $1-\lambda$.

$$S_L(t, e, a, w_c, \lambda) = S_{w_c}(t, e, a, w_c) \cdot \lambda \qquad (9)$$

To calculate the energy consumption at year *t* from engine type *e* of vehicle age *a* from weight class w_c in loaded operation λ, the supply at year *t* from engine type *e* of vehicle age *a* from weight class w_c in loaded operation λ is multiplied with the corresponding specific energy consumption э for the production year, which is a function of year *t* and vehicle age *a*, as described in equation (10). For each baseline vehicle two different specific energy consumptions are applied, one for loaded operation and one for empty operation. For empty operation the λ is replaced by $1-\lambda$.

$$E(t, e, a, w_c, \lambda) = S_L(t, e, a, w_c, \lambda) \cdot \text{э}(t, a) \qquad (10)$$

The yearly energy consumption for each engine type, E_{ICE} and E_{BEV}, is then calculated as the sum of energy consumptions for loaded and empty operation for each vehicle age and weight class.

The yearly consumption of biofuel E_b is calculated by multiplying the total energy consumption for engine type *ICE* E_{ICE} at year *t* with the share of biofuel b for the same year, as seen in equation (11). For fossil fuels the b is replaced by $1-b$.

$$E_b(t) = E_{ICE}(t) \cdot b(t) \qquad (11)$$

2.4. Carbon footprint estimations and assumptions

As mentioned, the main aim of the study was to calculate the evolution of the annual carbon footprint of transportation by the Swedish heavy-duty lorry fleet (within Swedish borders). The objective was not to conduct a proper LCA according to ISO standards, but rather to collect, compile and utilise previously developed life cycle inventories (LCI) and prospective LCA-data matching the designed scenarios. The assumed carbon intensities between years 2025 – 2060 are presented in chapter 4 and 5.

In the model, the carbon footprint of the fleet each year is calculated as the sum of GHG emissions from production of new vehicles, maintenance of vehicles, and disassembly of end-of-life vehicles (vehicle cycle emissions), production of fuels and electricity for charging (fuel cycle emissions) and from tailpipe emissions, see equation (12). The cycles and corresponding assumptions are explained in more detail in the following chapters.

$$GHG_{fleet}(t) = Vehicle\ cycle\ emissions\ (t) + fuel\ cycle\ emissions\ (t) + tailpipe\ emissions\ (t) \quad (12)$$

2.4.1. Functional unit

The functional unit of the study is defined as Swedish heavy-duty lorry transport within Swedish borders. It was chosen as the study aims to capture the carbon footprint of the entire national fleet, with regards to its transports within Swedish borders.

2.4.2. Vehicle cycle emissions

The vehicle cycle emissions in the model cover the manufacturing of vehicle parts, vehicle assembly, disassembly, and tyre changes (maintenance). Global average production processes were assumed for most production and assembly. This was assumed since Scania and Volvo Trucks, which dominate the Swedish market on heavy-duty lorries[6], have production units for lorries and components spread across Europe, Asia, Africa, Oceania, South America, and North America (Mobility Sweden 2023; Scania n.d.-a, n.d.-b; Volvo Group n.d.). For production of the lead-acid battery and the disassembly process, there was a lack of data based on global production and instead LCA-data assuming European manufacturing processes was used. The vehicle cycle predominantly only covered CO_2 emissions, as other non-CO_2 GHGs can be considered of negligible importance for the vehicle cycle (Lane 2006; Morfeldt et al. 2021).

Vehicle parts were assumed to be produced and assembled the same year as being sold and disassembled at end-of-life (point of scrappage). The maintenance was allocated to the production year of the vehicle as a simplification, which overestimates emissions slightly since maintenance should be spread across the vehicle lifetime and emissions are assumed to decrease

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[6] Almost 86 % of new registrations of lorries over 16 tonnes in 2022 were produced by Volvo Trucks or Scania (Mobility Sweden 2023).

over time. Two complete tyre changes over the lifetime were assumed, based on estimates by Scania (2021). According to Scania (2021), other maintenance such as change of oil, brake pads etc., are estimated to contribute to 0.1 – 0.3 % of emissions and are insignificant from a life cycle perspective and can be disregarded. Therefore, these emissions were excluded. Since the change of fluids are excluded based on environmental insignificance, fluids were excluded altogether in the carbon footprint estimations.

No replacement of the lithium-ion battery for the BEV was accounted for in the model. It would have been desirable to include one replacement, to confidently avoid underestimation. However, due to delays in the model development there was not enough time to implement this in the code. Estimations in literature seem to generally vary between 0 - 1 replacements, although up to two could potentially be necessary for some vehicles (depending on driving cycles and lorry characteristics) (European Commission 2020; O’connell et al. 2023; Sacchi, Bauer, and Cox 2021; Scania 2021). The European Commission (2020) argues that due to increased battery capacities and life cycles, heavy-duty lorries produced post year 2030 can be expected to not need any replacements.

Most of the emissions of the vehicle cycle were calculated on a material basis, by multiplying the weight of the material with a weight-based emission factor. This applied to steel, iron, rubber, aluminium, plastics, and copper. The emissions connected to the lead-acid battery and the li-ion battery for the BEVs were calculated on a component basis. Together, these materials and components were estimated to cover over 95 % of the material masses. The material and component weight estimations are presented in appendix B.

2.4.3. Fuel cycle emissions

The fuel cycle covers emissions from a well-to-tank perspective, including emissions from production and distribution of fuel and electricity for charging. For fossil fuel, global average production was assumed including crude oil production, transportation to refinery and the refinery process (Morfeldt et al. 2023). Transportation to market was not included for fossil fuels, which was deemed acceptable to omit as it constitutes as small share of the total emissions (European commission and Joint Research Center 2020). For biofuels, typical Swedish supply with EU as major origin was assumed, including production and distribution (Swedish Energy Agency 2022a). Swedish grid mix was assumed for the electricity for charging, including production and infrastructure for distribution (Morfeldt et al. 2021; Swedish Energy Agency 2023e). See section 5.3.3 for details.

The annual fuel cycle emissions were calculated for each energy carrier at a certain year by multiplying the assumed carbon intensities from literature (in unit gCO_2-eq per kWh) with the corresponding annual energy consumption (in unit kWh).

2.4.4. Tailpipe emissions

The tailpipe emissions cover emissions from a tank-to-well perspective, i.e., exhaust emissions during driving. The resulting emission factors are presented in section 4.4. To obtain the annual tailpipe GHG emissions, an emission factor (in unit g CO_2-eq per kWh) was multiplied with the fuel consumption (in unit kWh). The emission factor was assumed to remain constant over time.

2.5. General fleet characteristics

In this section, model assumptions on general fleet characteristics, that are not governed by scenarios, are presented and motivated. These include lifespan of vehicles, annual vehicle mileages, weight classes and baseline vehicles in the model, weight distribution of the fleet, load factors (assumptions on the loads), and energy consumption.

2.5.1. Lifespan of vehicles

In the model, the lifespans of the vehicles are estimated by a survival probability function. The function estimates the probability of survival at a certain age and is used to calculate the number of vehicles in each age group that “survives” another year, and the number of vehicles in each age group that reach end-of-life. Two methods were considered for estimating the survival probability for different age groups, presented below.

Method 1) (The selected method) Using extracted statistics from the Swedish vehicle registry *(Swedish: fordonsregistret)* regarding the age at point of scrappage for heavy-duty lorries in Sweden, acquired from Transport Analysis (2023a) These show the number of scrapped vehicles by age, between years 2017 and 2021. The mean number of scrapped vehicles per age group was calculated and inserted to the distribution fitter in MATLAB, where the most suitable distribution was found to be the Weibull distribution as it accounted for the skewedness and long tail of the data.

These statistics did not include vehicles sold on the second-hand market to other countries, or information on whether the vehicles were in traffic or deregistered at the point of scrappage. Neither did the statistics include information on whether the vehicles had previously been deregistered at any point(s) during their lifetime or not. As such, the data set could give a misleading representation of the actual time in traffic, possibly overestimating it.

Method 2) Using lifespan curves for heavy-duty lorries from *The Handbook Emission Factors for Road Transport* (HBEFA), acquired from Cecilia Hult at IVL (Cecilia Hult, mail correspondence, March 22, 2023). The survival rate is here defined as the probability that a vehicle remains in traffic the following year, and has not been developed on an individual level, but by considering the survival of entire groups of lorries over time (Cecilia Hult, mail correspondence, March 22, 2023).

A comparison of the results from method 1) and 2) are presented in figure 5.

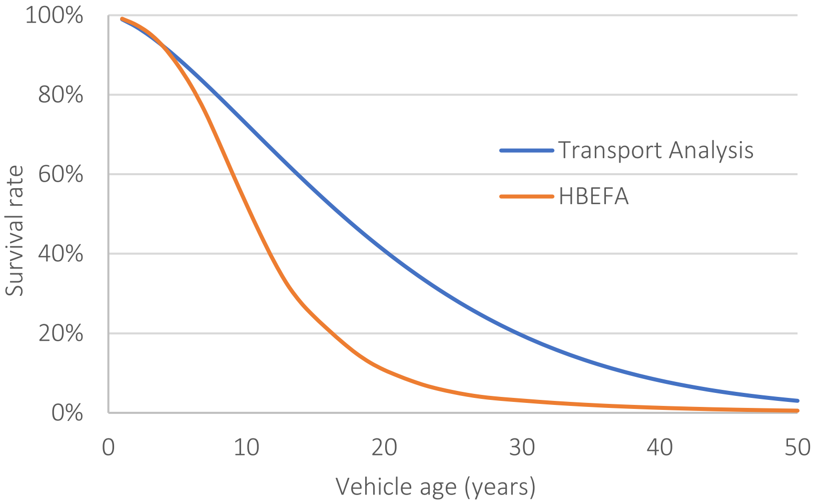

Figure 5: Estimated survival rates depending on vehicle age.

Both methods were tested by running the simulations from 2004 – 2022 and comparing the simulated yearly sales to statistics on sales, see appendix F0. The probability function developed by data from Transport Analysis gave results that closest resembled actual sales and was a such used in the model.

2.5.2. Annual vehicle mileages

The annual average mileage of a heavy-duty lorry at a certain age was based on statistics on mileages per age group by (Transport Analysis 2022b). An average of the mileages reported for years 2017 to 2021 was used in the model. The resulting mileages per age group are displayed in figure 6. The same annual mileage is assumed, regardless of the lorry weight. However, the average annual mileage is only used in calculations on a fleet basis, not individually for the weight classes, which makes this simplification of little concern for the model.

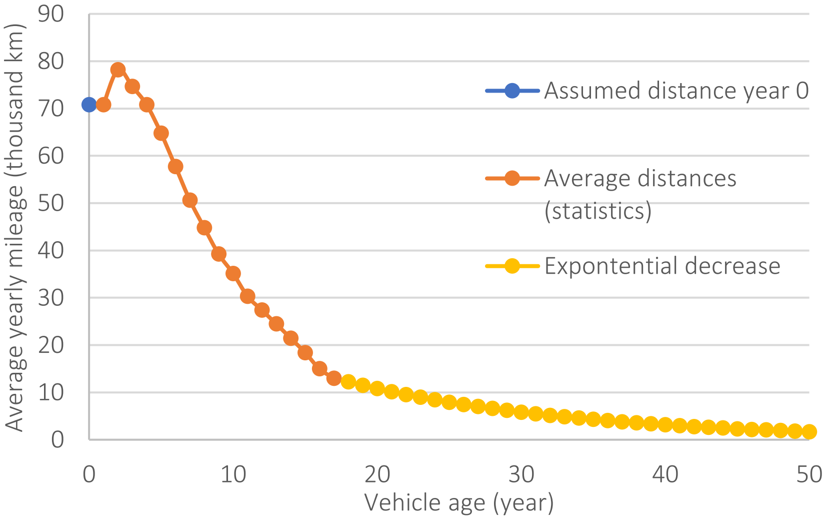

Figure 6: Estimated yearly average mileage depending on vehicle age.

In the statistics, annual mileages are presented for ages 0 – 17 separately. For ages 18+, the mileages are aggregated into a single group. To achieve an estimation of the disaggregated yearly mileages per age group for the 18 + ages, the total mileages were distributed across the age groups by matching a fitting decrease to the existing curve, resulting in an exponential decrease by a factor of 0.06 with each age over 18. This approximation was deemed good enough for the purpose of this thesis, considering that the 18 + groups only contributed to a total of 2.6 – 2.8 % of the total mileages between 2017 and 2021, as well as considering the lower survival probability for these age groups.

The model makes no distinction in annual mileages between ICEVs and BEVs, since the purpose is to compare the carbon footprint if ICEVs are directly replaced by BEVs.

2.5.3. Weight classes and baseline vehicles

Some Swedish roads allow for lorries up to a gross combination weight up to 74 tonnes (Swedish Transport Administration 2023a). As such, the gross combined vehicle weight (GCVW) of Swedish heavy-duty lorries can range from just over 3.5 tonnes up to 74 tonnes. To account for varying material demands and fuel/electricity consumption of different lorry sizes, baseline vehicles were created for the model, see table 5. The aim was to consider the varieties of lorries on the Swedish roads, by defining four weight classes with one respective baseline vehicle each. The gross combined vehicle weight rating (GCVWR)[7], total curb weight[8], weight of components as well as material demand for each lorry were estimated based on literature findings and can be found in appendix B.

Table 5: Assumed weight characteristics for the baseline lorries.

ICEV/BEV	**ICEV/BEV**	**ICEV**		**BEV**	
Weight class (tonne)	*GCVWR (tonne)*	*Total curb weight (tonne)*	*Maximum load (tonne)*	*Total curb weight (tonne)*	*Maximum load (tonne)*
> 3. 5 – 17.9	12.0	6.3	5.7	7.4	4.2
18 – 39.9	28.0	12.0	16.0	12.9	15.1
40 – 54.9	44.0	16.2	27.8	18.7	25.3
55 +	60.0	21.1	38.9	25.2	34.8

The assumed weights and capacities for the batteries in the BEV baseline vehicles are presented in table 6. The most common batteries for EVs are lithium-ion batteries with an NMC cathode chemistry (nickel, manganese, cobalt) (International Energy Agency 2023). In the model, an

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[7] The maximum allowed total weight for a vehicle and loaded trailer, including passengers, fuel and cargo within the vehicle and cargo in the trailer.

[8] The weight of the vehicle in its entirety, excluding cargo and driver (Bennett 2016).

NMC622 chemistry (60 % nickel, 20 % manganese and 20 % cobalt) was assumed, with a specific weight of 6.45 kg/kWh (Morfeldt et al. 2023, 2021).

The capacities for each battery were chosen based on reported typical capacities by the International Energy Agency (2020) and O'connell et al. (2023), as well as by reviewing electric lorries currently available on the market by Scania and Volvo[9]. According to the International Energy Agency (2020), typical battery capacities for lorries within between 3.5 – 15 tonnes in gross vehicle weight range between 70 – 300 kWh, and for lorries above 15 tonnes between 200 – 1000 kWh.

Table 6: Assumed battery capacities and weights for the baseline lorries.

Total vehicle weight (tonnes)	**Battery capacity (kWh)**	**Battery weight (kg)**
12	200	1290
28	350	2257
44	625	4031
60	1000	6450

2.5.4. Weight distribution of the fleet

Different lorry weight classes contribute with unequal shares of the total yearly mileage covered by the fleet (Transport Analysis 2022c). In the model, the assumed contribution (%) of each weight class to the total fleet supply (vkm) is based on the conclusions of a report by the Swedish National Road and Transport Research Institute (VTI) (2018). The report estimates the share of the total mileages (by Swedish-registered lorries on Swedish roads) supplied by different weight classes of the fleet (VTI 2018). The results are based on observations, which are scaled to a fleet level by applying a correcting factor based on statistics (VTI 2018). These results were processed to match the weight spans used in the model. The resulting shares are presented in table 7.

Table 7: Assumed contributions per weight class to the yearly fleet supply.

Weight class (tonnes)	**Share of total fleet supply (% of vkm)**
> over 3.5 – 17.9	11.4
18 – 39.9	29.8
40 – 54.9	33.0
55 +	25.8

The shares were kept constant over time in the model. In the past two decades, the heavier segments have contributed with a consistently larger share of the total mileage, which is shown

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[9] https://www.volvotrucks.se/sv-se/trucks/trucks/alternative-fuels/electric-trucks.html
https://www.scania.com/se/sv/home/products/trucks/battery-electric-truck.html

in section 3.4.1 (Transport Analysis 2022d). This trend could continue in the future. However, there are also indications that the future expansion of the fleet will be reserved primarily to the lighter segments (Transport Analysis 2020). Moreover, the estimates made by VTI (2018) were favoured over statistics, as comparisons with data from car inspections imply that the statistics don't represent the lighter heavy-duty lorry segments correctly (VTI 2018). The statistics give rise to significantly different estimations and are presented in appendix A.

To consider the uncertainties regarding the shares, a sensitivity analysis of the weight distribution was included in the simulations. The shares for the two heaviest weight classes were adjusted by ± 20 %, as presented in table 8. The remaining percentages were spread evenly across the two lightest weight classes.

Table 8: Sensitivity analysis assumptions for the weight class distribution.

Weight class (tonnes)	**Share of total fleet supply (% of vkm)**	
	Lighter fleet	*Heavier fleet*
> over 3.5 – 17.9	26	15
18 – 39.9	26	15
40 – 54.9	26	40
55 +	21	31

2.5.5. Load factors

The average cargo weights during transport, *the average payloads*, can be estimated with so called *load factors.* The load factor is the percentage of the maximum load capacity that is used during the transportation and can be expressed in either weight or volume percentage depending on the freight characteristics (IVA 2019; Sacchi et al. 2021). For Swedish heavy-duty lorries, the load factor in weight percent can vary between 32 – 98 % depending on type of load (IVA 2019). However, within the heavy-duty lorry fleet, the load factor does not seem to vary over different vehicle weight classes. (Klimatmärkning för mat 2010; Network for Transport Measures n.d.; TRACCS 2013). An average load factor for Swedish heavy-duty lorries can be estimated to 50 – 60 weight- % (IVA 2019a; Network for Transport Measures n.d.; TRACCS 2013).

In the model, a load factor of 50 % is applied to the ICEVs to estimate an average payload. Due to different powertrain weights between ICEVs and BEV (primarily due to the li-ion battery weight), the maximum load capacities differ between the vehicle types. To avoid differences in road freight activity, the same payloads are applied to the BEVs as for the ICEVs. Consequently, the resulting load factors for BEVs are higher than for ICEVs. This means that the model assumes a somewhat higher transport efficiency for the BEVs. In practice, the lower load capacity for BEVs might require a higher number of BEVs to transport the same amount of goods as ICEVs. The payloads are assumed constant over time and are presented in table 9.

Table 9: Assumed payload per baseline vehicle.

Baseline vehicle GCWVR (tonnes)	**Payload (tonnes)**
12	2.90
28	8.60
44	14.5
60	20.0

Some distances covered by heavy-duty lorries are unloaded, i.e., no goods are being transported. To account for loaded versus empty operations, a share of the distances covered by loaded operation (% of vkm) is used in the model. Based on statistics between 2015 – 2020 for the Swedish heavy-duty fleet, the share of loaded distances was estimated to 0.8 (Transport Analysis 2023c).

2.5.6. Energy consumption

The large variety of vehicle configurations and usage intentions within the heavy-duty lorry fleet can result in large differences in fuel consumption (International Energy Agency 2017). Two major influences are payload and duty cycles, while vehicle characteristics such as aerodynamic drag, engine efficiency and rolling resistance also affect the fuel economy (Delgado et al. 2016; International Energy Agency 2017). Duty cycles include various real world driving scenarios where differences in parameters such as speed, number of stops and route profiles occur (Delgado et al. 2016). The payloads can differ from zero, i.e., lorries running unloaded, to maximum payload capacity and thereby increase the fuel consumption with 60 – 90 % (Delgado et al. 2016).

Fuel consumption has decreased over time and further reductions can be expected in the future due to technology advancements (Delgado, Muncrief, and Rodríguez 2017). For ICEVs, the fuel consumption has historically decreased by 1 – 1.5 % per year (Fossilfritt Sverige 2020). Improvements can for instance involve engine downsizing, aerodynamics, lightweighting of material and reduction of rolling resistance (MIT Energy Initiative 2019). For BEVs, additional savings can be realised through advancements in battery technology, electric driveline configurations and thermal management systems (Basma, Beys, and Rodríguez 2021). Predictions of future energy consumption savings for BEVs vary greatly; between 7 – 27 % within the coming decade, and long-term it could reach 0.8 – 0.4 kWh/km, corresponding to a decrease of approximately 40 – 70 % (Basma et al. 2021; Burke and Zhao 2017; Smallbone et al. 2020; Wang, Fulton, and Miller 2022).

In the model, the energy consumption for lorries operating empty and on the average payload are estimated based on literature findings, primarily simulation studies. The baseline vehicles' total weights and payloads were matched with similar vehicles found in literature for duty cycles with regional and long-haul delivery to obtain a fleet-wide representation. For ICEVs, no distinction in energy consumption is made for operation on fossil diesel or biodiesel. The resulting model input for diesel consumption in 2023 ranges from 1.82 – 4.13 kWh/km[10]. For BEVs the input data for electricity consumption is 0.90 – 1.69 kWh/km[11]. The assumed energy consumptions for 2023 are presented in tables 10Table 10 and 11 for ICEVs and BEVs respectively, and the complete literature basis is presented in appendix C.

The fuel consumption for newly produced ICEVs is set to decrease by 1 % per year, in line with historical developments and scenarios by Fossilfritt Sverige and an Irish freight transport study (Fossilfritt Sverige 2020; Yan et al. 2021). For new production of BEVs, the energy consumption reduction is assumed to linearly decrease with 55 % until 2065, based on mean from literature findings presented above.

Table 10: Specific energy consumption for the model's baseline ICEVs in year 2023.

GCCWR (tonnes)	Energy consumption, Unloaded (kWh/km)	Energy consumption, Avg. payload (kWh/km)
12	1.82	1.97
28	2.29	2.68
44	2.40	3.31
60	2.64	4.13

Table 11: Specific energy consumption for the model's baseline BEVs in year 2023

GCCWR (tonnes)	Energy consumption, Unloaded (kWh/km)	Energy consumption, Avg. payload (kWh/km)
12	0.90	1.01
28	1.03	1.14
44	1.15	1.49
60	1.30	1.69

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[10] Based on estimates by (Delgado et al. 2016, 2017; HBEFA 2019; International Energy Agency 2017; Sacchi et al. 2021; Swedish Transport Administration 2022a; Volvo Trucks 2018; Zacharof et al. 2017). See appendix D for more information.

[11] Based on estimates by (Basma et al. 2021; Hildermeier et al. 2020; Link and Plötz 2022; Mareev, Becker, and Sauer 2018; Sigle and Hahn 2022). See appendix D for more information.

3. Background

This chapter presents current and historical information about the Swedish heavy-duty lorry fleet, as well as relevant policy and pathways to decarbonise the fleet.

3.1. The Swedish vehicle fleet on road

The Swedish vehicle fleet on road consists of over 8 million vehicles in active use (8 075 344 in 2021) and is composed of passenger cars, light-duty lorries, heavy-duty lorries, buses, motorcycles, class I mopeds, tractors, snowmobiles, all-terrain vehicles (ATVs) and trailers (Transport Analysis 2022a). The term “trailers” refers to all vehicles being pulled behind a towing vehicle, for example caravans, lorry trailers and boat trailers (Transport Analysis 2022a)[12]. Passenger cars is the dominating vehicle type, accounting for 61.8 % of the total fleet in 2021, followed by trailers at 16.0 %. Heavy-duty lorries account for a modest fraction, accounting for 1.1 % of the total fleet (Transport Analysis 2022a). The total amount of active vehicles based on vehicle segments, and their respective shares, are presented in table 12.

Table 12: Composition of the active Swedish vehicle fleet (road traffic) in 2021.

Vehicle type	**Number of vehicles in traffic (1000s)**	**Share (%)**
Passenger cars	4 987	61.8
Light-duty lorries	606	7.5
Heavy-duty lorries	86	1.1
Buses	14	0.2
Motorcycles	313	3.9
Class 1 mopeds	102	1.3
Tractors	374	4.6
Snowmobiles	198	2.5
All-terrain vehicles	104	1.3
Trailers	1 292	16.0

The domestic transport sector accounted for approximately a third of the annual territorial GHG emissions in Sweden in 2021 (Swedish Environmental Protection Agency 2021b), whereof traffic on roads contributed to over 94 % of the emissions (Swedish Environmental Protection Agency 2021a). The development during the past thirty years of the total emissions from passenger cars, light-duty lorries, heavy-duty lorries, buses, mopeds and motorcycles are presented in figure 7. Amongst these vehicle types, heavy-duty lorries have consistently contributed with over 20 % the past twenty years. Note that in figure 7, vehicles being towed (denoted “trailers” in table 12) are not presented separately from the towing vehicle.

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[12] More information can be found at https://www.trafa.se/en/road-traffic/vehicle-statistics/.

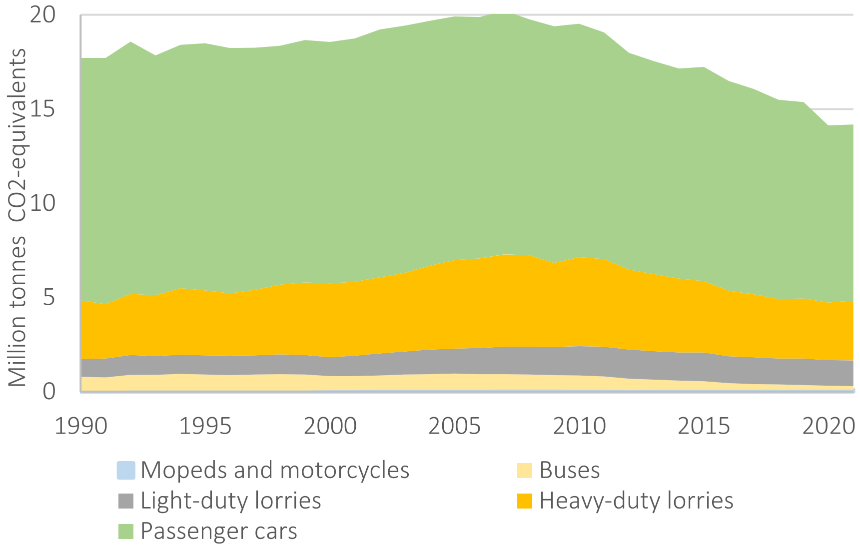

Figure 7: Yearly emissions from road traffic categories 1990 – 2021. Based on statistics from Swedish Environmental Protection Agency (2021a).

3.2. Lorry definitions and categories

Lorries are separated into light-duty and heavy-duty lorries. Heavy-duty lorries are defined as lorries with a total weight >larger than 3.5 tonnes, whereas light-duty lorries have a maximum total weight of 3.5 tonnes (Swedish Transport Agency 2013). Furthermore, Swedish vehicles are categorised based on European classifications. According to the definitions by the European Union, lorries fall under *"vehicle category N"* and are defined as *"Power-driven vehicles having at least four wheels and used for the carriage of goods"* (European Commission n.d.-a). The vehicles falling under category N are further divided into categories N1, N2 and N3 as presented in table 13 below (European Commission n.d.-a). Out of these, categories N2 and N3 fall within the Swedish definition of heavy-duty lorries and N1 regards light-duty lorries.

Table 13: EU classification categories of lorries.

Lorry Category	**Description**
N1	Vehicles used for the carriage of goods, with a maximum mass not exceeding 3.5 tonnes.
N2	Vehicles used for the carriage of goods, with a maximum mass exceeding 3.5 tonnes but not exceeding 12 tonnes.
N3	Vehicles used for the carriage of goods, with a maximum mass exceeding 12 tonnes.

The total freight transport within Swedish borders consists of the transport that both Swedish and foreign lorries contribute with (Transport Analysis 2022e). These transports have different start and finish points, within or outside Swedish borders, and can therefore be divided into four different groups based on the overall geographical parameters of the transport, as presented in table 14. These are Swedish – domestic transport, Swedish – international transport, Foreign – international transport and Foreign – cabotage transport (Transport Analysis 2022e).

Table 14: Categories of freight transport within Swedish borders.

Geographical category	Description
Swedish – domestic	Freight transport by Swedish-registered vehicles, with start and finish within Swedish borders.
Swedish – international	Freight transport by Swedish-registered vehicles, with start within Swedish borders and finish outside (departing transport) or start outside of Swedish borders and finish within (arriving transport).
Foreign – international	Freight transport by foreign-registered vehicles, with start within Swedish borders and finish outside (departing transport) or start outside of Swedish borders and finish within (arriving transport) or start and finish outside of Swedish borders (transit).
Foreign – cabotage	Freight transport by foreign-registered vehicles, with start and finish within Swedish borders.

The transports by Swedish-registered lorries are predominantly domestic, accounting for 99 % of all transports in 2021 (Transport Analysis 2022c). Out of these, 73 % started and finished within the same county. Consequently, most transports by Swedish lorries are short distance transports, with 65 % traveling a distance of less than 50 km (Transport Analysis 2022c). Considering the amount of goods, 53 % of the total freight mass was transported less than 50 km (Transport Analysis 2022c). The total number of transports and amount of goods for different transportation distances in 2021 is presented in figure 8.

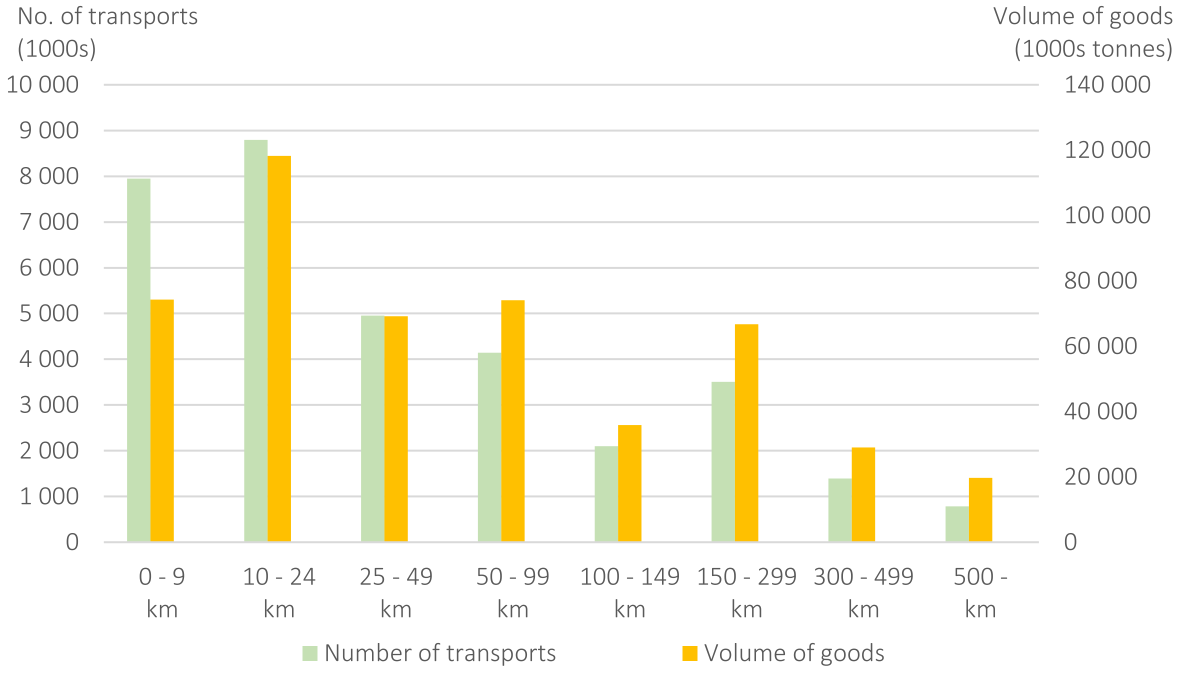

Figure 8: Transportation distances and transported volume of goods, per transport. Based on statistics by Transport Analysis (2022d).

Foreign-registered lorries accounted for 6 – 7 % of the transports within Swedish borders in 2021, both with regards to number of transports and freight mass, and 20 % of the total vehicle activity and freight activity (Transport Analysis 2022c).

3.3. Powertrain and fuel technologies

In this section powertrain and fuel technologies relevant to the current and historical fleet are presented.

3.3.1. Internal combustion engine vehicles

Heavy-duty lorries are conventionally powered by internal combustion engines (ICEs), where fuel and air are combusted in a closed chamber (Lakshminarayanan and Kumar Agarwal 2020). The most common engine type for these vehicles is the compression ignition engine run on fossil diesel (Lakshminarayanan and Kumar Agarwal 2020b). Albeit significantly less common, heavy-duty lorries can also run on petrol or gas, in which case spark ignition engines are used (Lakshminarayanan and Kumar Agarwal 2020b). ICEs can also be used with biofuels such as ethanol and biodiesel although this may require some alterations of the engine, depending on fuel properties and shares in mixtures (Swedish Energy Agency 2021a).

In Sweden, the most common types of biodiesels are hydrogenated vegetable oil (HVO) and fatty acid methyl ester (FAME) (Swedish Energy Agency 2021c). Due to its chemical resemblance with diesel, a large share of HVO can be mixed into fossil diesel or used on its own since most heavy-duty vehicle manufacturers approve the substitution (Swedish Energy Agency 2021c). The properties of FAME are not as compatible with fossil diesel as HVO (Swedish Energy Agency 2021c). Therefore, FAME is only allowed to constitute 7 % in mixes with fossil diesel and alterations of the engine are required to use pure FAME (Swedish Energy Agency 2021c). Similarly, ethanol can be introduced in mixtures with petrol or used on its own (Swedish Energy Agency 2022a). Heavy-duty vehicles running on ethanol in Sweden commonly use ED95 which contains approximately 95 % ethanol (Miljöfordon 2017). Biogas can be used in compressed or liquid forms in mixtures with natural gas or pure on its own (Swedish Energy Agency 2022a).

3.3.2. Electric vehicles

Electric motors can be used to power heavy-duty lorries, although not widely used today (Cunanan et al. 2021). In battery electric vehicles (BEVs), the propulsion is fully electrified as an electric motor is powered by battery packs that have been charged from the grid (Cunanan et al. 2021). For heavy-duty vehicles, the lithium-ion battery is the most common type due to its high energy density, high energy efficiency and long lifespan (Cunanan et al. 2021). The use of electricity to propel a vehicle does not entail any tailpipe emissions, however the well-to-wheel emissions can be significant if the electricity is produced using fossil fuels (Cunanan et al. 2021). There are also semi-electric powertrains, such as in plug-in hybrid electrical vehicles

(PHEVs) and hybrid electric vehicles (HEVs) (Nikowitz 2016). A PHEV can run on fuel or electricity from the grid and possesses a powertrain similar to an ICE configuration, with the addition of an electric engine and a battery pack (Nikowitz 2016). A HEV runs on fuel only and its powertrain is similar to that of an ICEV, with the addition of an electric engine that enables energy from braking to be utilised which increases the efficiency of the powertrain (Nikowitz 2016).

3.3.3. Fuel cell electric vehicles

Fuel cell electric vehicles (FCEVs) is a developing vehicle type that could be used for heavy-duty lorries, although only a few vehicles currently exist in the fleet (Energigas Sverige 2022; Fossilfritt Sverige 2020). In these vehicles, a fuel cell is used in conjunction with an electric motor to produce electricity (Cunanan et al. 2021). The fuel cell converts chemical energy into electricity, which in turn powers the electric motor and propels the vehicle (Cunanan et al. 2021). FCEVs can be fuelled by hydrogen, which is traditionally produced from fossil fuels (Everett, Peake, and Warren 2023). However, hydrogen can also be produced with low carbon footprint, such as electrolysis with the input of renewable electricity (Everett et al. 2023). In addition, some FCEVs could also be fuelled by ethanol, methanol, and biogas (Government Offices of Sweden 2021a).

3.3.4. Historical use of energy carriers

Diesel is the current and historically dominating energy carrier within the Swedish heavy-duty lorry fleet, and ICEVs fuelled by diesel contributed to 97 % of vehicles in use in 2021 (Transport Analysis 2022a). The development from 2012 to 2021 is displayed in figure 9, showing that the number of heavy-duty lorries propelled by petrol has been constant whereas lorries fuelled by gas have doubled during this time period (Transport Analysis 2022a). Only a small share of the fleet, barely visible in figure 9, is running on ethanol or electricity (electric drive includes BEVs, PHEVs and HEVs) (Transport Analysis 2022a).

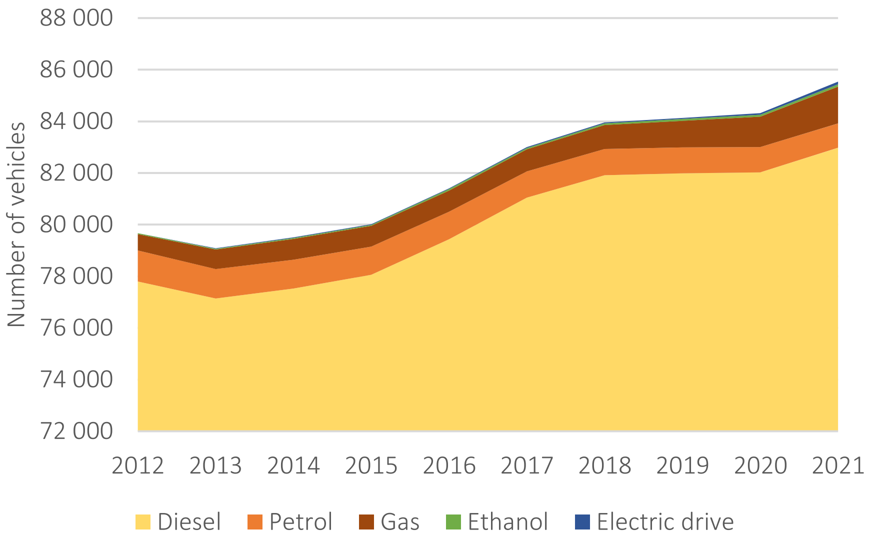

Figure 9: Fuel usage of the Swedish heavy-duty lorry fleet 2012 – 2021.
Based on statistics by Transport Analysis (2022a).

The remaining 3 % of vehicles in use in 2021, i.e., not registered as fuelled by diesel, were powered by gas (1.7 %), petrol (1.1 %), ethanol (0.1 %) and electric drive (0.1 %), see figure 10 below (Transport Analysis 2022a). This translates to 82 975 lorries run on diesel, 1 426 lorries run on gas, 945 lorries run on petrol, 87 on ethanol, 72 BEVs and 34 HEVs (Transport Analysis 2022a). It should be noted that the statistics do not distinguish biofuels from fossil fuels (Transport Analysis 2022a). The number of lorries propelled by diesel presented above includes use of both fossil diesel and biodiesel (Transport Analysis 2022a). Likewise, the statistics for gas represent both natural gas and biogas (Transport Analysis 2022a). The number for petrol only includes fossil components, whereas ethanol represents all mixtures with a low or high share of ethanol (Transport Analysis 2022a).

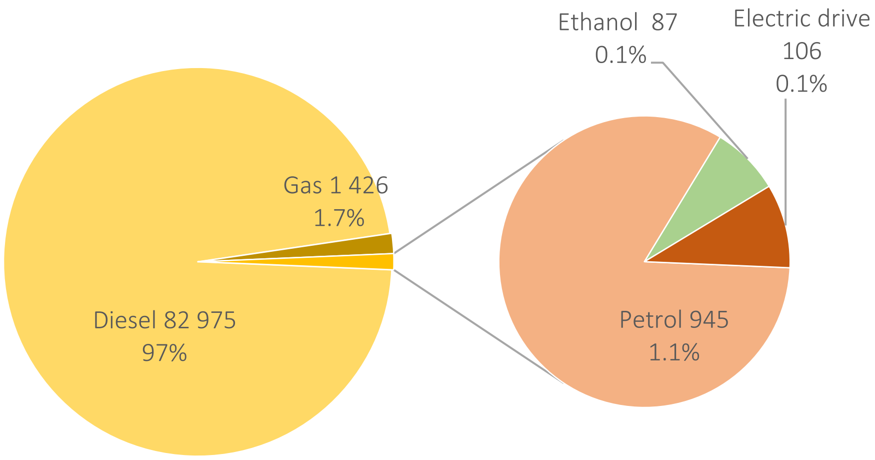

Figure 10: Fuel usage of the Swedish heavy-duty lorry fleet in 2021
Based on statistics by Transport Analysis (2022a).

In order to gain an understanding of the share of bio components in diesel and gas for the heavy-duty lorry fleet, statistics for the whole transport sector in Sweden is presented. The development over the past ten years for diesel is presented in figure 11 and for gas in figure 12. Drop-in of biodiesel has increased over the past ten years, reaching approximately 30 % in 2020 (Swedish Energy Agency 2022a). The use of pure HVO and FAME is not included in the statistics for drop-in, but was 3 TWh and 1 TWh, respectively, in 2020 (Swedish Energy Agency 2022a). In 2018, 155 heavy-duty lorries were registered as certified for pure biodiesel (Transport analysis 2019). However, the number may be higher in practice as it is not mandatory to state this information at registration (Transport analysis 2019).

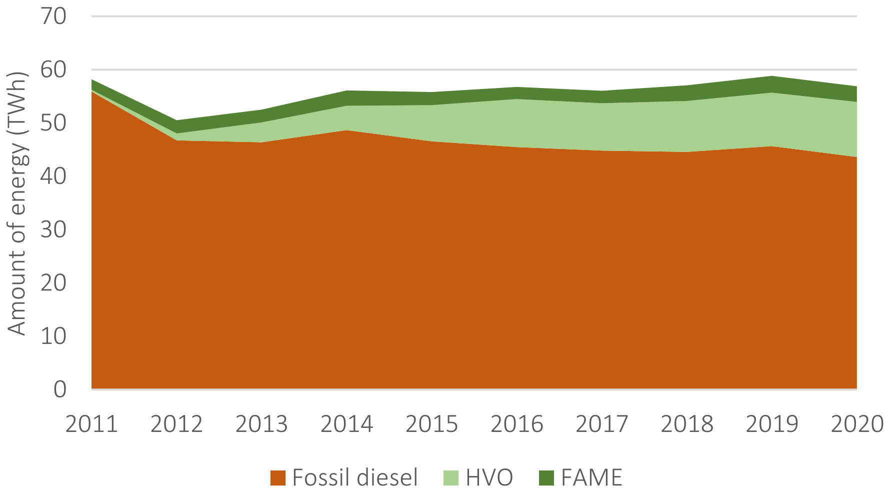

Figure 11: Bio components in diesel mixture for the Swedish transport sector 2011 – 2020. Based on statistics by the Swedish Energy Agency (2022a).

In figure 12 the increase in shares of bio-components in gas (both compressed and liquified) for the Swedish transport sector is displayed (Swedish Energy Agency 2022a). The share of biogas has steadily increased since 2013, and in 2020 almost all natural gas was phased out (Swedish Energy Agency 2022a).

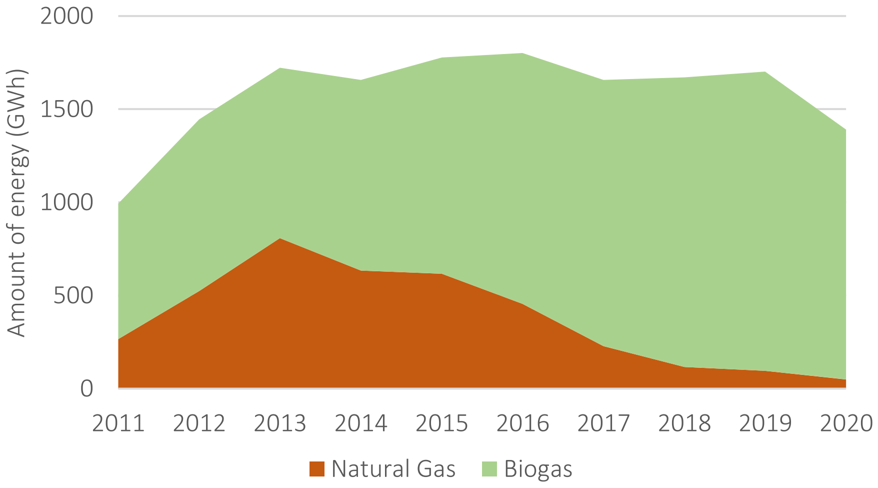

Figure 12: Bio components in gas for the Swedish transport sector 2011– 2020. Based on statistics by the Swedish Energy Agency (2022a).

3.4. Current and historical transportation demand

The current and historical transportation demand of the Swedish heavy-duty lorry fleet is presented in this section.

3.4.1. Road freight activity

The historical demand for goods transport can be portrayed by statistics on the road freight activity, which is given in the unit tonne kilometres (tkm) (Transport analysis 2022). A tonne kilometre is equal to the work required to transport one tonne of goods over a distance of one kilometre (Transport analysis 2022). As such, it captures both transportation distance and volume of goods (Transport analysis 2022).

From year 1950 until 2000, the total freight activity on Swedish roads is estimated to have increased from approximately 3 to 37 billion tkm, as displayed in figure 13 (Transport analysis 2015). This includes domestic transports as well as international transports taking place within Swedish borders (Transport analysis 2015). From 1972 forwards, statistics on domestic transports by Swedish heavy-duty lorries are presented separately as well and can be seen to increase from 18 billion tonne-km in 1972 to 31.4 billion tkm in 2000 (Transport analysis 2015).

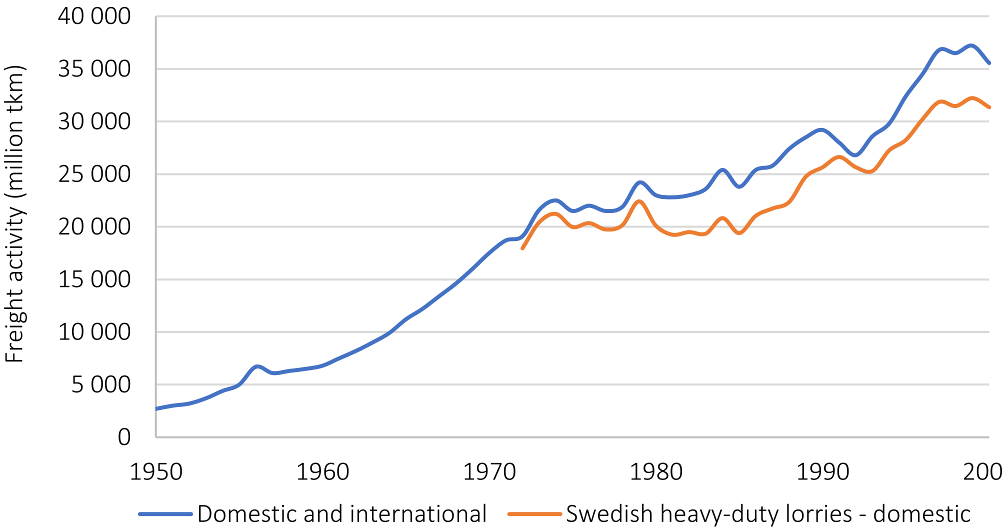

Figure 13: Road freight activity by Swedish-registered vehicles 1950 – 2000. Based on statistics by Transport analysis (2015).

The statistics for the years 2000 – 2021 consist of data from a different set than for 1950 – 2000 and due to different calculation methods and included segments, there is a gap between the two data sets (Transport Analysis 2022e). Hence, they are presented separately and are not directly comparable. The statistics for years 2000 – 2021 include Swedish-registered heavy-duty lorries, foreign-registered heavy-duty lorries arriving and departing, as well as light-duty lorries (not divided based on nationality in the statistics), see figure 14 (Transport Analysis 2022e). The freight activity of Swedish-registered heavy-duty lorries include domestic transport, international arriving transports and international departing transports, which is presented in figure 15 (Transport Analysis 2022e). The freight activity can be seen to have steadily increased until 2008, from 47 billion tkm to 59 billion tkm, whereafter it decreased sharply following the financial crisis (Transport Analysis 2022e). From 2009 and forwards, the transport work fluctuated and ultimately yielded a marginal overall increase of a total of 56.6 billion tkm in 2021 (Transport Analysis 2022e). As can be seen, most of the freight activity is accounted for by Swedish heavy-duty lorries throughout the timeline (Transport Analysis 2022e).

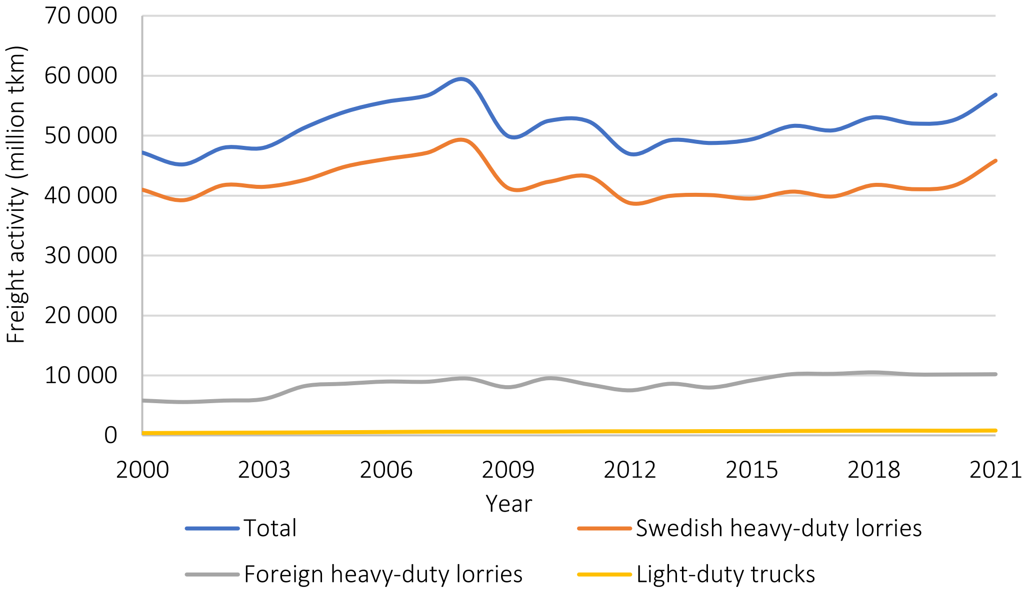

Figure 14: Road freight activity within Swedish borders 2000 – 2021.
Based on statistics by Transport Analysis (2022f).

Figure 15 displays the shares of the different freight transport segments that contributed to the total road freight activity in 2021. The domestic transportation by Swedish-registered lorries accounted for 79 %, followed by international transportation by foreign lorries at 15 % of the total share. Freight activity from international transportation by Swedish-registered heavy-duty lorries, cabotage and light-duty vehicles only accounted for 2 %, 3 % and 1 %, respectively.

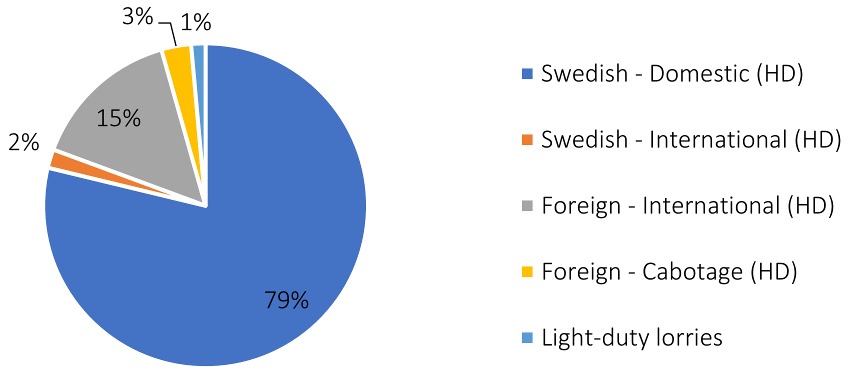

Figure 15: Contribution of transport segments to the total road freight activity in 2021.
Based on statistics by Transport Analysis (2022f).

3.4.1. Vehicle activity

The vehicle activity reflects the total mileages covered by the fleet during one year (Transport Analysis 2022d). As mentioned, the model created for this study is based on vehicle activity (not freight activity). The historical development of the vehicle activity in Sweden by heavy-duty lorries (by both Swedish-registered and foreign-registered ones) between years 1990 – 2021 is displayed in figure 16 which is based on statistics from Transport Analysis (2022d). The total vehicle activity in vehicle kilometres (vkm) of the fleet increased by 36 % from 1990 until 2021, and both the absolutive and relative contributions from different vehicle groups have changed over time (Transport Analysis 2022d). From contributing with less than 10 % of the vehicle activity in 1990, the lorries with a total weight of over 26 tonnes have become the dominant contributors over the past two decades (Transport Analysis 2022d). In 2021, the contribution from these vehicles amounted to approximately 80 % of the vkm covered by the heavy-duty lorry fleet (Transport Analysis 2022d). As shown by the statistics, the trend of transportation by increasingly heavier heavy-duty lorries has been constant during the recent decades.

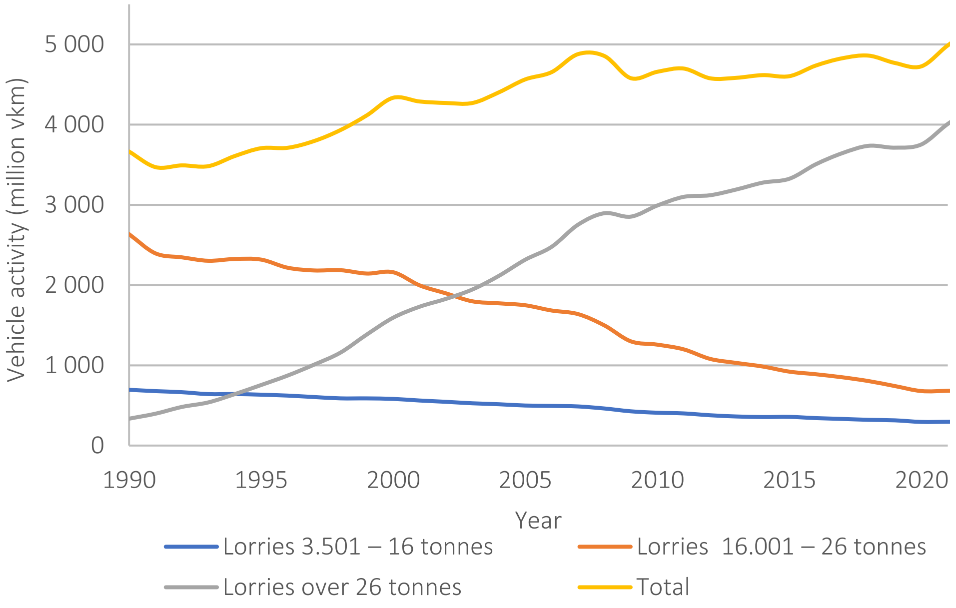

Figure 16: Total vehicle mileages by heavy-duty lorries on Swedish roads 1990 – 2021. Based on statistics by Transport Analysis (2022e).

3.5. Climate policies for the transport sector

3.5.1. EU-level policy

Domestic and international transport within the EU accounted for 29 % of the total greenhouse gas emissions in 2018, representing a growth of 33 % from 1990 (Buysse 2021). Heavy-duty vehicles accounted for approximately 6 % of the total emissions, equivalent to 25 % of the overall road transport in the EU (European Commission n.d.-b). As a result, regulation *(EU)*

2019/1242 of the European Parliament and of the council of 20 June 2019 setting CO2 emission performance standards for new heavy-duty vehicles entered into force on the 14th of August 2019. In February 2023, a revision of regulation (EU) 2019/1242 was published in the form of an official proposal (European Commission 2023b).

The aim of the first EU-wide CO_2-emissions standard for heavy-duty vehicles, is to reduce greenhouse gas emissions stemming from the sector in alignment with the Paris Climate Agreement (Regulation (EU) 2019/ 1242) The regulation imposes targets on manufacturers to reduce the fleet-wide average CO_2-emissions from new lorries, starting in 2025 (Regulation (EU) 2019/ 1242). The targets are set in relation to the EU average during a reference period (1 July 2019 – 30 June 2020) and takes a stepwise approach (Regulation (EU) 2019/ 1242). The first version of the regulation, released in 2019, insisted on a 15 % reduction from 2025 and onwards, and a 30 % reduction from 2030 and onwards by increased shares of low and zero-emission vehicles in the vehicle fleet (Regulation (EU) 2019/ 1242) . This only applied to lorries intended for delivery of goods part of categories N_2 and N_3, as presented in table 13, that also simultaneously fulfilled certain criteria, see table 15 (Regulation (EU) 2019/ 1242). This means that only rigid and tractor lorries with axle configurations of 4x2 and 6x2 and with a gross vehicle weight (GVW) exceeding 16 tonnes were included in the original version of the regulation (Regulation (EU) 2019/ 1242). Combined, these vehicle groups amount to an estimated 65 – 70 % of the heavy-duty vehicle CO_2-emissions (Regulation (EU) 2019/ 1242).

Table 15: Criteria, pertaining to category N_2 and N_3 lorries, currently falling under regulation (EU) 2019/1242.

(a)	rigid lorries with an axle configuration of 4×2 and a technically permissible maximum laden mass exceeding 16 tonnes;
(b)	rigid lorries with an axle configuration of 6×2;
(c)	tractors with an axle configuration of 4x2 and a technically permissible maximum laden mass exceeding 16 tonnes; and
(d)	tractors with an axle configuration of 6x2.

To encourage early transition the regulation imposed so called *incentive mechanisms* to promote investments in zero- and low-emissions vehicles (ZLEVs) (Regulation (EU) 2019/ 1242). From 2019 to 2024, a so-called *super-credits* system is in place, which allows manufacturers to count ZLEVs as more than one vehicle when calculating the average fleet emissions (Regulation (EU) 2019/ 1242). Zero-emissions vehicles count as two vehicles, and low-emissions vehicles count as between 1 – 2 vehicles, depending on CO_2-emissions levels (Regulation (EU) 2019/ 1242). The reductions of a manufacturer's calculated CO_2-emissions through the incentive mechanism are capped at 3 %. From 2025 to 2030, a *benchmark* system is adopted in place of the super-credit system (Regulation (EU) 2019/ 1242). If ZLEVs account for more than 2 % of the manufacturer's heavy-duty vehicles fleet (the benchmark), the calculated emissions of the manufacturer are reduced by 1 % for each percentage exceeding said benchmark (Regulation (EU) 2019/ 1242). The ZLEVs accounting towards the benchmark do not necessarily need to be covered by the regulation, however at least 0.75 % amounting to the 2 % benchmark needs to be (Regulation (EU) 2019/ 1242).

The newly adopted proposal states that the incentive mechanisms should be removed as of 2030 (European Commission 2023a). It also suggests stricter and expanded targets for heavy-duty lorries from 2030 and onwards, now including lorries with a GVW exceeding 5 tonnes (as opposed to 16 tonnes in the original version) (European Commission 2023a). According to this revision, CO_2-emissions reductions should reach 45 % from 1 January 2030, 65 % from 1 January 2035 and 90 % from 1 January 2040, compared to the reference period (European Commission 2023a). Through the stated targets, the overall objectives of the proposal are stated as follows:

> *"The first is to reduce CO2 emissions from heavy-duty vehicles cost-effectively, in line with the EU climate goals while contributing to improving EU energy security.*
>
> …
>
> *The second specific objective is to provide benefits for European transport operators and users, most of which are SMEs*[13]*, resulting from a wider deployment of more energy-efficient vehicles.*
>
> …
>
> *The third specific objective is to strengthen the EU's industrial technological and innovation leadership by channelling investments into zero-emission technologies"* (European Commission 2023a).

The proposal highlights the importance of the objectives in order to reach a timely shift of the fleet considering its turnover inertia and consequently delayed effect of emissions (European Commission 2023a). Likewise, the importance of reducing the total cost of ownership (TCO) as to enable customers to invest in ZLEVs (European Commission 2023a). The updated targets only concern big volume manufacturers, registering > 100 vehicles in each reporting period, in order to target producers that can take advantage of economy of scale (European Commission 2023a). Thereby negative impact on small producers can be avoided, whilst still maintaining sufficient emissions reduction (European Commission 2023a). Figure 17 displays a comparison between the adopted reduction targets in 2019, and the newly proposed targets in 2023.

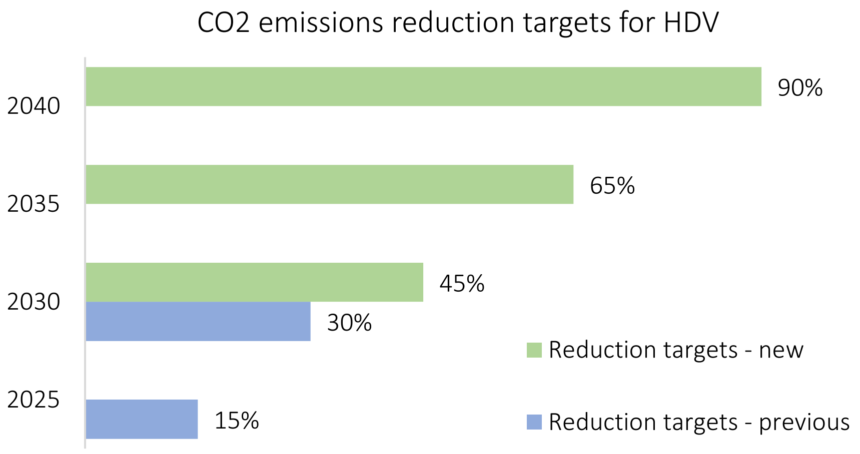

Figure 17: Reduction targets in Regulation (EU) 2019/1242 vs. targets in new proposal.

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[13] Small and medium-sized enterprises (SMEs).

3.5.2. National policy

Mitigating the emissions from the domestic transport sector is an imperative part of reaching the Swedish climate goal of net zero emissions by 2045 (Naturvårdsverket n.d.). As such, an intermediate national target has been set for the transport sector until 2030, stating that emissions from domestic transport (excluding domestic flights, which are covered by the EU Emissions Trading System) should be reduced by 70 % until 2030, compared to 2010 (Sveriges Riksdag 2022b). Thereby, the vehicle fleet needs to move beyond fossil fuel dependence and towards zero- and low emissions vehicles (Sveriges Riksdag 2022b).

Working in favour of the national target for the transport sector is the governmental investment support *"Klimatklivet"* (Authors' English translation: "the Climate step") and the climate premium for environmental vehicles (Government Offices of Sweden 2022; Swedish Energy Agency 2023b). The climate step is aimed at organisations, with the goal to facilitate decarbonisation on a regional and local level throughout the country (Government Offices of Sweden 2022). To enable the expansion of electric vehicles on the roads by improving the charging infrastructure, the government increased the appropriation for the Climate step with 400 million SEK in 2023 and 500 million SEK in 2024 and 2025, respectively (Government Offices of Sweden 2022). Similarly, the climate premium is a support for organisations purchasing environmental lorries, electric working machines and environmental working machines (Swedish Energy Agency 2023b). Heavy-duty lorries that are electrically propelled by a battery, fuel cell or an external source are eligible for the support, as well as those using 100 % bioethanol or biogas/natural gas (Swedish Energy Agency 2023b). Through the premium, organisations can receive up to 20 % relief of the purchase price (Swedish Energy Agency 2023b).

The Swedish government also introduced a greenhouse gas reduction mandate in 2018 to encourage the use of biofuels in order to reduce the GHG emissions from the transport sector (Swedish Energy Agency 2023c). In this study, the reduction mandate is used for the scenario design and is further investigated in section 4.2.

3.6. Pathways towards a fossil-free fleet

The shift towards a fossil free heavy-duty lorry fleet over the coming decades can materialise in varying ways, depending on factors such as technology advancements, cost-efficiency, policy and policy instruments (Government Offices of Sweden 2021a). The overall strategies for decarbonising the heavy-duty lorry fleet can be summarised into three main areas 1) electrification, 2) increased shares of renewable fuels and 3) improved transport efficiency (Fossilfritt Sverige 2020; Government Offices of Sweden 2021a; Scania 2018; Swedish Transport Administration 2020b).

The overall time aspect of the transition of the fleet is an important factor when estimating *when*, and consequently *how*, the phase-out of fossil fuels should take place (Government

Offices of Sweden 2021a). The transition will be gradual as the aging fleet, predominately ICEVs running on diesel, reach end-of-life and are continuously replaced by ZLEVs (European Commission 2023a). As such, the inertia of the transition will affect the rate at which CO_2-emissions reductions take place (European Commission 2023a). The Government official report (SOU) 2021:48 from 2021 states that in order to reach the national climate goal by 2045, the transition towards a fossil-free fossil transport sector should be completed by year 2040 (Government Offices of Sweden 2021a). A phase-out of fossil fuels earlier than 2040 is regarded as unrealistic with regards to the large changes required to sustainably realise the shift, especially whilst also acting as a role model for other countries (Government Offices of Sweden 2021a).

Principally, the baseline for a future a fossil-free transport sector is utilising primary energy originating either from renewable electricity or biomass (Government Offices of Sweden 2021a). In this future transportation system, renewable electricity could be distributed either through charging stations or electric road systems and used in a BEV or a PHEV (Government Offices of Sweden 2021a). Biofuels could be produced from biomass and used in pure form or as drop-in fuels (Government Offices of Sweden 2021a). Moreover, biomass or electricity could be used to produce hydrogen gas, to be used in a vehicle with a combustion engine, a FCEV, or to produce electro-fuels (synthetic fuels) by reacting with CO_2[14] (Government Offices of Sweden 2021a). Other possible fuel alternatives for FCEVs include methanol, ethanol, and biogas (Government Offices of Sweden 2021a). In practice the transition towards a decarbonised fleet will rely on a combination of these measures, influenced by technology and cost-efficiency developments (Government Offices of Sweden 2021a).

In the following section, electrification of the fleet and use of renewable fuels are investigated.

3.6.1. Electrification

Direct electrification is considered a main pathway to achieve a timely, sustainable, and economically viable phase-out of fossil fuels in the road transport sector, including for heavy-duty lorries (Fossilfritt Sverige 2020; Government Offices of Sweden 2021a; Nordic Energy Research 2021; Scania 2018; Swedish Transport Administration 2020b). Battery electric and hybrid heavy-duty lorries are limited on the market today, and due to the longer and heavier transports the obstacles to electrify the fleet is greater than for the passenger car fleet (Fossilfritt Sverige 2020). However, the technology for battery electric heavy-duty lorries exist, is scalable, and their expansion can be expected to take off in the near future (Fossilfritt Sverige 2020, Nordic Energy Research 2021). While other pathways than battery driven vehicles have previously been suspected to be economically favourable to heavy-duty lorries, recent estimations of the cost-efficiency suggest that BEVs can be expected to be competitive against for instance FECVs and biofuels (Nordic Energy Research 2021). This can be attributed to increased energy densities in batteries and decreased costs (Nordic Energy Research 2021). In

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[14] Produced for instance by combustion of biomass (Government Offices of Sweden 2021a)..

a 2018 report where Scania investigates potential pathways to decarbonise commercial transport by 2050, BEVs were deemed the most cost-effective alternative even when considering necessary infrastructure investments and battery sizes (Scania 2018). As such, BEVs provide a promising alternative to drive the phase-out of fossil fuels, although continued battery technology developments will be an important role for the expansion of BEVs (Fossilfritt Sverige 2020, Nordic Energy Research 2021). Aside from battery cost and limited battery sizes (and thus transport distances), an important obstacle for large-scale implementation of BEVs is the lack of proper charging infrastructure (Fossilfritt Sverige 2020). In order to enable direct electrification of the heavy-duty lorry fleet, large investments to rapidly expand the charging infrastructure will be necessary, both with regards to charging stations and grid expansion (Government Offices of Sweden 2021b; Nordic Energy Research 2021).

An alternative to charging stations are Electric Road Systems (ERS), that could allow for dynamic charging on-the-go through, for instance, induction, conduction, or overhead lines (Government Offices of Sweden 2021b, 2021a; Nordic Energy Research 2021) Consequently, deployment of ERS could mitigate concerns related to battery size and enable longer and heavier goods transports by BEVs (Government Offices of Sweden 2021b; Nordic Energy Research 2021). Several pilots have been tested in Sweden, and the production of the first permanent electric road is planned for 2026 on E20 between Hallsberg and Örebro, which is one of the busiest roads in Sweden for heavy-duty transport (Government Offices of Sweden 2021b; Swedish Transport Administration 2023b). Due to larger costs and practicality concerns associated with dynamic charging, ERS can be expected to be used as a complement to stationary charging in the future (Government Offices of Sweden 2021b).

Besides BEVs, another electrification alternative is the use of FCEVs (Fossilfritt Sverige 2020). The potential advantages of FCEVs over BEVs are largely connected to shorter charger times coupled with longer possible driving distances (European Environment Agency 2022; Fossilfritt Sverige 2020). As such, in the long-term perspective FCEVs may provide a suitable way to electrify the heaviest and longest transport segments (Fossilfritt Sverige 2020). However, fuel cells suffer from challenges related to infrastructure and constitute a more costly alternative than BEVs (European Environment Agency 2022; Nordic Energy Research 2021). FCEVs are also less energy efficient, requiring 2 – 3 times more electricity than BEVs (European Environment Agency 2022; Government Offices of Sweden 2021a). In the near future, the expansion of electrification within the heavy-duty lorry fleet can predominantly be expected to occur for of short- and medium distance transports, which dominate domestic transports in Sweden (Fossilfritt Sverige 2020; Nordic Energy Research 2021). This points towards a larger expansion of BEVs, whereas FCEVs could play an increasingly larger role close to the 2050s (Fossilfritt Sverige 2020; Nordic Energy Research 2021).

3.6.2. Biofuels and other renewable fuels

Biofuels are used extensively in today’s transport sector and aside from electrification, liquid biofuels and biogas are likely necessary as complements to achieve a transition of the heavy-duty lorry fleet in accordance with the climate goals set for the sector (Fossilfritt Sverige 2020, Nordic Energy Research 2021). The use of biofuels seems particularly important in order to decarbonise heavy and long goods transports, and the replacement of diesel with biofuels is facilitated by the fact that many ICEVS can be run on them, particularly HVO which can act as a direct substitute (Fossilfritt Sverige 2020, Nordic Energy Research 2021). However, Sweden has an ambition to act as a role-model for other countries' transitions which should be considered since an increasing dependence on biofuels would require an expansion of the supply, while Sweden already single-handedly using about 1/3 of the global supply of HVO (Fossilfritt Sverige 2020). In SOU 2021:48 It is suggested that renewable liquid and gas fuels should primarily be reserved for transport segments where electrification is considered less viable, such as flights, sea freight and for use of work machines (Government Offices of Sweden 2021a). It is argued that by enabling a high electrification rate, the share of biofuels can be kept at levels similar to the current one (Government Offices of Sweden 2021a). Nonetheless, the electrification rate is limited by factors such as charging infrastructure and grid capacity developments (Fossilfritt Sverige 2020). Thereby, increased shares of biofuels will likely be an important factor in decarbonising the fleet, especially in the short- and medium-term timeframe (Fossilfritt Sverige 2020).

Other renewable fuel alternatives, such as electro-fuels (e-fuels), are developing and may have the potential to reach large-scale deployment in the future (Nordic Energy Research 2021). These are synthetic fuels produced by using "Power-to-X" technology, which involves generating hydrogen from electricity and letting the hydrogen react with CO_2 captured from air or acquired through combustion of biomass (Andersson and Börjesson 2021; Government Offices of Sweden 2021a; Nordic Energy Research 2021). Thereby, renewable energy carriers such as such as e-methane, e-methanol, e-gasoline, and e-diesel can be produced (Andersson and Börjesson 2021). However, the process of converting power to fuels is significantly less energy efficient than using electricity directly, and combustion engines using electro-fuels require up to 5 – 6 times more electricity than directly electrified vehicles (Government Offices of Sweden 2021a).

4. Foreground system scenario design

This chapter presents literature findings and model assumption for scenarios and carbon intensities in the foreground system.

4.1. Electrification rate

The rate of electrification of the Swedish heavy-duty lorry fleet has been estimated in scenarios by Fossilfritt Sverige (2020) until 2030 and Government Offices of Sweden (2021a) until year 2050. Based on assessments by vehicle manufacturers, Fossilfritt Sverige (2020) estimated that the new sales share of electric vehicles will increase to between approximately 12 – 18 % in 2025 and 30 – 50 % in 2030. The total share of distances by electric vehicles was estimated to approximately 2 – 3 % in 2025 and 10 – 16 % in 2030, see figure 18 below (Fossilfritt Sverige, 2020).

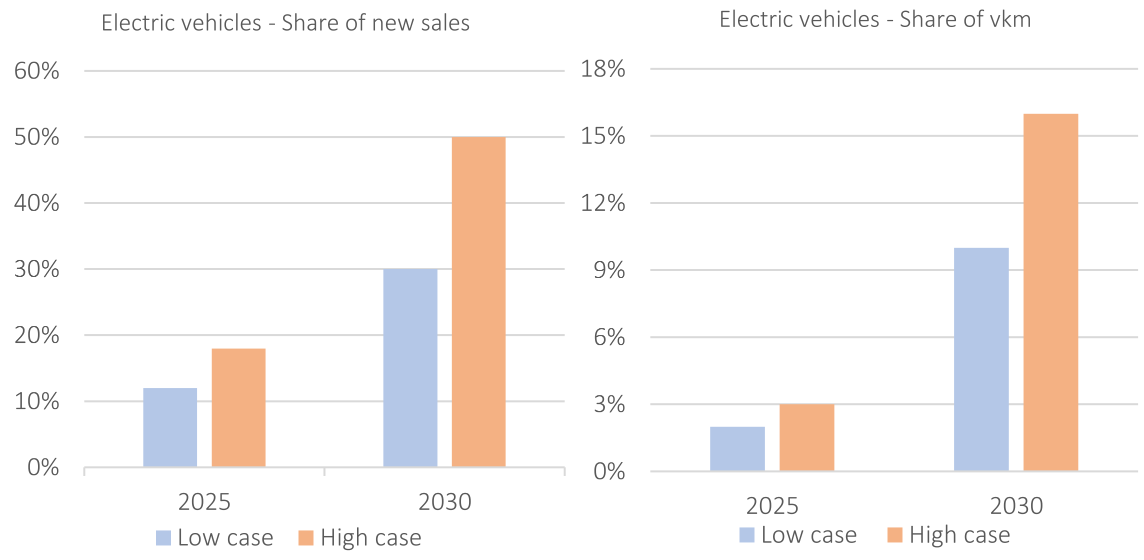

Figure 18: Rate of electrification. Share of new sales and share of vehicle activity. Scenario by Fossilfritt Sverige (2020).

Government Offices of Sweden (2021a) present a low, medium, and high scenario until 2050, where the low scenario is based on a reference scenario for electrification by the Swedish Energy Agency, the medium scenario is based on a base prognosis by the Swedish Transport Administration, and the high scenario is based on the scenario presented above by Fossilfritt Sverige and assuming a continuous increase until 2050 (Government Offices of Sweden 2021a). The new sales share of electric vehicles was assumed to reach between approximately 5 – 54 % in 2030, 11 – 90 % in 2040 and 11 – 100 % in 2050 (Government Offices of Sweden 2021a). The total share of the vehicle activity covered by electric vehicles was estimated to between 2 – 20 % in 2030, 10 – 65 % in 2040 and 12 – 83 % in 2050 (Government Offices of Sweden 2021a). The shares are presented in figure 19.

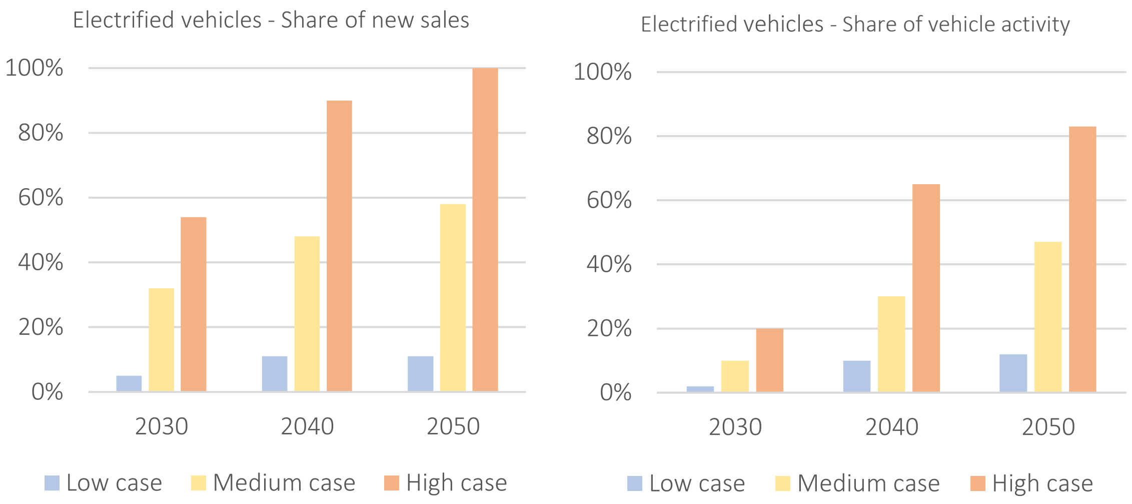

Figure 19: Rate of electrification. Share of new sales and share of vehicle activity. Scenarios by Government Offices of Sweden (2021a).

4.1.1. Model assumptions

In the model, the electrification rate reflects the share of sold vehicles that are BEVs. The estimated shares are based on the estimations presented by Fossilfritt Sverige (2020) and Government Offices of Sweden (2021) which both present possible developments of this parameter for Swedish heavy-duty lorries. As presented in the previous section, their results show similar developments and have acted as basis for the assumptions used in the simulations which are presented in figure 20.

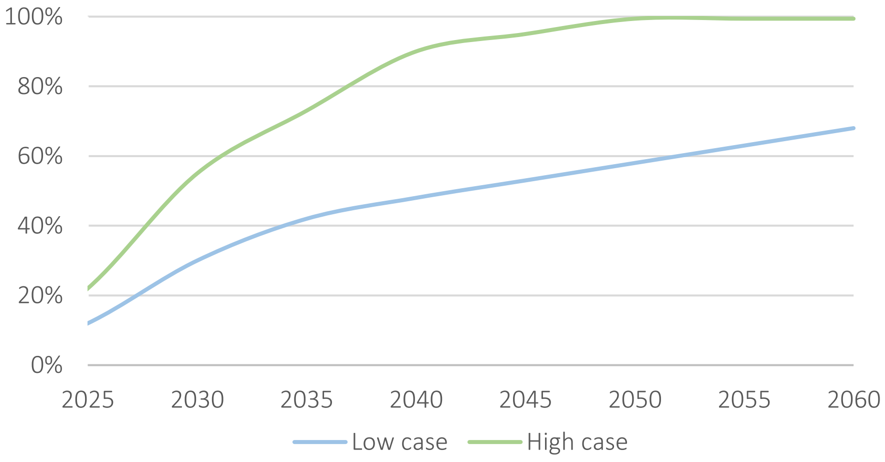

Figure 20: Assumed shares of new sales (%) accounted for by BEVs.

The low and high scenarios aim to represent a span covering the possible outcomes regarding the rate of electrification but does not explicitly take into consideration possible issues such as material shortages, or price and global economic development affecting the purchasing power.

Initially another, even lower, electrification rate scenario was considered as well. This was to be represented by the low case by the Government Offices of Sweden (2021a) as presented in section 4.1. However, this case was excluded from the study. This was motivated by 1) time constraints and 2) the slow electrification rate would cause a relatively small deviation from the current fleet composition, where a maximum of 11 % of the fleet would be assumed electrified by 2060. As such, this scenario was considered of little interest to investigate.

4.2. Share of biofuels

In 2018, the Swedish government introduced a greenhouse gas reduction mandate (henceforth denoted as the reduction mandate) to support a reduction of the GHG emissions of the transport sector in line with the 70 % reduction target until 2030, by promoting the use of biofuels (Swedish Energy Agency 2023c). In 2021 the reduction mandate was updated to also include other renewable and fossil-free fuels (Swedish Energy Agency 2022b).

The reduction mandate states that fuel suppliers are obligated to reduce the fuel’s greenhouse gas emission by a set percentage that increases each year until 2030. The emissions are calculated from a life cycle perspective and the reduction is in comparison with the corresponding product of 100 % fossil origin (Swedish Energy Agency 2023c). However, a pause of the mandate was demanded by the government in 2022, and the emission reduction target levels of 2023 is currently halted at the levels for 2022 pending a decision on the future of the mandate (Sveriges Riksdag 2022a). There are political suggestions to lower the reduction levels, while other authorities emphasise the reduction mandate’s considerable contribution to reaching national climate goals (Dagens Nyheter 2023; Swedish Environmental Protection Agency 2023). In a scenario report by the Swedish Energy Agency in 2023, the share of biofuels was expected to follow legislated reduction levels until 2030 and thereafter remain constant until 2050 (Swedish Energy Agency 2023d).[15]

At the end of 2022, the Swedish Energy Agency published a report in which the reduction mandate is evaluated and suggestions for future target levels presented (Swedish Energy Agency 2022b). It is argued that the mandate is necessary to achieve the target of 70 % emission reductions until 2030 (Swedish Energy Agency 2022b). However, fuel quality criteria are identified as possible hindrances for future increases of bio components in both petrol and diesel (Swedish Energy Agency 2022b). Due to current quality legislation and fuel standards the maximum accepted share of bio components in fuel mixtures might be reached in 2027, leaving subsequent reduction targets unattainable (Swedish Energy Agency 2022b).

Consequently, the Swedish Energy Agency provides alternative formulations of the future target levels (Swedish Energy Agency 2022b). The main suggestion is in line with the 70 % goal for 2030 and it involves three main measures: (1) a transition from use of fossil diesel type MK1 to the European type MK3, since the latter enables mixtures with a larger share of bio

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[15] In May 2023 the Swedish government announced a reduction to 6 % at the end of the year.

components, (2) pure biofuels and mixture with a high share of bio components are included in the reduction mandate and (3) due to low allowance of biofuels in petrol mixtures in regards to fuel quality, a large share of the target levels are allocated to diesel (Swedish Energy Agency 2022b). The original[16] legislated emission reduction targets and proposed new levels are presented in table 16.

Table 16: Original and suggested emission reduction targets for the Swedish greenhouse gas reduction mandate. Based on data from Swedish Energy Agency (2022b).

Year	***Petrol (%)***		***Diesel (%)***	
	Original	*Suggested*	*Original*	*Suggested*
2024	12.5	11.0	40.0	40.0
2025	15.5	14.0	45.0	46.0
2026	19.0	14.0	50.0	51.5
2027	22.0	14.0	54.0	57.5
2028	24.0	14.0	58.0	63.5
2029	26.0	14.0	62.0	69.0
2030	28.0	14.0	66.0	75.0

An approximation of future volume shares of bio-components in diesel are presented by the Swedish Energy Agency for two scenarios: 1) scenario with original reduction levels and 2) a scenario where the limitations of mixtures with petrol is compensated by higher shares in diesel, presented in figure 21 (Swedish Energy Agency 2022b). The latter is in line with the main suggested scenario mentioned above (Swedish Energy Agency 2022b).

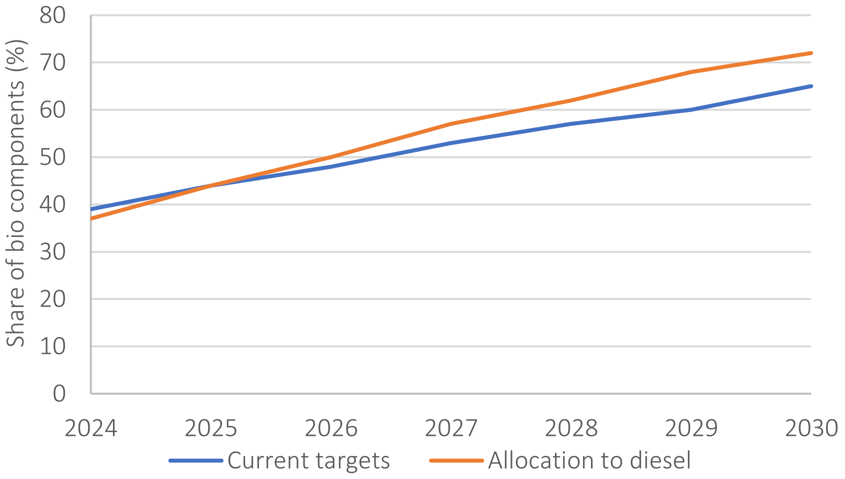

Figure 21: Approximation of shares of biofuels in future diesel mixtures between years 2024 – 2030. Based on data from Swedish Energy Agency (2022b).

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[16] Original legislation refers to a scenario where the legislated reduction mandate is resumed in 2024, following the pause issued in 2022.

The report also presents a reference scenario where the national greenhouse gas reduction mandate is cancelled, and drop-in levels are only required to satisfy the EU demand of emission reduction of 6 % (Swedish Energy Agency 2022b). The energy share of bio components in diesel is expected to remain constant at 9.9 % until 2030 and the national goal of 70 % emission reduction to 2030 is expected to require other measures than increased use of biofuels in the transport sector to attain the goal (Swedish Energy Agency 2022b).

4.2.1. Model assumptions

In the main biofuel scenario, the emission reduction mandate is expected to continue as legislated until 2030 and thereafter the levels are assumed to remain constant until 2065, influenced by a scenario report by the Swedish Energy Agency (Swedish Energy Agency 2023d). The share of biodiesel is thus expected to reach 70 % in 2030 and then remain constant. The biofuel scenario does not consider other renewable and fossil-free fuels, although these are included in the reduction mandate.

Considering the uncertainty connected to the future biofuel usage with regards to policy, quality standards and raw material availability, a sensitivity analysis is included. It contains a high and low case. The high case is based on a higher allocation of the reduction mandate to diesel until 2030 (Swedish Energy Agency 2022b), and thereafter the drop-in level in diesel increases linearly to 100 % in 2040 in line with the suggested phase-out year presented in the government official report (SOU) 2021:48 (Government Offices of Sweden 2021a). In the low case, a removal of the emission reduction mandate is considered, and the composition of the Swedish diesel mixture is adjusted to EU minimum policy resulting in a level of 9.5 % based on an evaluation by the Swedish Energy Agency (2022b). The level is held constant until 2060. Scenarios for the sensitivity and main scenarios are displayed in figure 22.

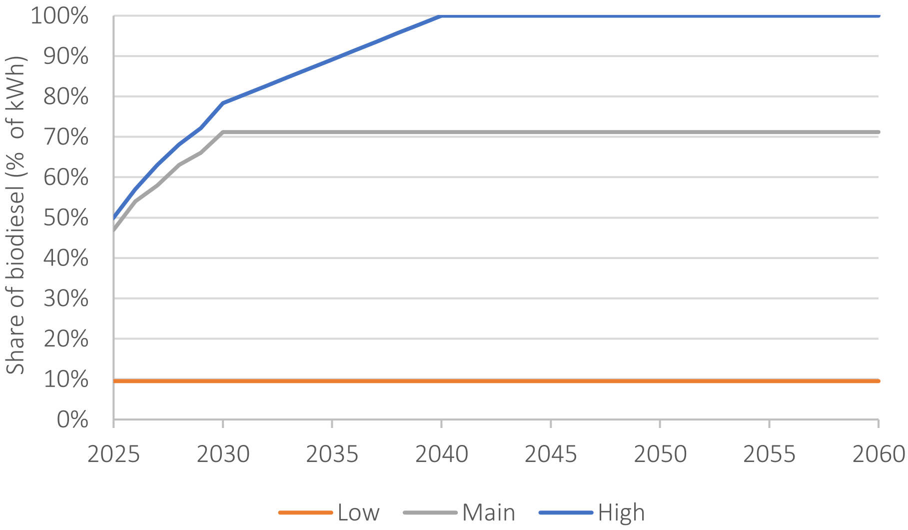

Figure 22: Shares of biodiesel for main and sensitivity scenarios.

4.3. Road freight transport demand

The demand for freight transport is the prime driver for increasing CO_2 emissions from heavy-duty lorries (European Environment Agency 2022). The evolution of the demand is tied to the economic development and connecting factors such as demographics, technology, politics and economic behaviour of individuals (Swedish Transport Administration 2020a). In order to estimate how the future demand for freight transport in Sweden may change throughout the modelling timeframe, prognoses from the Swedish Transport Administration and the Swedish Energy Agency present were investigated.

4.3.1. Prognoses on road freight activity

The Swedish Transport Administration (2020a) has developed prognoses that estimate how the overall demand of freight activity on Swedish roads might develop until year 2040. These include transports in Sweden by Swedish heavy-duty lorries, as well as lorries from EU/EES countries (Swedish Transport Administration 2020a). The prognoses consist of a main reference scenario (REF18) and two sensitivity analyses that are shown in figure 23[17] below (Swedish Transport Administration 2020a).

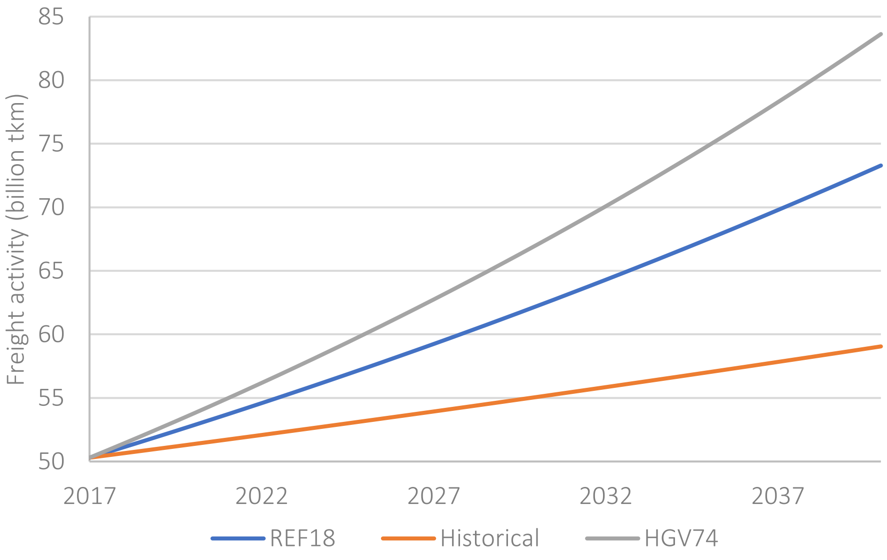

Figure 23: Road freight activity prognosis between years 2017 – 2040. Based on prognoses by the Swedish Transport Administration (2020a).

The main scenario is based on the long-term economic development in Sweden, as estimated in the reference scenario by the National Institute of Economic Research (Swedish Transport Administration 2020a). It estimates an increase of approximately 23 billion tkm, from 50 in 2017 to 73 in 2040, with a yearly increase of + 1.65 % (Swedish Transport Administration 2020a). This result is built on assumptions of a significant growth in revenue in the goods

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[17] The plot is based on the yearly estimated increase in demand of freight activity as presented in the report by the Swedish Transport Administration (2020a).

handling business and a growth, albeit not as aggressive, of the goods values (Swedish Transport Administration 2020a). As a result, the demand of freight transport is estimated to have a steeper growth rate than what has been observed in the long-term historical development (Swedish Transport Administration 2020a). In a 2022 report, the Swedish Transport Administration (2022b) state that these previous prognoses on freight transportation may overestimate the future development, and refer to the marginal increase that has been observed in the last 20 years, despite the economic growth.

The main scenario does not consider the potential expansion of lorries with a gross maximum weight of 74 tonnes (Swedish Transport Administration 2020a). However, since 2018 these lorries are allowed, albeit only on limited segments of the Swedish road systems (Swedish Transport Administration 2020a). In the HGV74-scenario, these lorries are assumed to be allowed on the entire transport system for heavy-duty transport (Swedish Transport Administration 2020a). As such, the road freight activity is estimated to increase by 2.2 % on a yearly basis (whilst simultaneously reducing the transport work on rail and at sea), reaching almost 84 billion tkm in 2040 (Swedish Transport Administration 2020a).

Should the growth rate instead be assumed to follow the historical trends, such as in the historical scenario, the freight activity is estimated to increase by 0.7 % on a yearly basis (Swedish Transport Administration 2020a). This results in a transport work of 59.4 billion tkm in 2040 (Swedish Transport Administration 2020a).

4.3.2. Prognoses on vehicle activity

The Swedish Transport Administration also published prognoses regarding the evolution of the vehicle activity until year 2040 and year 2065, respectively (Swedish Transport Administration 2021). These prognoses are built on the main scenario (REF18) presented in the previous section, complemented with EU-level prognoses for the Swedish development between years 2030 – 2050 as a basis for the prognosis until 2065 (Swedish Transport Administration 2021). The growth rate between years 2030 – 2050 is assumed to be 75 % of the growth between years 2010 – 2030 (Swedish Transport Administration 2021). The calculated total growth rate per year until 2040 is estimated to be + 1.58 %, and + 1.37 % until 2065 (Swedish Transport Administration 2021).

Similarly, the Swedish Energy Agency has created a prognosis on the vehicle activity until year 2050[18], which is used in the report by Government Offices of Sweden (2021a). In their main scenario, the vehicle activity by heavy-duty lorries is estimated to increase by almost 29 % between years 2018 – 2050, from 4.9 billion vkm in 2018 to 6.3 in 2050[19] (Helen Lindblom,

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[18] In the report, only the relative development, and only until year 2040 is presented. The absolute numbers until year 2050 were acquired from Helen Lindblom at the Swedish Transport Administration (mail correspondence, 18 April 2023).

[19] Includes transport within Swedish borders by both Swedish-and foreign-registered heavy-duty lorries.

mail correspondence, 18 April 2023)[20]. This prognosis estimates a smaller increase in the demand than the prognosis by the Swedish Transport Administration (Government Offices of Sweden 2021a). For instance, the Swedish Energy Agency estimates an increase of 18 % from 2018 to 2040 whereas the Swedish Transport Administration estimates a 44 % increase from 2017 to 2040 (Government Offices of Sweden 2021a). As a reference, the near-term historical increase between years 2000 – 2018 was 12 % (Government Offices of Sweden 2021a).

According to the Government Offices of Sweden (2021a) the prognosis by the Swedish Energy Agency is assumed to capture the ongoing development trends amongst heavy-duty lorries more accurately than the one by the Swedish Transport Administration, proposing that the estimates by the latter are likely overestimated. The motivation is that while there is a stated connection between the demand for freight transport, industry production and GDP growth, the connection has continuously grown weaker over time (Government Offices of Sweden 2021a). As mentioned in the previous section, the Swedish Transport Administration (2022b) themselves also state that their previous prognoses on freight transportation may overstate the future development.

The prognoses for the vehicle activity by heavy-duty lorries within Swedish borders between years 2018 – 2040 developed by the two authorities are shown in figure 24.

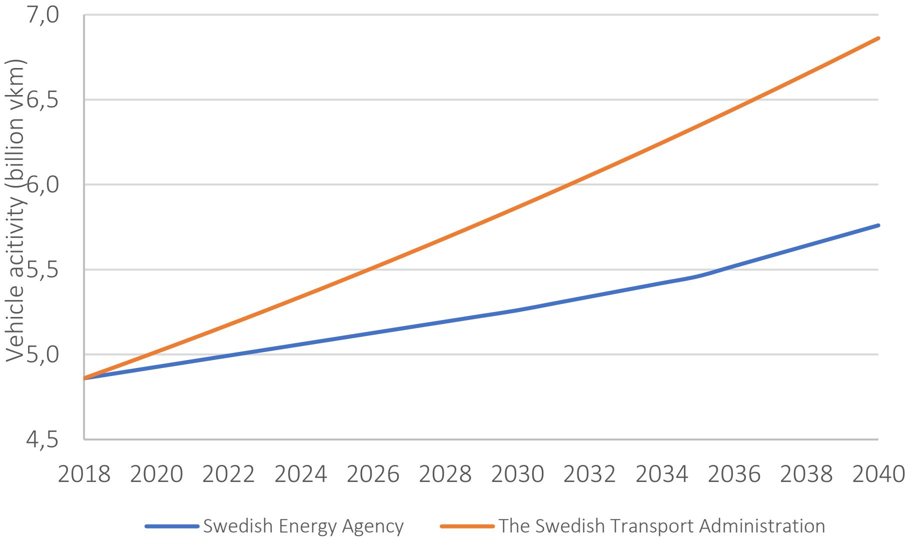

Figure 24: Vehicle activity prognoses between years 2018 – 2040.
Based on prognoses by the Swedish Energy Agency and the Swedish Transportation Administration.

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[20] Helen Lindblom works at the Swedish Transport Administration but supplied the data for the Swedish Energy Agency prognosis.

4.3.3. Model assumptions

The future transport demand in the model is based on the prognosis made by the Swedish Energy Agency as presented in section 4.3.2. These estimations were chosen in favour of the prognosis by the Swedish Transport Agency due to the indications that the latter is likely to have overestimated the development.

However, the prognosis by the Swedish Energy Agency includes all heavy-duty lorry transport within Swedish borders (Government Offices of Sweden 2021a). As this study only considers transports by Swedish-registered lorries, the percentual increases from year 2018 and onwards as estimated by the Swedish Energy Agency was used and applied to vehicle activity statistics for year 2018[21] that had been adjusted to only include transports by Swedish lorries. The share of kilometres supplied by Swedish-registered lorries versus foreign-registered lorries was then assumed to remain constant over time. The data processing is further explained in appendix C. Moreover, since this study includes simulations until year 2060, the same yearly increase in transport demand was assumed between years 2050 – 2060 as between years 2045 – 2050.

The main scenario was complemented with a sensitivity analysis consisting of a low case and a high case. These correspond to a difference of ± 20 % of the vehicle activity in year 2050 as compared to the main scenario. Thereafter a linear increase is assumed until 2060. A difference of + 20 % in 2050 is similar to the main scenario in the prognosis by the Swedish Transport Agency (Government Offices of Sweden 2021a). The resulting transport demand between years 2025 – 2060 for the main scenario and sensitivity analyses is shown in figure 25.

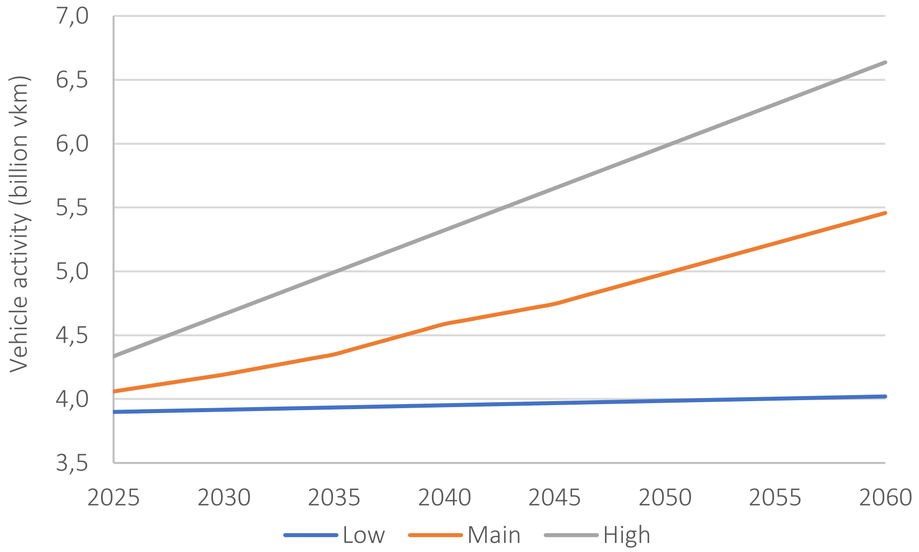

Figure 25: The assumed evolution of the vehicle activity.

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[21] Statistics on the vehicle activity in year 2018 was acquired from Helen Lindblom at the Swedish Transport Administration (mail correspondence, 18 April 2023), which corresponds to the statistics for year 2018 by Transport Analysis (2022e).

The corresponding freight activities, based on the assumed loads and weight distribution as presented in section 2.5.3 – 2.5.5 are presented in figure 26Figure 26. Calculation of freight activities is further explained in appendix C.

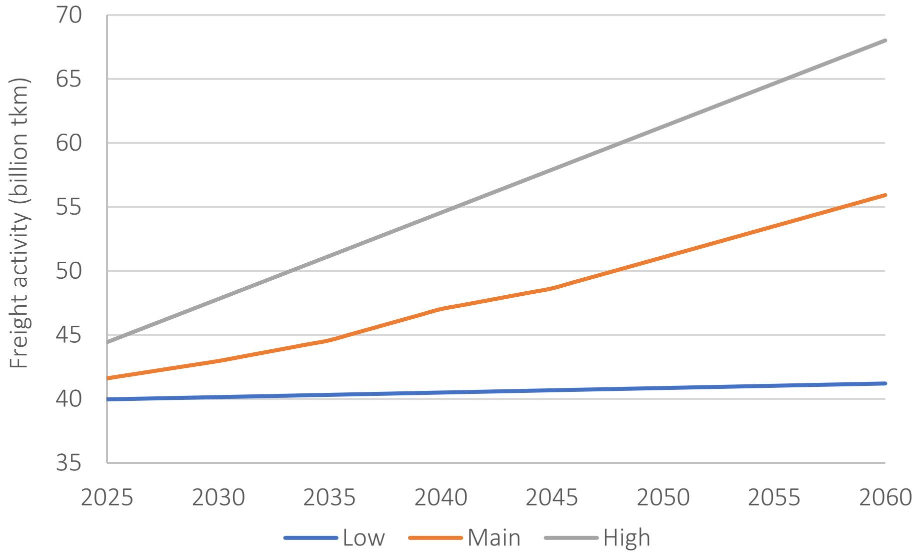

Figure 26: The assumed evolution of the freight activity.

In figure 27 the assumed freight activities in the model are compared to the prognosis by the Swedish Transport Administration (2020a) for years 2025 – 2040, although the prognosis estimates have been adjusted to exclude transport by foreign lorries to make the numbers comparable [22].

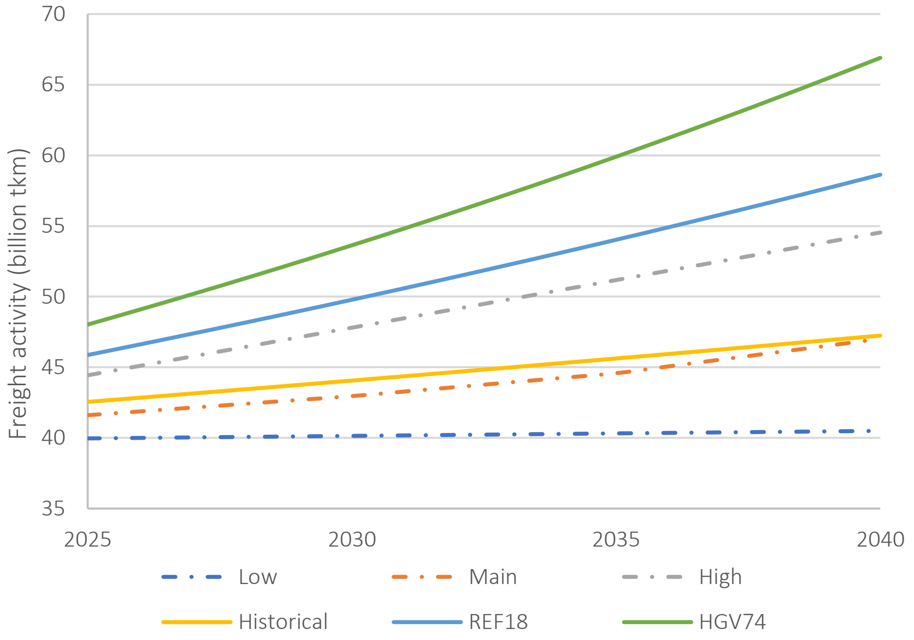

Figure 27: Study assumptions on freight activity vs estimations by the Swedish Transport Administration (2020a)*.*
The estimations by the Swedish Transport Administration have been adjusted to exclude transport by foreign lorries.

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[22] Foreign lorries account for approximately 20 % of the freight activity within Swedish borders (Transport Analysis 2022c). This estimate is assumed constant over the time period in the model.

As can be seen the main scenario of the model is more similar to the historical scenario by the Swedish Transport Administration (2020a), which was deemed desirable due to the indications of the REF18 scenario overestimating the development, as explained in section 4.3.1. The high case of the model is more similar to the REF18 case.

4.4. Tailpipe carbon intensities

In this section potential emission factors for fossil diesel, biofuels and electricity are investigated, followed by the resulting model assumptions.

4.4.1. Fossil diesel

The amount of exhaust emissions from transport with fossil fuel combustion-based propulsion depends on several factors such as vehicle type, fuel, and powertrain as well as engine temperature at start (European Environment Agency 2019). The most important GHG emissions to consider for road transport are carbon dioxide (CO_2) methane (CH_4) and nitrous oxide (N_2O) (European Environment Agency 2019). Emission factors for general vehicle transport have been estimated to 2.54 – 2.58 kg CO_2 per litre diesel (Drivkraft Sverige n.d.; European Environment Agency 2019) . The contribution from CH_4 and N_2O for general vehicle transport propelled by fossil diesel has shown to be between 1.5 – 1.9 % in terms of kg CO_2-eq per kWh diesel[23] (Serrano-Guevara and Huertas 2022; Swedish Environmental Protection Agency n.d.-a) .

4.4.2. Biodiesel

Combustion of biofuels generates biogenic emissions due to its origin from biomass (Swedish Environmental Protection Agency n.d.-b). The cycle from atmospheric carbon to stored carbon in biomass is relatively short compared to carbon from fossil sources (Swedish Environmental Protection Agency n.d.-b). For sustainably produced biofuels, the biogenic emissions can therefore be considered as carbon neutral (Swedish Environmental Protection Agency n.d.-b). Thereby the tailpipe emissions can be approximated to zero (Swedish Environmental Protection Agency n.d.-b).

4.4.3. Electricity for charging

As direct electricity is used as an energy carrier for BEVs, there are no resulting tailpipe emissions (International Energy Agency 2017).

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[23] Sources provide data for CH_4 and N_2O in kg per MJ diesel, this has been further processed in the study by means of global warming potential factors to estimate the impact in terms of CO_2-eq.

4.4.4. Model assumptions

Due to the model approach where fuel consumption is adjusted to weight classes, payload and development over time, an average emission factor for fossil diesel in road transport is used and assumed equal for all ICEVs and constant over time for all scenarios. Based on literature findings above, an average emission factor for CO_2 is used with the addition of the GHG contribution from CH_4 and N_2O. The resulting input data to the model is 266 gCO_2-eq per kWh fossil diesel.

The emission factors for biofuels are set to zero and no emission factor is required for electricity.

5. Background system scenario design

This chapter presents literature findings and model assumption for the scenarios and carbon intensities in the background system.

5.1. Global climate change mitigation scenarios

The carbon emissions from the background system (connected to the vehicle and fuel cycle) are dependent on the developments within the energy sector. The International Energy Agency (IEA) publishes the yearly report *"World Energy Outlook"* with analysis and projections of the future global energy sector, including scenario developments that are used to investigate potential consequences of various climate change mitigation ambition levels among decision makers (International Energy Agency 2022). In the report from 2019, three scenarios were presented: *Current policies*, *Stated policies* and *Sustainable development* (International Energy Agency 2019). The current policies scenario reflects the future developments if only currently implemented policies are considered (International Energy Agency 2019). The stated policies scenario considers implemented policies, as well as announced, but not yet implemented, policy and stated targets (International Energy Agency 2019). The sustainable development scenario intends to capture a development aligned with the Paris Agreement, representing a trajectory where global CO_2 emissions reach net zero in 2070 (International Energy Agency 2019). In 2022, the sustainable development scenario was replaced by two others; one where current climate mitigation targets are assumed to be reached as planned, and another where net zero emissions are predetermined to be achieved in 2050 (International Energy Agency 2022).

In Morfeldt et al. (2021), the stated policies and sustainable development scenarios by the IEA were used as conceptual basis to formulate prospective LCA scenarios for parameters influencing the vehicle cycle emissions and fuel cycle emissions for the Swedish passenger car fleet. Thereby, the report presents estimations on how the carbon intensities of the cycles may change in alignment with the scenarios. In 2023, these estimations were updated in a new report by Morfeldt et al. (2023).

In this study, the background system developments are primarily based on the scenarios and data from Morfeldt et al. (2021), with the updated carbon intensities from Morfeldt et al. (2023). Thus, the background scenarios are divided in *Stated policies* and *Sustainable development*, in alignment with (International Energy Agency 2019) but with the adoptions made by Morfeldt et al. (2023, 2021). By primarily using the prospective LCA from these two articles, assumptions regarding the developments in the background system could be kept uniform and consistent. Details on the GHG emissions intensities of the background system is presented in the following chapter.

5.2. Vehicle cycle carbon intensities

The vehicle cycle of a heavy-duty lorry includes all processes connected to vehicle production, maintenance, and disposal at end-of-life (O'connell et al. 2023). In this section, the various components and materials of heavy-duty lorries are presented, followed by model assumptions on material composition and GHG intensities.

5.2.1. Vehicle components and materials

The component categories of a heavy-duty lorry can be divided into the glider, powertrain components and trailer/body. The components of the glider and powertrain for an ICEV and BEV are presented in table 17 below, based on findings in Wolff et al. (2020).

Table 17: Glider and powertrain components for ICEVs and BEVs. Based on wolff et al. (2020).

Category	**Component**	**ICEV**	**BEV**
Glider	Chassis	X	X
	Suspension	X	X
	Cab	X	X
	Tires and wheels	X	X
	Others	X	X
Powertrain components	Engine	X	
	Exhaust	X	
	Electric motor		X
	Li-ion battery		X
	Diesel tank	X	
	Transmission	X	X
	Lead-acid battery[24]	X	
	Retarder	X	X
	Others	X	X

5.2.1.1. Glider

The glider consists of supporting elements such as the chassis and suspension, as well as the driver's cabin, tyres, and wheels (Wolff et al. 2020). These components are all common between the ICEV and the BEV (Wolff et al. 2020).

The chassis/frame is the main structural component, acting as the skeleton of the vehicle, to which the suspension, powertrain, and other components are connected to (Wolff et al. 2020). The wheels are connected to the suspension, which contains springs and dampeners (Wolff et

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[24] Wolff et al. (2020) do not include a lead-acid battery for a BEV in their LCI. In the model for this study, a similar lead-acid battery was assumed for a BEV as for an ICEV based on suggestions from supervisor (Johannes Morfeldt, mail correspondence, 4 May 2023) and other sources stating that similar lead-acid batteries are used in BEVs (Chumchal and Kurzweil 2017; ILZSG SECRETARIAT 2023).

al. 2020). The cabin is the space that the driver occupies while driving and which can also act as the living and sleeping space during longer transportations (Wolff et al. 2020).

According to Wolff et al. (2020) the main materials, on a mass basis, of the glider include steel (63 %), iron (8 %), rubber (6 %) and plastics (14 %)[25]. There is also aluminium, glass, copper and paint, as well as other minor materials such as organic material, zinc and magnesium (Wolff et al. 2020).

5.2.1.2. Trailer/body

The part of the lorry containing the load is called “the body” (Bennett 2016). The body may be attached directly to the lorry, or to a trailer being pulled behind the tractor (Swedish Transport Agency 2021). There are many kinds of body types to contain the payload of the lorry, depending on the properties of goods to be transported (Hill et al. 2015).

So called “box-bodies” are common alternatives for general goods transportation, and include dry boxes, curtain-siders and reefers (European Commission 2019; Hill et al. 2015). Dry boxes have a hard shell, typically made of aluminium or steel (European Commission 2019; Hill et al. 2015). Instead of a hard shell, curtain-siders are made of fabric, which facilitate loading and offloading, supported by a skeletal upper structure on top of a platform (European Commission 2019; Hill et al. 2015). Reefers are used to transport temperature-sensitive goods, and consist of a hard, insulated shell and often with a refrigeration unit (European Commission 2019; Hill et al. 2015). Non-box bodies include flatbeds, tank bodies, container carriers, tippers, vehicle transporters and others (European Commission 2019). Flatbeds solely consist of a platform on top of the trailer and can be used to transport for instance building materials or industrial goods (European Commission 2019; Hill et al. 2015). Tank bodies are commonly used to transport liquids or gases, including dangerous goods (European Commission 2019). Tippers have an open box structure which can be lifted in the front, to easily dispose of the goods (commonly gravel, grains, or aggregate goods) (European Commission 2019; Hill et al. 2015).

Box-bodies are popular within the EU heavy-duty lorry fleet, covering 69 % of new registrations in 2016 (Rodriguez and Sharpe 2018). In 2017, the most registered body type throughout the EU countries was the curtain-sider (38.5 % of new trailers), followed by reefers (13.1 %), tippers (13 %) and closed box vans (9.6 %) (European Commission 2019). For rigid lorries, dry boxes, curtain-siders, and tippers are the most common bodies and are equally as common (17 % of the rigid lorry fleet each), whereas for articulated lorries curtain-siders are the dominating type (45 %) (Hill et al. 2015).

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[25] Percentages within parantheses are the authors’ calculations based on presented masses in Wolff et al. (2020).

5.2.1.3. Powertrain components and battery

The main components of the powertrain are the internal combustion engine (ICE) for the ICEV, and the electric machine and battery for the BEV (Wolff et al. 2020). The ICE is typically a diesel engine[26], due to its high efficiency and the higher energy density of diesel compared to petrol (Wolff et al. 2020). Electrical machines can be permanent magnet synchronous machines (PSM) or asynchronous (ASM) (Wolff et al. 2020). Other components are lead-acid battery, transmission (gearbox), retarder, exhaust system (ICEV), fuel tank[27] (ICEV), radiator (ICEV) and fluids such as engine oil, coolant etc (Wolff et al. 2020).

For an internal combustion engine, Wolff et al. (2020) identifies the main materials on a mass basis as iron (44 %), steel (29 %), aluminium (15 %), rubber (4 %) and plastic (4 %)[28]. Other minor materials are copper and oil (Wolff et al. 2020). Similarly, Wolff et al. (2020) identifies the main materials of the electric machine as steel (67 %), aluminium (22 %), copper (7 %)[29]. Other materials are iron, plastics, impregnation, neodymium, fiberglass, boron, nickel, silicone, and paint (Wolff et al. 2020).

The largest difference between vehicle cycle CO_2 emissions for BEVs and ICEVs is connected to the battery manufacturing for the BEV (O'connell et al. 2023). The battery raw materials vary depending on the type of battery utilised (International Energy Agency 2020). Today, lithium ion (li-ion) batteries dominate the electric vehicle market, with the most common battery chemistries being nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP) and nickel cobalt aluminium oxide (NCA) (International Energy Agency 2020). The corresponding market shares of these are 60 % for NMC, almost 30 % for LFP and 8 % for NCA (International Energy Agency 2023). Amongst the NMC chemistries, NMC622 and NMC822 batteries are currently favoured which can be connected to their lower cobalt contents, as compared to NMC111 and NMC333 which have equal ratios of the three substances (International Energy Agency 2023). The demand for batteries with a lower content of cobalt is tied to increasing costs, as well as ethical concerns connected to the mining process (International Energy Agency 2023). According to the IEA, the li-ion battery can be expected to continue being the major battery type over the coming decade (International Energy Agency 2020). Although, there may be concerns regarding the future supply of li-ion batteries due to scarcity of raw materials (Dunn et al. 2021). Moreover, new battery types are expected to emerge in the near future, which could include sodium-ion batteries, lithium-sulphur, lithium-metal-solide-state and lithium-air batteries (International Energy Agency 2020, 2023). Regardless, li-ion batteries are expected stay a strong contender on the market for some time to come, considering the time it takes for new technologies to go from lab-scale to large-scale deployment (International Energy Agency 2020).

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[26] Also called compression ignition (CI) engine.
[27] Not technically part of the powertrain, included as an equivalent to the BEV battery as in Wolff et al. (2020).
[28] Percentages within parantheses are the authors' calculations based on presented masses in Wolff et al. (2020).
[29] Percentages within parantheses are the authors' calculations based on presented masses in Wolff et al. (2020).

5.2.2. Estimated material demand

Based on the scalable life cycle inventory (LCI) for European heavy-duty lorries by (Wolff et al. 2020) and supplementary sources, material composition calculations were made for the baseline vehicles. According to these, the weights of steel, iron, rubber, aluminium, plastics, copper and the NMC622 battery (for BEV) cover over 95 % of the curb weights of the vehicles. The complete component and material compositions estimations and weight estimations are presented in appendix B. The results are presented in figures 28 and 29.

It should be noted that the total weights presented are the curb weights excluding the body. As presented in section 5.2.1.2, there is a large variety of bodies on the market with different weights and material composition depending on the transportation purpose. Instead of assuming a baseline body for all baseline vehicles, the body was excluded from the vehicle cycle emissions[30]. As the study aims to highlight the change of the carbon footprint by electrifying the fleet, excluding the body does not affect this change since the bodies are the same for BEVs and ICEVs.

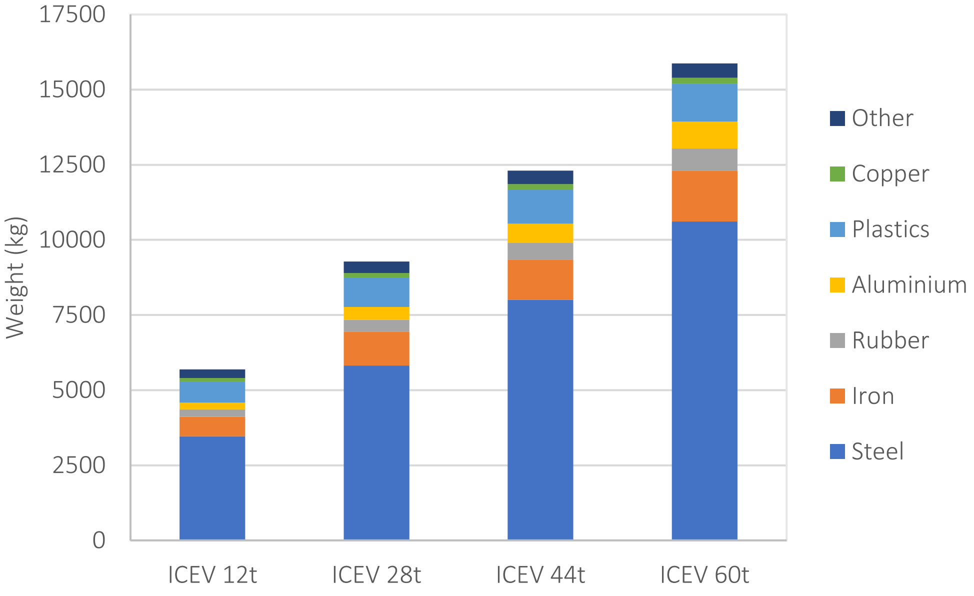

Figure 28: Material weights for each baseline ICEV.

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[30] NOTE: for the fuel cycle and tailpipe emission the GCVW is considered, thus including the weight of body.

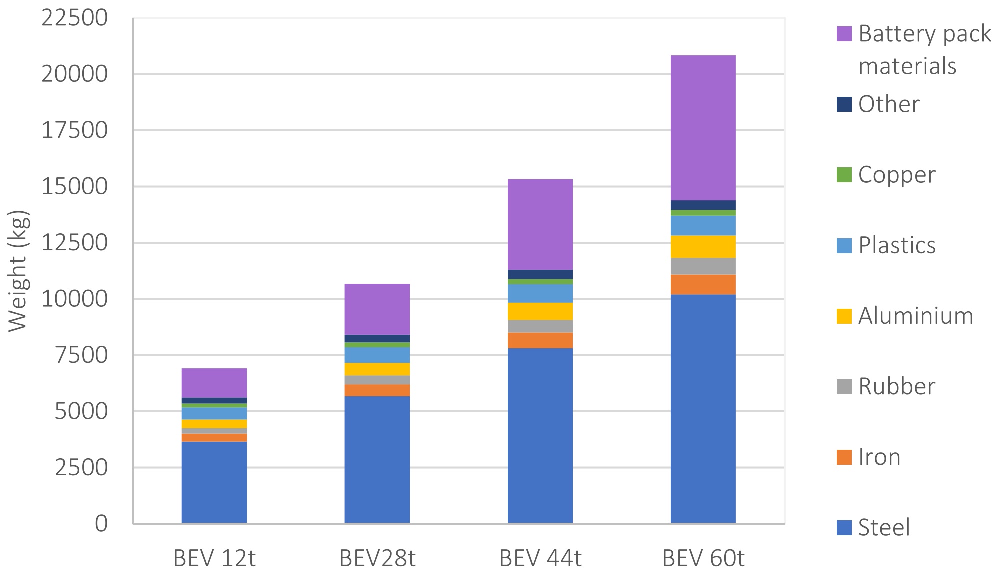

Figure 29: Material weights for each baseline BEV.

5.2.3. Model assumptions

For the vehicle cycle, the primary sources on the carbon intensities and their developments over time were the articles by Morfeldt et al. (2023, 2021). This applies to the carbon intensities for steel, iron, rubber, aluminium, plastics, copper, the NMC622 battery as well as the disassembly process. The emissions connected to the assembly were acquired from Wolff et al. (2020) and scaled based on tractor size. The assembly emissions were then assumed to decrease over time with the same intensity as the assembly process does in Morfeldt et al. (2023)[31]. For the lead-acid battery, no prospective LCA estimations on the carbon intensity were found, and as such it was kept constant over the simulation period.

The carbon intensities for the different materials and components are presented in appendix E. General information on the LCA data used for the vehicle cycle is presented in table 18 and table 19.

Table 18: Information on LCA data used for the assembly and disassembly.

Other energy usage	Location of production	Prospective LCA data Yes (Y) / No (N)	Source
Assembly	Europe	Y*[32]	Wolff et al. (2020) / Morfeldt et. al (2023, 2021)
Disassembly	Global average	Y	Morfeldt et. al (2023, 2021)

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[31] This was done as Morfeldt et al. presents assembly emissions per passenger car, not heavy-duty lorries.

[32] The emissions connected to the assembly were acquired from Wolff et al. (2020) and scaled based on vehicle size. The emissions were then assumed to decrease over time with the same intensity as in Morfeldt et al. (2023, 2021).

Table 19: Information on LCA data used for the vehicle cycle materials and components.

Material/ component	**Location of production**	**Prospective LCA Yes (Y) / No (N)**	**System boundary**	**Source**
Steel	Global average	Y	Cradle-to-grave	Morfeldt et al. (2023, 2021)
Iron	Global average	Y	Cradle-to-grave	Morfeldt et al. (2023, 2021)
Rubber	Global average	Y	Cradle-to-grave	Morfeldt et al. (2023, 2021)
Aluminium	Global average	Y	Cradle-to-grave	Morfeldt et al. (2023, 2021)
Plastics	Global average	Y	Cradle-to-grave	Morfeldt et al. (2023, 2021)
Copper	Global average	Y	Cradle-to-grave	Morfeldt et al. (2023, 2021)
Li-ion battery	Global average	Y	Cradle-to-grave	Morfeldt et al. (2023, 2021)
Lead-acid battery	Europe	N	Cradle-to-gate	Wolff et al. (2020)

Morfeldt et al. (2023, 2021) estimated the carbon intensities using GREET® 2 – Version 2019 – LCA model and adjusted the findings to suit the *Stated policies* and *sustainable development scenarios* by IEA. Global average production processes were assumed. For the stated policies scenario, current manufacturing processes were chosen which Morfeldt et al. (2021) argue makes the scenario justifiably conservative considering the difficulties in reducing emissions of these processes. For the sustainable development scenario, innovative technologies were assumed to be introduced to the market at different years, and then expanding following a logistic growth trajectory until reaching full market domination in year 2070 (Morfeldt et al. 2021).

An overview of the assumptions for the stated policies and sustainable development scenarios found in Morfeldt et al. (2021) is provided in table 20.

Table 20: Production process assumptions for stated policies and sustainable development scenarios.
Source: Morfeldt et al. (2021)

Materials & battery	**Stated policies**	**Sustainable development measures**
Steel and iron	Current processes in GREET®.	Hydrogen-based production of steel from iron ore. Replacement of fossil gas with natural gas in hot rolling and forging processes. Implementation in 2035.
Average plastics	Current processes in GREET®.	Renewable fuels in production. Implementation in 2020.
Rubber	Current processes in GREET®.	Switch to non-petroleum based synthetic rubber (biosprene produced from bacteria). Implementation in 2020.
Aluminium	Current processes in GREET®.	Use of inert anode (produces oxygen instead of CO2 in aluminium smelter). Implementation in 2025.
Copper	Current processes in GREET®.	Electrification of production. Scenario assumes increase of energy use, due to decreasing ore grade. Implementation in 2020.
NMC622 battery	Current processes in GREET®.	Electrification of heat and steam used in manufacturing. Implementation in 2020.

Based on the weights presented in section 5.2.2 and the carbon intensities for the materials and components found in literature, presented in appendix EE, the total carbon intensities for the vehicle cycle were calculated. In the following section, the assumed CO_2 emissions per produced vehicle (including production of components and assembly), disassembled vehicle, and tyre change (maintenance) are presented. In the figures, *12t*, *28t*, *44t* and *60t* refer to the assumed baseline vehicles presented in section 2.5.2.

Figures 30 and 31 display the amount of CO_2 emissions per produced baseline vehicle (i.e., excluding maintenance and disassembly) between years 2025 – 2060 for the stated policy scenario.

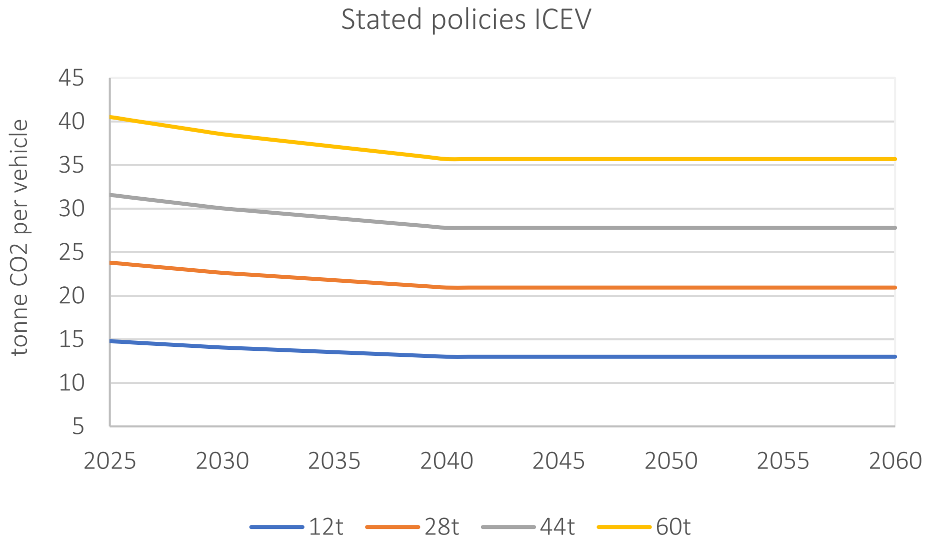

Figure 30: Stated policies CO_2 emissions per produced ICEV.

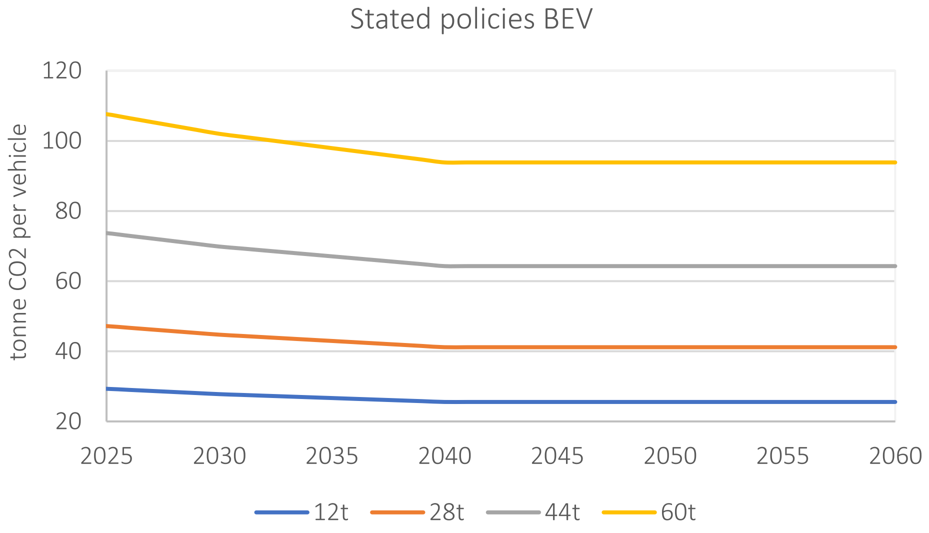

Figure 31: Stated policies CO_2 emissions per produced BEV.

Figures 32 and 33 display the amount of CO_2 emissions per produced baseline vehicle (i.e., excluding maintenance and disassembly) between years 2025 – 2060 for the sustainable development scenario.

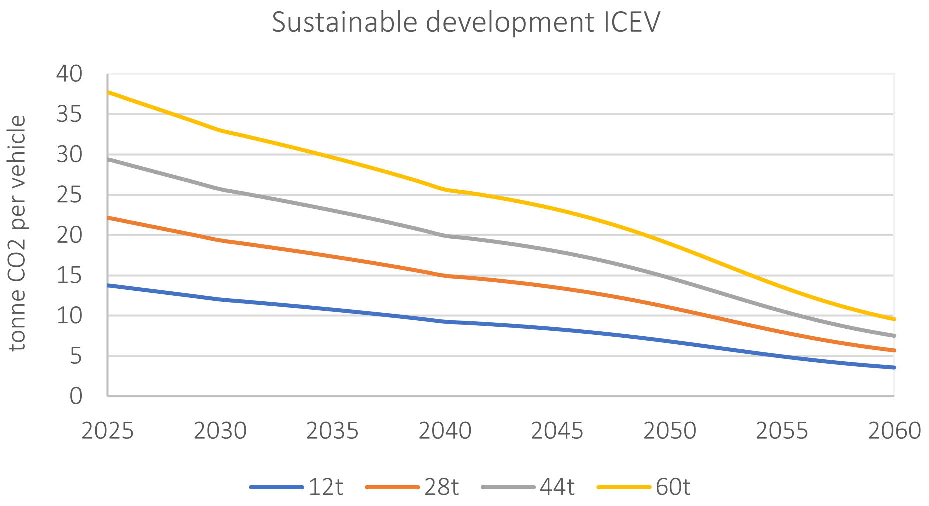

Figure 32: Sustainable development CO_2 emissions per produced ICEV.

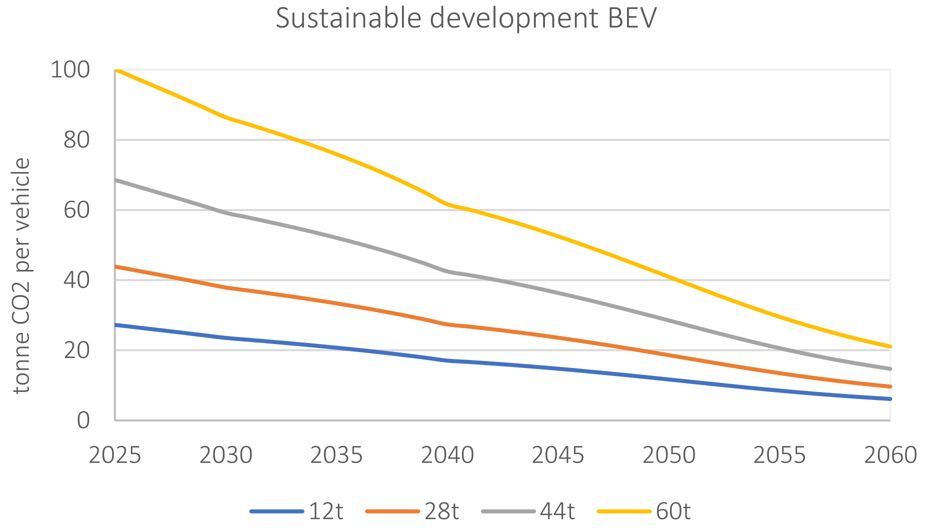

Figure 33: Sustainable development CO_2 emissions per produced BEV.

Figures 34 and 35 display the amount of CO_2 emissions per disassembled vehicle between years 2025 – 2060 for the stated policy scenario.

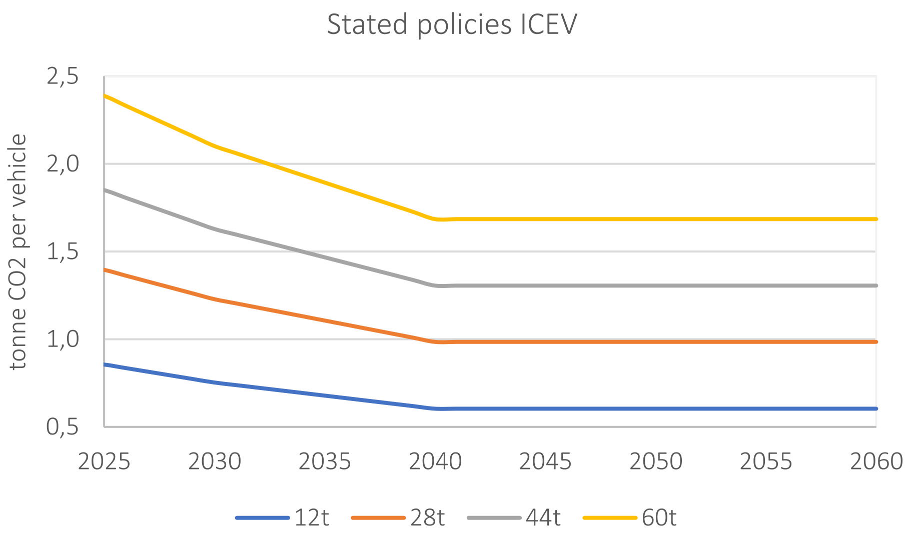

Figure 34: Stated policies CO_2 emissions per disassembled ICEV.

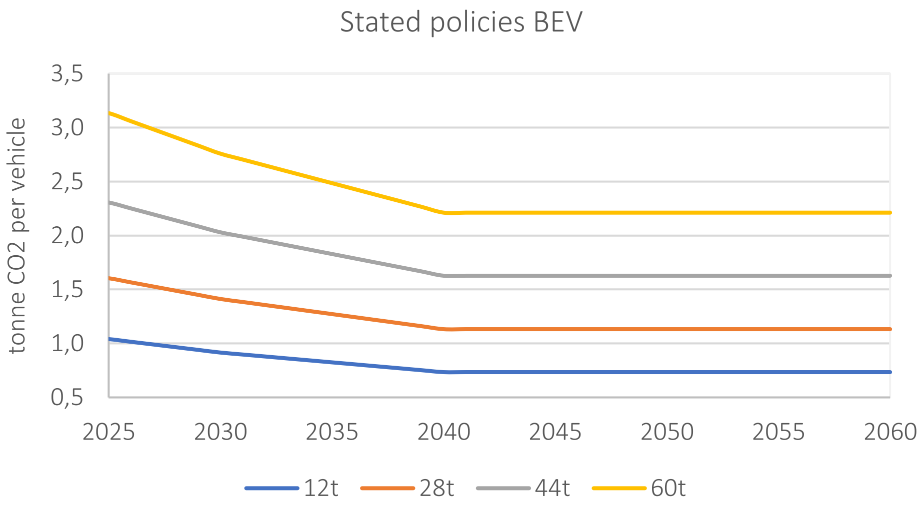

Figure 35: Stated policies CO_2 emissions per disassembled BEV.

Figures 36 and 37 display the amount of CO_2 emissions per disassembled vehicle between years 2025 – 2060 for the sustainable development scenario.

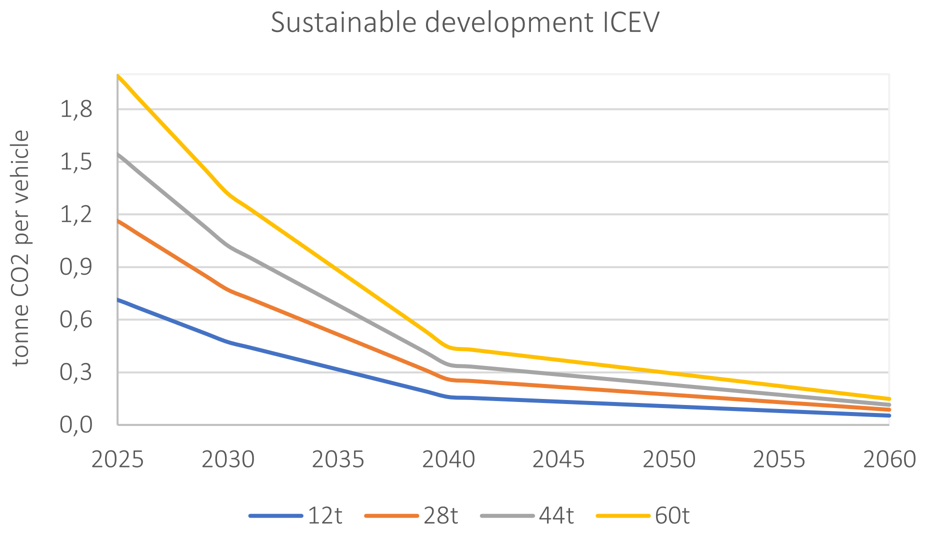

Figure 36: Sustainable development CO2 emissions per disassembled ICEV.

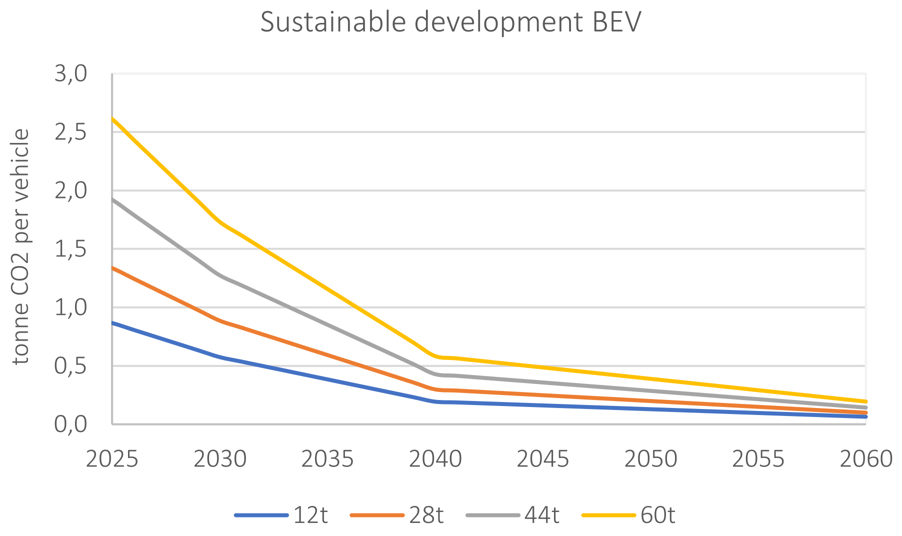

Figure 37: Sustainable development CO_2 emissions per disassembled BEV.

Figures 38 and 39 display the amount of CO_2 emissions per tyre change between years 2025 – 2060, for the stated policy scenario versus sustainable development scenario. As mentioned in section 2.4.2, two complete tyre changes are assumed in the model.

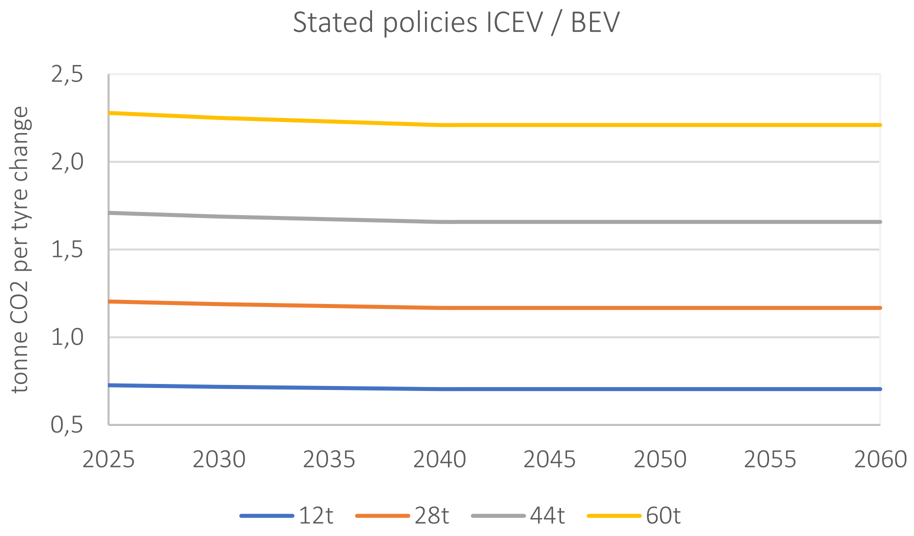

Figure 38: Stated policies.CO₂ emissions per tyre change.

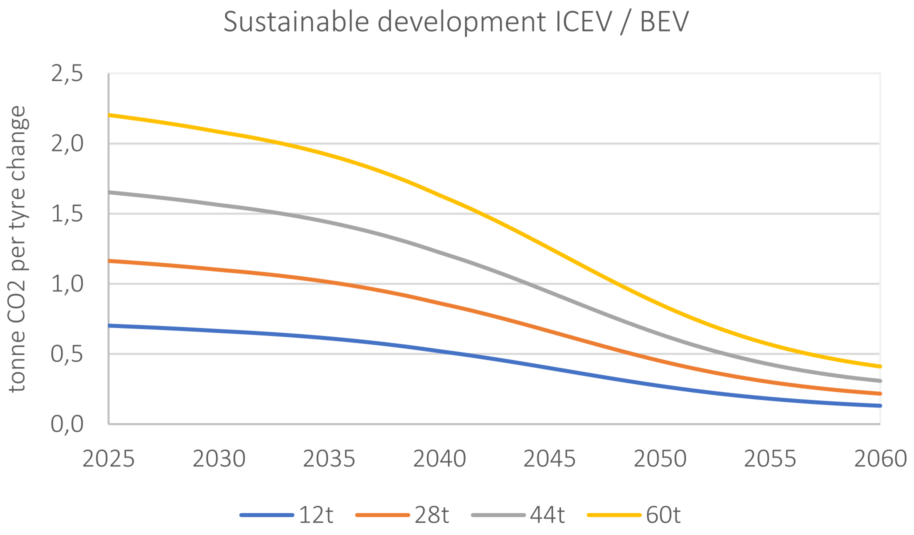

Figure 39: Sustainable development. CO₂ emissions per tyre change.

5.3. Fuel cycle carbon intensities

In this section the fuel cycle emissions intensities are investigated for fossil fuels, biofuels and electricity, followed by the resulting model assumptions.

5.3.1. Fossil fuels

The majority of diesel used in Sweden come from conventional crude oil. However, the country of origin is only known for almost half of the fossil components due to lack of reporting demand for products outside the EU (Swedish Energy Agency 2022a). Some fossil fuels are refined from crude oil in Swedish refineries and others are imported (Swedish Energy Agency 2022a).

The main findings on the fuel cycle emission intensities for fossil diesel are shown in table 21. The Swedish Energy Agency provide average well-to-wheels data for fuels used in Sweden. However, the well-to-tank data is not distinguished from tailpipe emissions and is thus not applicable to the model in this study (Swedish Energy Agency 2022a). In a study by the European commission and Joint Research Center (2020), well-to-tank values is shown to vary depending on LCA approach. The report uses a consequential approach where life cycle data for fuels in a European context (representing typical EU supply for crude oil, sea transportation, refining in the EU and average distribution and retail) is estimated by modelling a generic supply-chain, resulting in 68 gCO$_2$-eq per kWh for fossil diesel (European commission and Joint Research Center 2020). The majority of the emissions (approximately 96 %) are connected to the crude oil production and refining while the transportation to market comprises around 4 % (European commission and Joint Research Center 2020). In the study, the result is compared to literature findings of values based on an attributional approach where average data from real supply chains is used, showing 39 gCO2-eq per kWh for fossil diesel (European commission and Joint Research Center 2020). Additional reviews on emissions allocated to refining show a range from 12 to 24 gCO2-eq per kWh (European commission and Joint Research Center 2020). The consequential approach is advised to be used in policy context, whereas an attributional approach is more suitable for carbon footprint and GHG intensity estimations due to its employment of average data (European commission and Joint Research Center 2020).

A global life cycle average for crude oil production and refining for 2019 is estimated to 62.9 gCO2-eq per kWh by Morfeldt et al. (2023, 2021) based on previous research with extensive data collection (Jing et al. 2020, Masnadi et al. 2018). The GHG emissions for crude oil production was based on almost 800 sources and include exploration, drilling and development, production and extraction, surface processing, and transport to the refinery inlet (Masnadi et al. 2018). The data for refining was based on 478 refineries situated in 83 countries, representing 343 different crude oil processes (Jing et al. 2020).

Table 21: Litterateur findings for the fossil diesel fuel cycle emission intensity.

Fuel cycle emission intensity (gCO2-eq/kWh)	**Source**
39.0 – 68.0	(European commission and Joint Research Center 2020)
62.9	(Morfeldt et al. 2023, 2021)

5.3.2. Biofuels

Due to the domination of diesel within the heavy-duty fleet, as mentioned in the background chapter, life cycle assessments for biofuels are based on biodiesel.

Biodiesel use in Sweden comprised around 76 % HVO and 24 % FAME in 2020 (further details are found in the background chapter) (Swedish Energy Agency 2022a). FAME is mainly produced from rapeseed. However, during the past years use of other vegetable oils, such as cooking and sunflower oil, has slowly increased (Swedish Energy Agency 2022a). HVO is mainly produced from animal fat originating from slaughterhouse and food industry waste. Other raw materials are raw tall oil, a by-product from paper and pulp industry, rapeseed and palm oil (Swedish Energy Agency 2022a). Previously, PFAD, which is a processing residue from palm oil production, constituted a large proportion of the raw materials for HVO (almost half of the raw materials in 2018), but has drastically decreased to a few percentages in 2021 (Swedish Energy Agency 2022a). This could be explained by the implementation of a new regulation in 2019, which classifies PFAD as a co-product instead of a by-product from palm oil production which entails stricter demand of product origin tracing. In addition, the greenhouse gas reduction mandate was updated in 2021 with sustainability criteria stating that bio components from production with high risk of indirect land use change (ILUC) are not allowed to be included in the mandate (Swedish Energy Agency 2022a). Regarding origin, the raw material supply for HVO originating from Sweden was approximately 10 % in 2021, 60 % from the rest of EU, and the remaining shares had a world-wide origin (Swedish Energy Agency 2022a). The origin of raw material for FAME is widespread, where Swedish supply contributed to approximately 4 % in 2021 and the EU approximately 40 % (Swedish Energy Agency 2022a). Thus, around half of the supply is from outside the EU, with Australia and Canada representing 18 % and 12 %, respectively (Swedish Energy Agency 2022a).

Every year, the Swedish Energy Agency provides well-to-wheels data for all Swedish fuels in the transport sector (Swedish Energy Agency 2021a). For biofuels that fulfil sustainability criteria, the tailpipe emissions are zero and consequently the well-to-wheels values represent well-to-tank (Swedish Energy Agency 2021a). An average value for each type of fuel is presented based on data for each product from every supplier (Swedish Energy Agency 2021a). For biodiesel the resulting LCA-data for HVO and FAME in 2021 were 6.2 and 22.9 gCO_2-eq per MJ, respectively (Swedish Energy Agency 2022a). This estimation of GHG emissions is conducted according to the Swedish implementation of the European parliament’s directive (EU) 2018/2001 (Directive (EU) 2018/2001 n.d.; Swedish Energy Agency 2021a). The calculation method includes production, extraction, processing, alteration of carbon reservoirs, transportation, and distribution, as well as life cycle data for products and processes used in the production chain for the fuel (Swedish Energy Agency 2021b). The GHG emissions from manufacturing of machinery and equipment are not included (Swedish Energy Agency 2021b).

5.3.3. Electricity for charging

The Swedish domestic electricity generation in 2020 consisted of 45 % hydro power, 29 % nuclear power and 17 % wind power, and the remaining production came from methods such as solar power and combined heat and power plants (Swedish Energy Agency 2023a). Electricity is also imported and exported throughout the year, with a resulting net export the past decade (Swedish Energy Agency 2023a).

Calculations by The Swedish Energy Agency state that the emission factor for the Swedish electricity mix[33] is 26 gCO2-eq per kWh for the low-voltage grid (Swedish Energy Agency 2023e). These estimations are based on a methodology developed by the European commission's Joint Research Center, and considered GHG emissions are carbon dioxide, CO_2, methane, CH_4 and nitrous oxide N_2O (SWECO 2021). The method considers upstream GHG emission and energy consumption for fuel supply to power plant, combustion emissions, and distribution losses from power plant to the low-voltage grid (GHG emissions generated from power plant and grid construction, maintenance and decommissioning are not included) (SWECO 2021). The result is then verified against other studies (SWECO 2021). To account for GHG emissions connected to infrastructure, Morfeldt et al. (2023, 2021) estimated current and future GHG emissions connected to infrastructure for electricity production and distribution. The resulting emissions were estimated to be 17.7 and 15.2 gCO_2-eq per kWh in 2023 for stated policies and sustainable development, respectively (Morfeldt et al. 2023, 2021). A decrease of 48 % and 67 % until 2045 was then applied to the respective scenario, followed by an additional reduction of 4 % and 55 % until 2060 (Morfeldt et al. 2023, 2021).

5.3.4. Model assumptions

Due to uncertainties of country of origin and large variations in GHG emissions specified for diesel production, the global average of 62.9 gCO2-eq per kWh from crude oil production and refining is used for the model. The prospective scenario for fossil diesel is assumed to remain constant in stated policies. For sustainable development the refining process is estimated undergo mitigation measures to reduce the GHG emissions by 50 % until 2070, a development assumed by Morfeldt et al. (2023, 2021). The reduction is expected to follow a logistic curve, which is argued to represent the market introduction of a new technology well, ultimately reaching 50.8 gCO_2-eq per kWh in 2060 (Morfeldt et al. 2023, 2021). The assumed carbon intensity developments for the fuel cycle of fossil diesel are displayed in figure 40.

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[33] The geographic boundary is Sweden although GHG emission originating from import and export of electricity are considered based on gross trade (SWECO 2021).

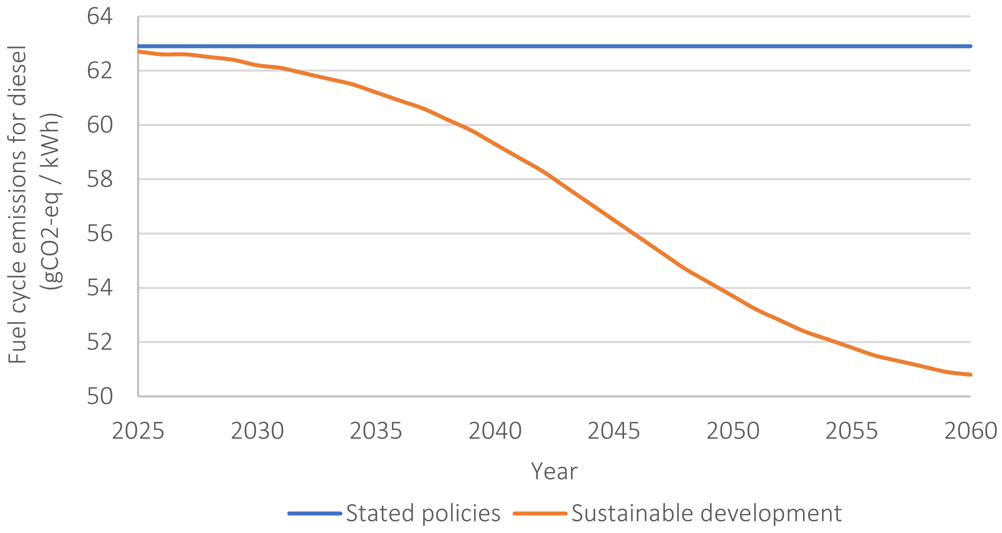

Figure 40: Background system development for fuel cycle emissions from fossil diesel.

For biodiesel, a weighted average value of 32.6 gCO_2-eq per kWh was calculated in this study, based on data for HVO and FAME (Swedish Energy Agency 2022a). For stated policies, the value is assumed to remain constant until 2060. For sustainable development, Fischer-Tropsch diesel is assumed to replace current biodiesel and the market introduction is assumed to follow a logistic curve, a scenario created by Morfeldt et al. (2023, 2021). Thereby, the carbon intensity decreases to 18 gCO_2-eq per kWh in 2070 (Morfeldt et al. 2023, 2021). The assumed carbon intensity developments for the fuel cycle of biodiesel are displayed in figure 41.

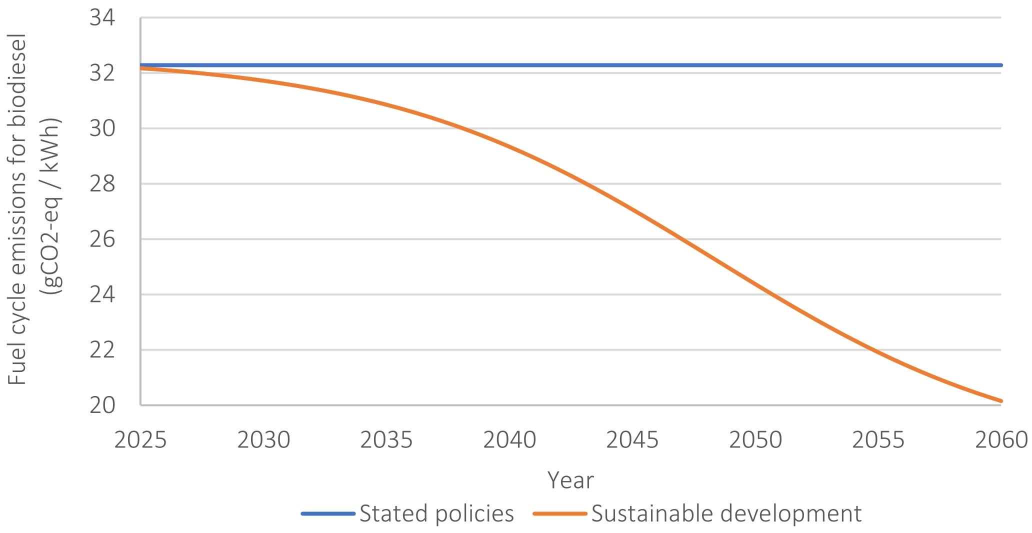

Figure 41: Background system development for fuel cycle emissions from biodiesel.

Since the aim of the study is to investigate transport within Swedish borders by Swedish-registered heavy-duty lorries, BEVs are assumed to be charged from the Swedish low-voltage grid. Emissions connected to the Swedish electricity mix, i.e., 26 gCO_2-eq per kWh, is assumed to decrease linearly to zero in 2045 in accordance with Swedish climate law (Klimat- och näringslivsdepartementet 2017). The same assumption is applied to both background scenarios since the law is in line with both stated policies and sustainable development. To account for the additional GHG emissions connected to infrastructure, data from Morfeldt et al. (2023, 2021) for the two background scenarios are added. The resulting carbon intensity developments assumed for the fuel cycle of electricity for charging are displayed in figure 42.

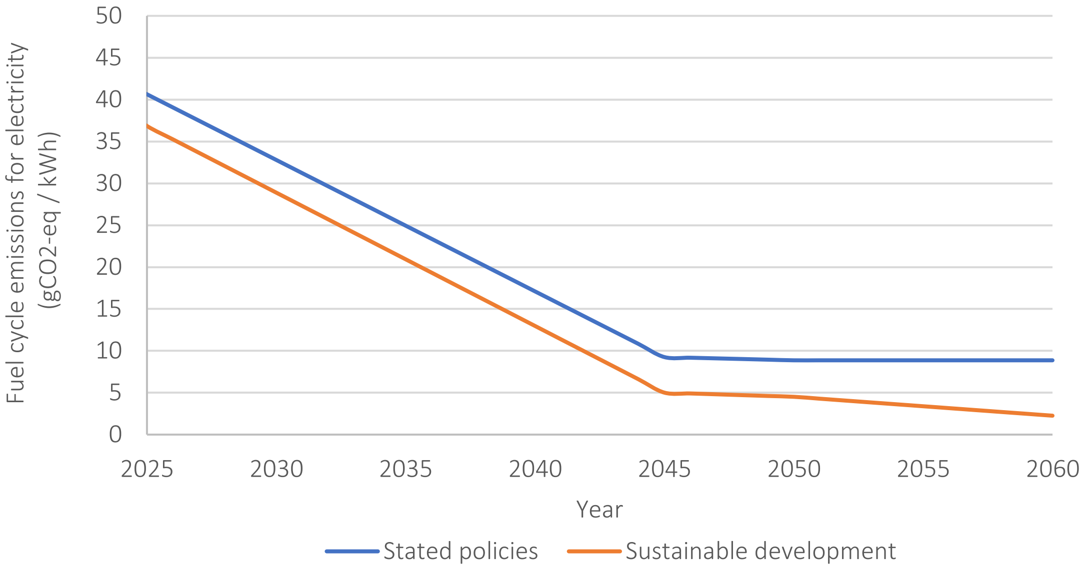

Figure 42: Background system development for fuel cycle emissions from electricity.

6. Simulation results and analysis

In this chapter an overview of the chosen scenarios and sensitivity analysis cases are presented, followed by the resulting simulation outputs.

6.1. Overview of main scenarios

Four main simulation scenarios denoted A, B, C and D were formulated based on the model assumptions in chapters 4 and 5. These are presented in table 22. In the foreground system the expansion of BEVs is represented by a low and a high electrification rate, defined as the share of sold BEVs each year, as presented in section 4.1.1. The background system has two scenarios. Firstly, *Stated policies*, which represents low global climate change mitigation ambitions. Secondly, *Sustainable development*, which represents high global climate change ambitions. These are based in the model assumptions presented in chapter 5.

Table 22: Main scenarios presentation

MAIN SCENARIOS	**FOREGROUND SYSTEM** *ELECTRIFICATION RATE*	**BACKGROUND SYSTEM** *GLOBAL CLIMATE CHANGE MITIGATION AMBITIONS*
A) Low electrification rate Low climate change mitigation ambitions	Low	Stated policies
B) High electrification rate, Low climate change mitigation ambitions	High	Stated policies
C) Low electrification rate, High climate change mitigation ambitions	Low	Sustainable development
D) High electrification rate, High climate change mitigation ambitions	High	Sustainable development

General assumptions for the foreground system are presented in table 23. These are mutual for all main scenarios. For the vehicle activity demand, the main scenario used is as presented in section 4.3.3. The biofuel use is assumed to develop according to the main scenario presented in section 4.2.1. The weight class distribution is based on the literature findings presented in section 2.5.4.

Table 23: General assumptions for foreground system.

ASSUMPTIONS: FOREGROUND SYSTEM	
Transport demand	Vehicle activity prognosis by The Swedish Energy Agency
Biofuel use	Original legislated national policy until 2030[34]
Weight class distribution	Estimations by VTI and constant shares over time

General assumptions for the background system are presented in table 24. These are mutual for all main scenarios. Details on model assumptions for the vehicle cycle emission are found in section 5.2.3 and fuel cycle emissions in section 5.3.4.

Table 24. General assumptions for background system.

ASSUMPTIONS: BACKGROUND SYSTEM	
Vehicle and fuel production	Global production[35]
Electricity consumption for BEVs	Average Swedish grid mix

6.2. Overview of sensitivity analysis

Sensitivity analysis cases were formulated to consider uncertainties in parameters stated in table 25. Each parameter has a high and a low case in addition to the main scenarios. As explained in section 4.3.3, the transport demand is adjusted with ± 20 % year in 2050 as compared to the main scenario, to account for uncertainties in the future prognosis. Biofuel scenarios are formulated for a low and a high case to capture the range of political ambitions mentioned in section 4.2. The weight class distribution is shifted to a larger share of lighter lorries in the low case, and heavier lorries in the high case, see section 2.5.4 for details.

Table 25: Sensitivity analyses.

PARAMETER	**SENSITIVITY CASE**	
	LOW	*HIGH*
Transport demand	-20 %	+20 %
Biofuel usage	EU: minimum levels	100 % biodiesel by 2040
Weight class distribution	Lighter fleet	Heavier fleet

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[34] Original legislation refers to a scenario where the legislated reduction mandate is resumed in 2024, following the pause issued in 2022.

[35] Except for lead-acid battery production and vehicle assembly where European production was assumed, as explained in section 5.2.3.

6.3. Simulation results & analysis

In this section, the simulation results of the main scenarios are presented and analysed. Firstly, the total annual emissions are shown, followed by the annual emissions from the vehicle cycle, fuel cycle and tailpipe separately. Moreover, the fuel and electricity demand are presented, as well as the battery capacity demand for BEVs.

6.3.1. Total emissions

The annual total emissions (vehicle cycle, fuel cycle and tailpipe emissions) for the main scenarios are displayed in figure 43. In table 26, the annual total emissions for each scenario year 2025, 2045 and 2060 are presented.

Between years 2025 – 2045, the emissions reduce between 52 – 79 % depending on scenario. Until year 2060, the corresponding reductions are between 56 – 92 %. During the entire simulation period, Scenario A generates the highest emissions and D the lowest, with an increasing difference over time that reaches about 0.9 million tonnes CO_2-eq in 2060. Scenario C yields the second highest emissions until 2054, when it replaces scenario B as the second lowest emission scenario. As such, the high electrification scenarios (B and D) yield lower emissions than the low electrification scenarios (A and C) regardless of background scenario during almost the entire timespan, until year 2054. At that point, the emissions reductions have already stagnated for scenario B and begin to increase, whereas the emissions for the other scenarios keep decreasing over the entire timespan. Consequently, a higher electrification rate of the fleet generally yields higher carbon emissions reductions than the assumed climate change mitigation scenarios in the background system - until around year 2054.

Table 26: Total emissions from main scenarios 2025, 2045 and 2060.

	Annual total emissions per scenario (Million tonnes CO_2-eq)			
Year	***A***	***B***	***C***	***D***
2025	2.5	2.4	2.5	2.4
2045	1.2	0.8	1.0	0.5
2060	1.1	0.8	0.6	0.2

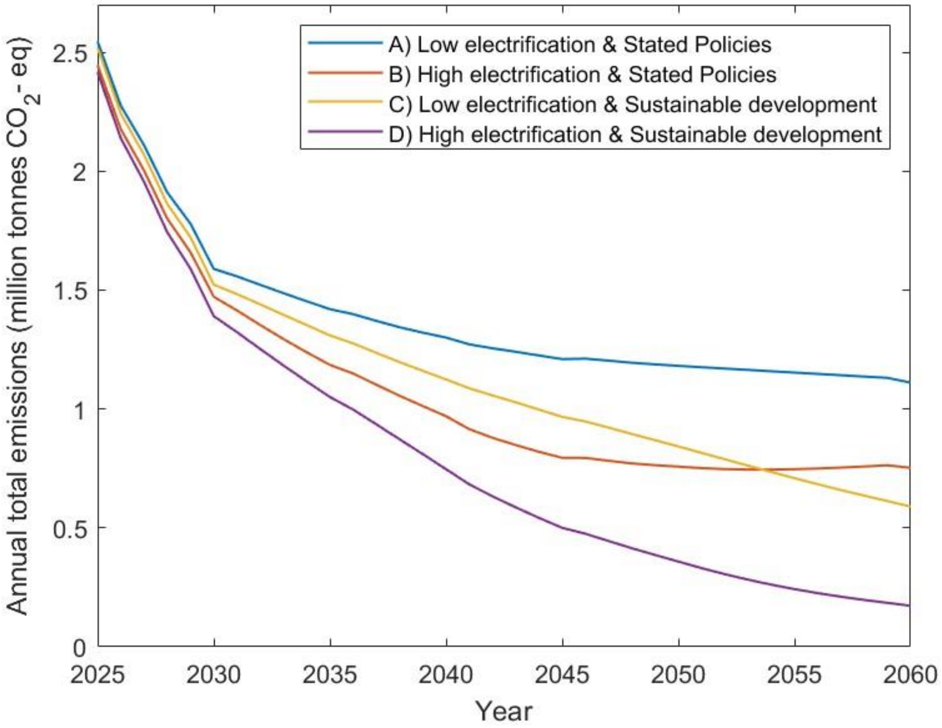

Figure 43: Annual total emissions for main scenarios 2025-2060.

The emissions reductions for scenario B have stagnated already year 2051. This development could be explained by a few factors. Firstly, the transport demand (vehicle activity) is assumed to increase throughout the entire simulation period. As the annual driving distance per vehicle age remain constant in the model, an increasing number of new vehicles needs to be produced in order to meet the transport demand. Therefore, it is possible that the energy demand for the vehicles increases, which affect fuel cycle and tailpipe emissions, and that the vehicle cycle emissions increase due to more vehicles being produces. However, as will be shown in in the next sections, the only cycle with increasing emissions over time is the vehicle cycles in the stated policies scenario, which means that the only increase in carbon emissions can be attributed to the vehicle cycle with stated policies as background scenarios. Secondly, the vehicle cycle emissions are dependent on the electrification rate due to the higher emission intensity for BEVs than ICEVs. In scenario B, the electrification rate reaches 100 % in year 2050 (all new sales are BEVs). Due to the high electrification of new sales during the years prior to 2050, the entire fleet constitute of 100 % BEVs shortly thereafter. Consequently, as the transport demand continue to increase, the emission reductions that can be attributed to replacing ICEVs with BEVs is outweighed by the increase in emissions from the vehicle cycle in the stated policies scenario which results in the increase in emission from 2051 onwards in scenario B.

The results also highlight the effect of the biofuel share. As can be seen, the inclination of the emissions reductions decreases after year 2030, which can be explained by the stagnation of drop-in shares of biofuels from 2030 and onwards.

6.3.2. Vehicle cycle emissions

The vehicle cycle emissions are displayed in figure 44 for the main scenarios. In table 27 the vehicle cycle emissions for year 2025, 2045 and 2060 is presented.

Scenario C (low electrification and sustainable development) results in the lowest emissions, whereas scenario B (high electrification and stated policies) results in the highest. The stated policy scenarios (A and B) result in an increase of emissions over time while the emissions in the sustainable development scenarios (C and D) begin to decrease from around 2037. The higher electrification rates yield higher emissions compared to the lower electrification rates, for the same background scenarios.

In scenario A (low electrification and stated policies) and B (high electrification and stated policies) the emissions increase with 81 % and 103 %, respectively, between 2025 and 2060. In contrast, the emission in scenarios C (low electrification and sustainable development) and D (high electrification and sustainable development) decrease with 53 % and 52 % respectively, between 2025 and 2060.

Table 27: Annual vehicle cycle emissions for the main scenarios in 2025, 2045 and 2060.

	Annual vehicle cycle emissions per scenario (Million tonnes CO_2-eq)			
Year	***A***	***B***	***C***	***D***
2025	0.32	0.35	0.30	0.33
2045	0.47	0.60	0.27	0.34
2060	0.58	0.71	0.14	0.16

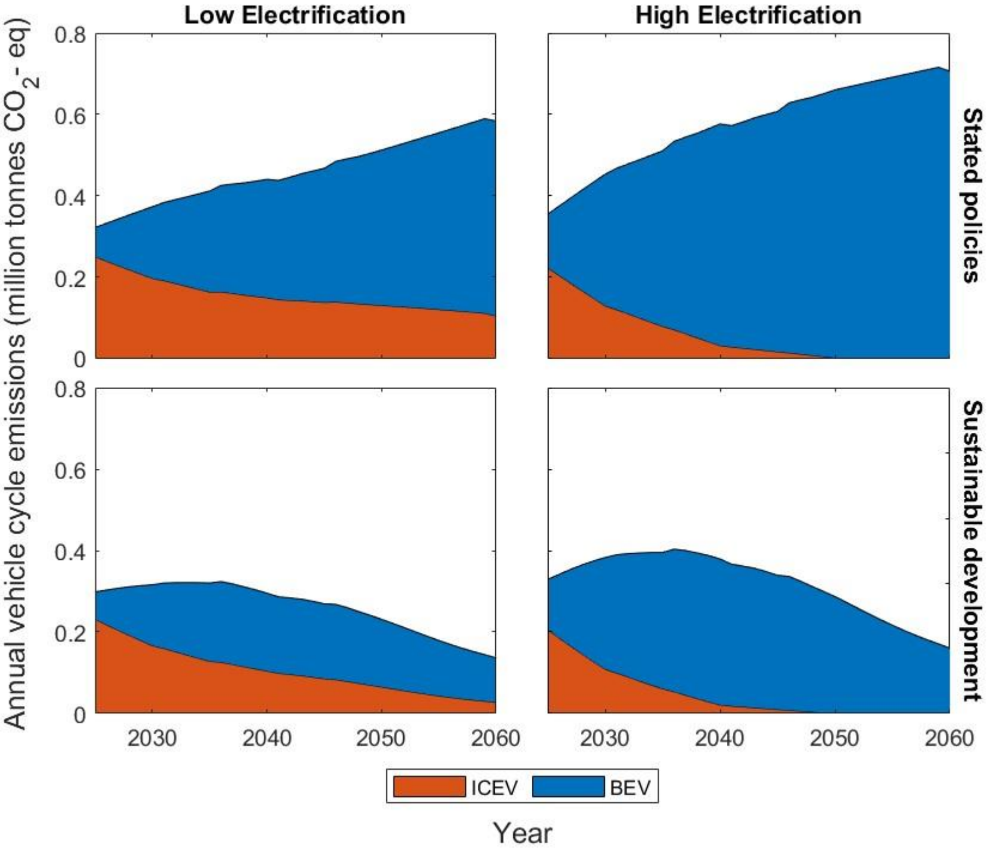

Figure 44:Annual vehicle cycle emissions for main scenarios 2025 – 2060.

For the sustainable development scenarios, the vehicle cycle emissions start to decrease at around year 2037 and continue to decrease throughout the time period despite the increasing number of new vehicles being produced (due to the increased transport demand). For the stated policies scenarios, the emissions instead increase steadily over the simulation period. As such, the results highlight the impact that the background system has on the carbon footprint of the vehicle cycle. The results also highlight the higher emissions connected to BEVs compared to ICEVs, as seen when comparing the high electrification scenarios to the low ones.

By comparing the vehicle cycle emissions with the total emissions in 2045 (the year that the fleet should have net zero emissions according to the national climate target) it is observed that around 40 % of the emissions stem from the vehicle cycle in scenario A), 70 % in scenario B), 25 % in scenario C) and around 70 % in scenario D). The vehicle cycle contributes to a larger share of the total carbon footprint in the high electrification scenarios, regardless of background system scenario. While the larger shares in the high electrification scenarios can be attributed lower fuel cycle and tailpipe emissions (as is suggested by the total emission results since the total emissions generally decrease over time, and will be shown in the following sections), this reflects that climate change mitigation measures of the vehicle cycle are of more concern for a predominately battery electric fleet.

It should be noted that the same average payload was assumed for BEVs and ICEVs in the simulations despite the potentially lower load capacity of BEVs, due to their higher curb weights. Therefore, BEVs are assumed to have higher load factors (gross load/load capacity) than ICEVs. Consequently, for a specific transport distance, the load transported by a BEV is assumed to match the load transported by an ICEV. In practice, more BEVs might be required to transport the same load as ICEVs, unless 1) the lower load capacities of BEVs are compensated by higher load factors[36] or 2) the battery weight reduces due to increased energy density, which would increase the load capacity. Consequently, in practice the vehicle cycle emissions connected to BEVs might be somewhat higher than estimated, as more BEVs might have to be produced to cover the same freight activity as ICEVs.

Moreover, the battery constitutes a significant portion of the vehicle cycle emissions of the BEV. Of the emissions that are connected to production of the vehicle (i.e., excluding disassembly and maintenance), the battery constitutes to between 46 – 64 % of the emissions, depending on the weight of the baseline vehicle, over the simulated time period in the stated policies scenario, and 40 – 64 % in the sustainable development scenario. Therefore, the potential need for battery replacement during the vehicle lifespan would have a significant impact on the vehicle cycle emissions for a BEV. The recycling and reuse potentials of batteries are also not considered in the model, which could lower the emissions due to decreased raw material demand. Consequently, important factors to consider that might affect the vehicle cycle emissions are the evolution of specific energies (Wh/kg) of BEV batteries, potential shifts in material composition due to lightweighting measures, potential need to replace the battery and future battery recycling possibilities.

6.3.3. Fuel cycle emissions

The fuel cycle emissions are displayed in figure 45Figure 45 for the main scenarios. In table 28 the annual fuel cycle emissions for year 2025, 2045, 2060 are presented for all main scenarios.

The emissions continuously decrease over the entire timespan in all scenarios, where scenario D (high electrification and sustainable development) results in the lowest and scenario A (low electrification and stated policies) the highest emissions. The high electrification scenarios, in B and D, consistently yield lower emissions than scenario A and C with low electrification. In all scenarios a low influence of the different background scenarios can be observed, with an accentuating impact from 2045 and onwards.

Emission reductions between 2025 – 2060 are 66 % for scenario A (low electrification and stated policies), 93 % in scenario B (high electrification and stated policies), 78 % in scenario C (low electrification and sustainable development) and 98 % in scenario D (high electrification and sustainable development).

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[36] Could be acquired through higher transport efficiencies due to route optimisations etc. However, this kind of improvement would likely apply to both ICEVs and BEVs, not just the latter - in which case, a difference in capacity remains.

Table 28: Annual fuel cycle emissions for the main scenarios in 2025, 2045 and 2060.

Year	Annual fuel cycle emissions per scenario (Million tonnes CO_2-eq) *A*	*B*	*C*	*D*
2025	0.58	0.55	0.58	0.55
2045	0.27	0.09	0.23	0.07
2060	0.20	0.04	0.13	0.01

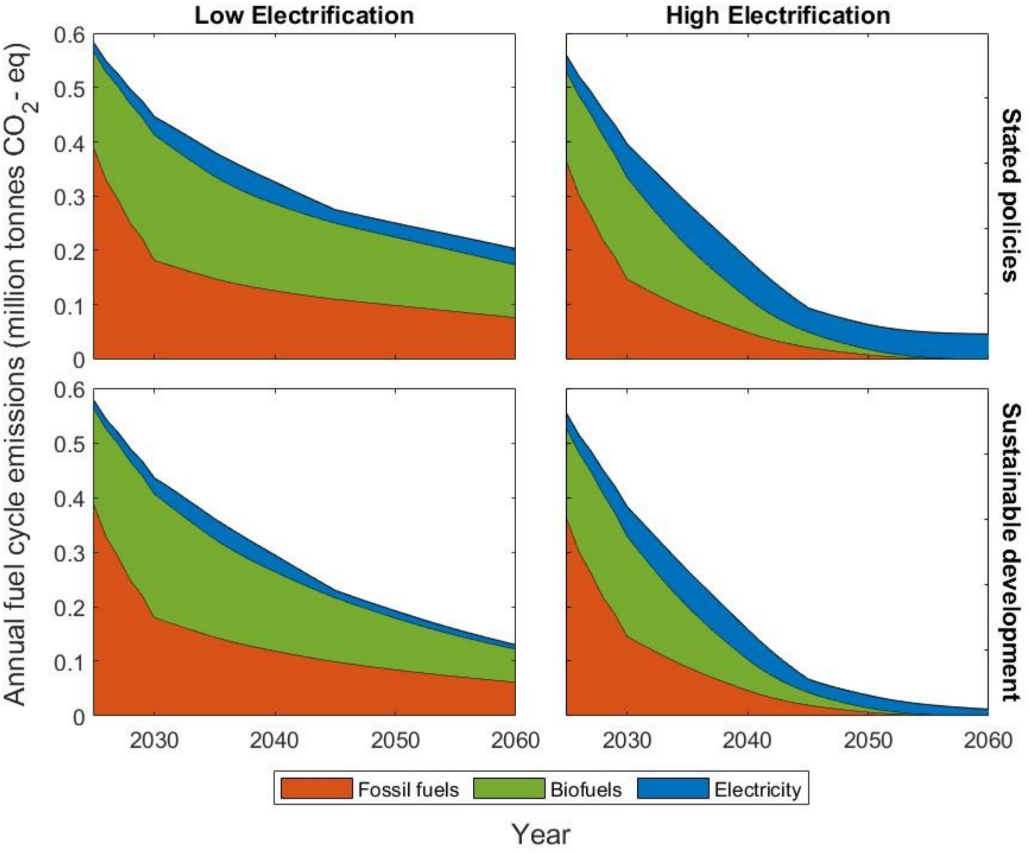

Figure 45: Annual fuel cycle emissions 2025 – 2060.

The continuous decrease in emissions over time despite the increasing transport demand can be explained by 1) the decrease in specific energy consumption over time as well as differences between ICEVs and BEVs and 2) the difference in fuel cycle emission intensities between the energy carriers.

The specific energy consumption for all baseline vehicles in the model, both ICEVs and BEVs, is assumed to decrease over time due to technology improvements, regardless of scenarios in the fore- and background systems. Consequently, the new sales of the fleet require less fuel or electricity for propulsion than the existing lorries, which continuously lowers the energy demand of the fleet and thereby the carbon footprint of the fuel cycle. Furthermore, the model's baseline BEVs have on average 55 % lower specific energy consumption than the ICEVs, thus the electrification rate also contributes to the lower energy demand, resulting in overall lower fuel cycle emissions.

The electrification rate shifts the fleet’s energy demand from liquid fuels to electricity as more BEVs are introduced to the fleet, and the fossil fuel cycle emission intensity is assumed to be higher than for electricity. Therefore, in combination with the lower specific energy consumption for BEVs as compared to ICEVs, a higher electrification rate yields lower fuel cycle emissions than a low electrification rate. In addition, the fuel use for ICEVs is altered by the biofuel scenario since the drop-in levels increases until 2030, and thereafter stagnates. Consequently, the lower fuel cycle emission intensity for biofuels compared to fossil fuels also contributes to the overall emission reductions.

In the high electrification scenarios, a difference in the resulting emissions attributed to electricity is observed between the background scenarios from 2045 onwards. This could be explained by the fleet being almost fully electrified and thus mainly dependent on electricity, followed by assumptions in the electricity fuel cycle where the emissions in sustainable development are assumed to decrease more rapidly after 2045 than in stated policies, where the emission reduction stagnates in 2050. In the low electrification scenarios, the emissions connected to all fuel cycles show a larger decrease in sustainable development than stated policies after 2045. This could be explained by the fleet not being fully electrified and thus still dependent on ICEVs running on biofuels and fossil fuels. Thereby, the assumptions in their fuel cycles, with a continuous decrease in emission for sustainable development and stagnation in stated policies, impact the resulting carbon footprint.

The fuel cycle’s contribution to the total emissions (vehicle cycle, fuel cycle and tailpipe) is around 20 % in 2025, developing to approximately 24 % in scenario A), 12 % in scenario B), 25 % in scenario C) and 16 % in scenario D) in 2045. Thus, the lowest contribution occurs in the scenarios with high electrification and vice versa. This indicates that a high electrification rate could reduce the impact of the fuel cycle on the total emissions over time, regardless of background scenario.

6.3.4. Tailpipe emissions

Annual tailpipe emissions of the fleet are shown in figure 46. As the background system has no impact on these emissions, the results are presented for the electrification scenarios only.

The low electrification scenario generates a higher amount of tailpipe emissions than the high scenario, and the difference between them increases over time, particularly after year 2030. Both electrification scenarios show a rapid decrease until 2030 followed by a slower decline rate.

The tailpipe emissions in 2025 are 1.6 and 1.5 million tonnes CO_2-eq in the low and high scenario, decreasing to 0.47 and 0.09 in 2045. In 2060 the low electrification scenario yields

0.32 million tonnes CO_2-eq, while the high electrification scenario almost intersects the y-axis as only 400 tonnes are emitted. Thus, the tailpipe emission reductions from 2025 to 2045 are 70 % and 94 % for the low and high electrification scenario, respectively. For the whole simulation period the decrease in emissions is 80 % for the low electrification scenario while almost a 100 % decrease is reached in the high electrification scenario.

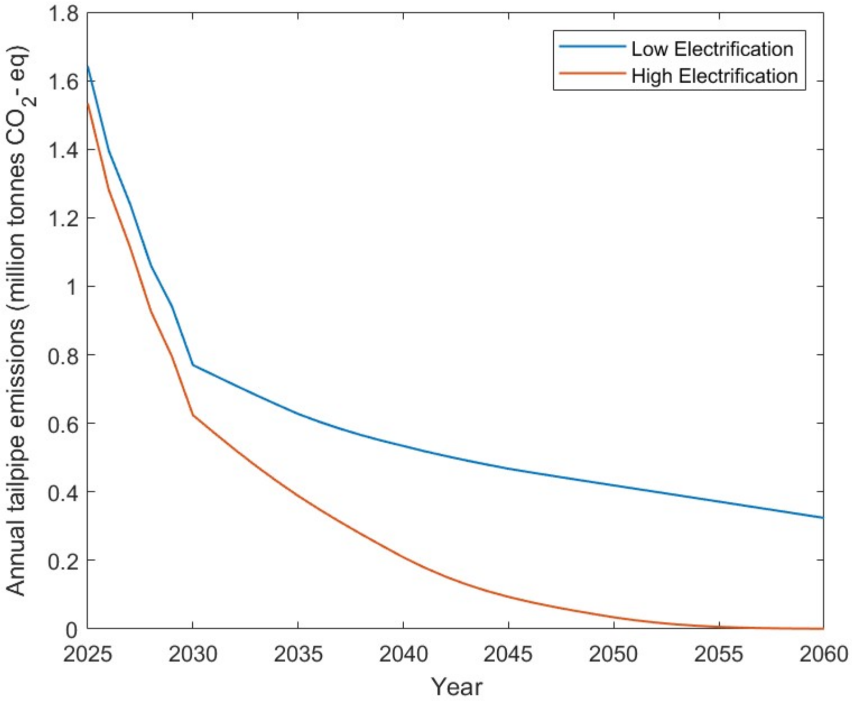

Figure 46: Annual tailpipe emissions 2025 – 2060.

The large reduction in tailpipe emissions over the timespan is connected to 1) differences in exhaust emissions depending on powertrain and use of energy carrier, and 2) decrease of specific energy consumption over time and the difference between BEVs and ICEVS, where the latter is explained in the previous section.

There are no tailpipe emissions from BEVs. Therefore, the electrification rate has a signification effect on the exhaust emissions as each ICEV being replaced with a BEV reduces the tailpipe emissions to zero. This is particularly evident from 2030 and onwards when the biofuel share is held constant, and the high electrification scenario continuously yields lower emissions than the low electrification scenario. In addition, the emission factor for biofuels is considered zero in the model. Therefore, an increase in biofuel use reduces the fossil fuel use in ICEVs and lowers the resulting tailpipe emissions. This explains the observed rapid emission reduction until 2030 as the biofuel scenario increases the drop-in levels until this year before it is held constant for the remaining period of the simulation.

The contribution of the tailpipe emissions to the total emissions (vehicle cycle, fuel cycle and tailpipe emissions) is around 62 % in 2025, decreasing to 40 % in scenario A), 12 % in scenario B), 50 % in scenario C) and 20 % in scenario D) in 2045. Thus, the tailpipe emissions in the high electrification scenarios are less dominant in the total carbon footprint over time, in contrast to low electrifications scenarios where it constitutes up to half of the total emissions in 2045.

6.3.5. Energy demand for vehicle propulsion

The energy demand for propulsion of the lorries in the fleet is presented in figure 47. In table 29 the energy demand for year 2025, 2045, 2060 are presented for all main scenarios. The demand is not affected by the background systems, therefore only the electrification scenarios are shown. The overall energy demand of the fleet is 12.1 and 11.6 TWh in 2025 for the low and high electrification scenarios, respectively. In 2060, these numbers have decreased to 6.8 and 4.2 TWh, respectively. This corresponds to an overall decrease of 43 % and 64 % for the low and high electrification scenarios.

In the low and high electrification scenarios the biofuel demand increases from 2025 until 2030 when it reaches its peak at 7 and 5.8 TWh, respectively. After 2030 the demand decreases in both scenarios, but with a higher decline rate in the high electrification scenario than the low. In 2060 the biofuel demand reaches 3 TWh in the low electrification scenario whereas in the high scenario the demand reaches zero around 2055.

The fossil fuel demand decreases by 53 % and 60 % between 2025 and 2030 in the low and high electrification scenarios, respectively. Thereafter, the decline rate is lower resulting in an overall demand reduction of 80 % and almost 100 % between 2025 and 2060 in the low and high electrification scenarios. In the high scenario the demand reaches zero around 2055.

The electricity demand continuously increases in both electrification scenarios. In the low electrification scenario, more than a six-fold increase of the demand is achieved between 2025 and 2060, while a slightly lower increase is observed in the high electrification scenario.

Table 29: Annual fuel and electricity demand for the main scenarios in year 2025, 2030 and 2060. Low and high refers to low electrification scenario vs high electrification scenario.

Year	**Annual fuel and electricity demand (TWh)**					
	Fossil fuels		***Biofuels***		***Electricity***	
	Low	*High*	*Low*	*High*	*Low*	*High*
2025	6.2	5.8	5.5	5.1	0.4	0.7
2030	2.9	2.3	7	5.8	1.0	1.9
2060	1.2	0.0	3	0.0	2.6	4.2

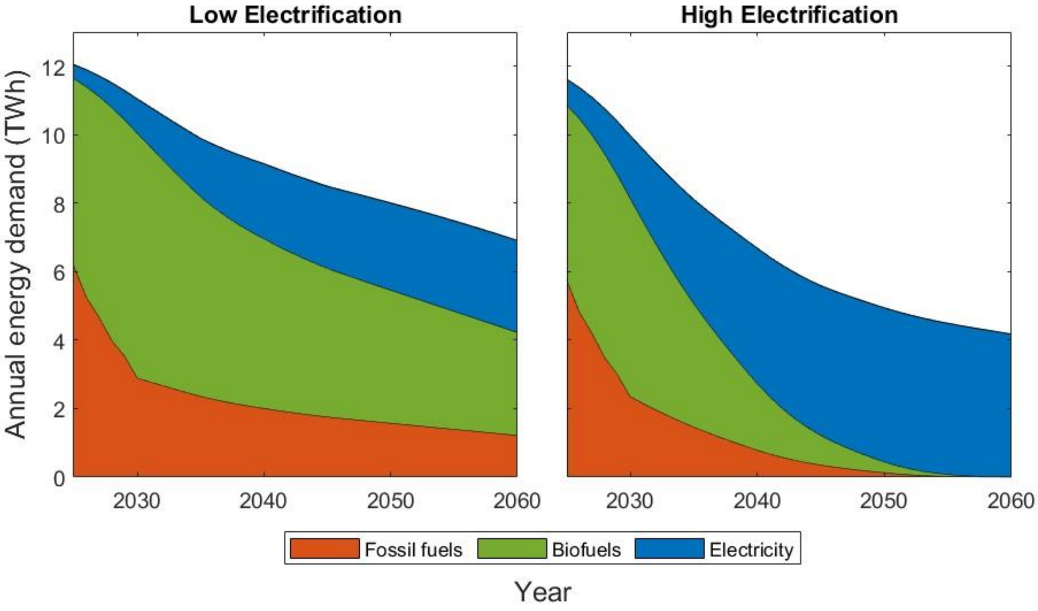

Figure 47: Annual fuel and energy demand for vehicle propulsion 2025 – 2060.

The total energy demand of the fleet decreases throughout the entire time period despite the increase in transport demand. This could be explained by two factors: 1) the specific energy consumption (in kWh/km) is on average 55 % lower[37] for BEVs than for ICEVs and 2) the energy efficiencies for both BEVs and ICEVs are assumed to decrease over time due to technology improvements. The difference in specific energy consumption between BEVs and ICEVs also explains the overall lower energy demand in the high electrification scenario compared to the low, since more BEVs are introduced to the fleet. This is further explained in the analysis of the fuel cycle emission.

The increase in electricity demand is explained by the increased introduction of BEVs into the fleet. In the high electrification scenario the fleet is fully electrified around 2055 which explains the zero fossil and biofuel demand at the same year, whereas full electrification is never reached in the low scenario and thus the fleet still has a demand of fossil and biofuels. The rapid increase in biofuel demand, and corresponding decrease of fossil fuel demand, until 2030 is due the influence of the biofuel scenario, as previously mentioned.

6.3.6. Battery capacity and material demand

The annual battery capacity demand connected to the production of BEVs is presented in figure 48. Since the background systems do not impact the battery demand, the result is shown for the electrification scenarios.

Between years 2025 and 2060, the annual demand increases from around 0.6 GWh to 4.4 GWh in the low electrification scenario and 1.1 GWh to 6.5 GWh in the high electrification scenario. As such, the annual demand for battery capacities is 48 % higher for the high electrification

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[37] An average based on the specific energy consumption for the baseline vehicles in the model from 2023-2060.

scenario than the low in 2060. In 2030 and 2045 demand in the higher electrification scenario is about 88 % and 77 % higher, respectively, than in the low electrification.

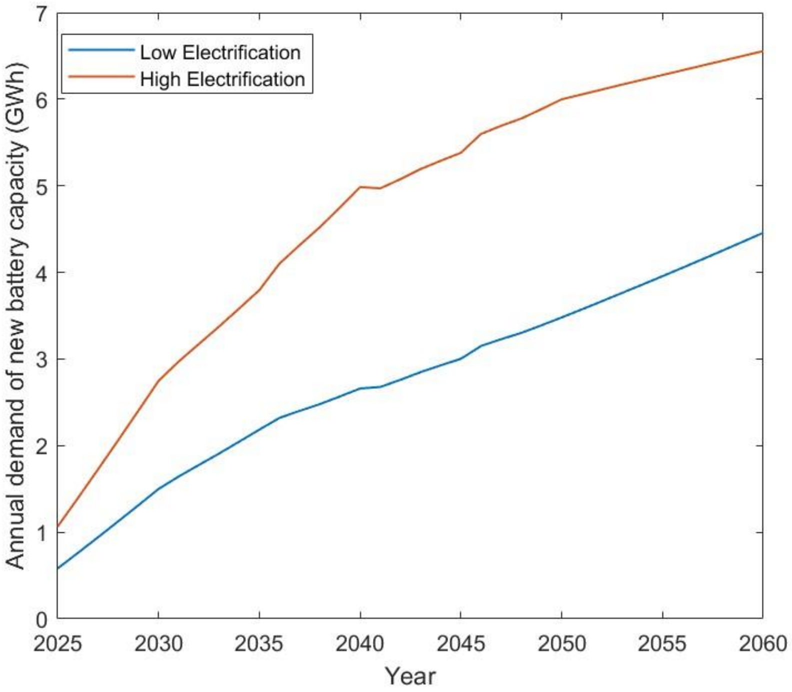

Figure 48: Annual demand of battery capacity for new BEVs 2025 – 2060.

The results depend on the estimated number of batteries produced each year, and their corresponding capacities. These are determined by the annual production of BEVs, the assumed battery capacities per baseline vehicle, and the weight distribution (which governs the number of vehicles produced in each weight group). As such, the results are heavily dependent on the assumed battery capacities which range between 200 kWh – 1000 kWh, as well as the weight distribution.

An increased demand of battery capacity involves a higher demand of critical materials, but an analysis of this was outside of the scope of this study. However, based on literature findings of material data for a NMC622 li-ion battery from Dunn et al. (2021), an estimation of the potential future demand of critical material was made which can be seen in appendix H.

6.4. Sensitivity analysis

In this section the simulation results from the sensitivity analysis are presented.

6.4.1. Transport demand

Annual total emissions for varying transport demands are shown in figure 49. The absolute differences in emissions between the main scenario and sensitivity cases increase over time for the low electrification scenarios, A and C, as well as the high electrification and stated policies scenario, B. In the high electrification and sustainable development scenario, D, the differences between the main scenario and sensitivity cases increase until year 2037 and then decrease for the remainder of the period.

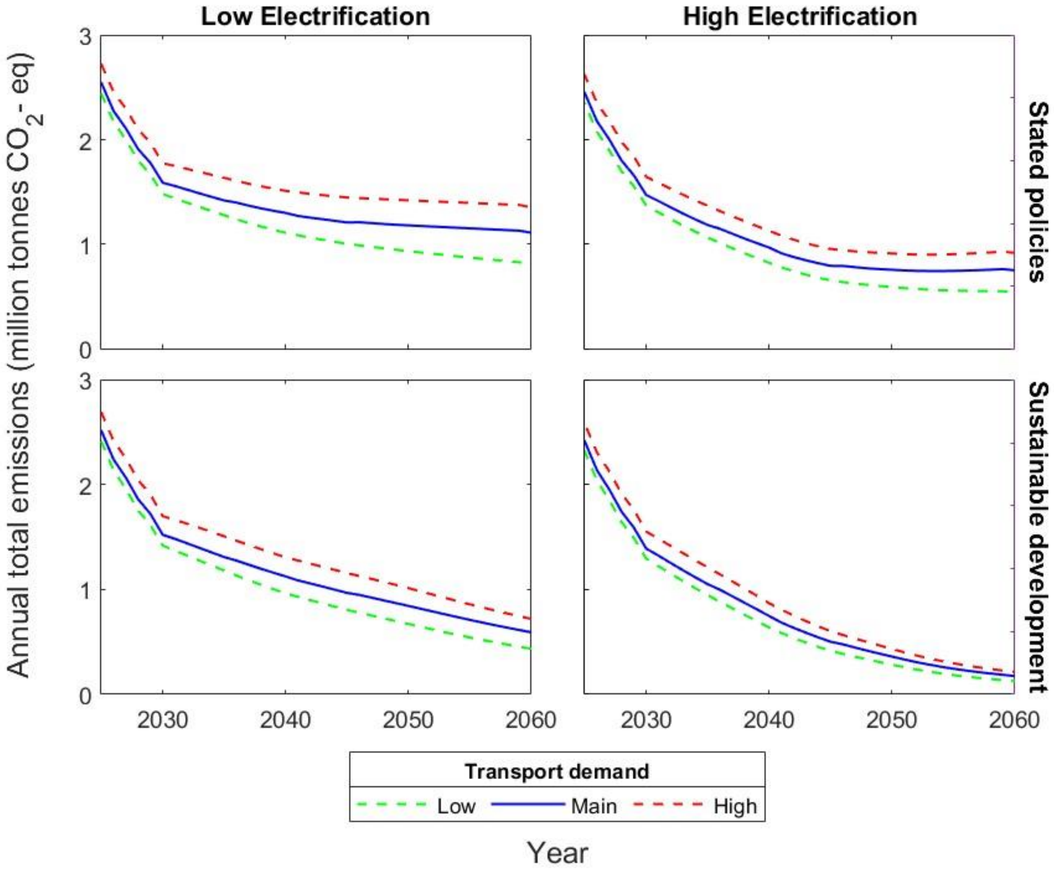

Figure 49: Annual fleet emissions for sensitivity scenarios of transport demand 2025 – 2060.

To recap, the sensitivity cases were created by assuming ± 20 % vehicle activity in 2050 as compared to the main scenario, and then assuming a linear increase until 2060. Meanwhile, the base year for the vehicle activity estimations was year 2018, which means that at the start year of the simulations (year 2025), the differences in transport demand between the main scenario and sensitivity cases are relatively small. Therefore, the differences in total emissions at this point in time are also relatively small.

Over time, the difference in transport demand increases between the main scenario and sensitivity cases. Since the transport demand influences the number of new sales, a higher transport demand in the model results in more vehicles[38], and a lower demand in fewer vehicles. The relation between transport demand and new sales explains the continuous increased differences in emissions between the main scenario and sensitivity cases for scenario A, B and C. However, for scenario D the differences in total emissions decrease post year 2037, despite

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[38] An increase in vehicle demand due to higher transport demands could be mitigated through transport efficiency measures, for instance by increasing the load per transport. However, this was not considered in the model.

increased differences in transport demand. As such, for a fleet with a high portion of electrified vehicles and ambitious climate change mitigation measures in the background system, the impact of the transport demand on the emissions decrease.

6.4.2. Share of biofuels

Annual total emissions for different shares of biofuel use are shown in figure 50. The low biofuel case has a significant impact on the total emissions until 2030 for all scenarios, while the high biofuel case shows a small deviation from the main scenarios. For the low electrification scenarios, the low biofuel case continues to have a large effect on the carbon footprint during the entire simulation period, whereas the high biofuel case shows an increased impact from year 2030 to 2040 and then decreases slightly until 2060. For the high electrification scenarios, the high biofuel case has similar emissions as the main biofuel scenario during the majority of the simulation period. During years 2030 – 2040, the difference temporarily increases.

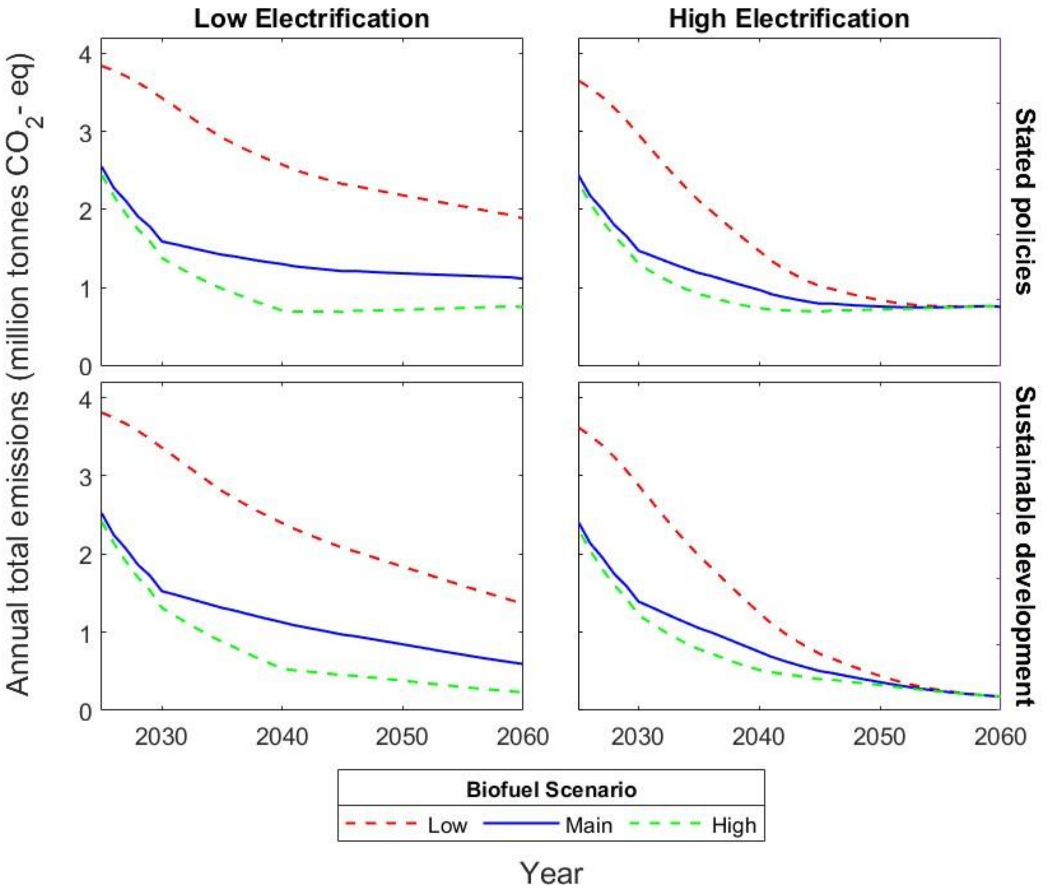

Figure 50: Annual fleet emissions for sensitivity scenarios of biofuels 2025 – 2060.

The low biofuel case has a large impact on the low electrification scenarios, as a higher share of the fleet consists of ICEVs, than in the high electrification scenarios. This explains the higher deviations from the main biofuel scenario seen for low electrification.

For the sustainable development scenarios, the high biofuel scenario result in more or less the same amount of emissions for both high electrification and low electrification. This can be explained by that both biofuels and electricity are assumed to have zero tailpipe emissions, while the vehicle cycle emissions are higher in the high electrification case (vehicle cycle emission are higher for BEVs than ICEVs) and the fuel cycle emissions are higher in a low electrification case.

6.4.3. Weight class distribution

The annual fleet emissions for different weight class distributions are shown in figure 51. It is important to note that, since the weight distributions are based on shares of vehicle kilometres per weight class (% of vkm), changing the distribution also leads to a change in freight activity (tkm) of the fleet. This will be discussed below in the analysis.

A heavier fleet can be seen to increase the emissions slightly, and a lighter fleet results in somewhat lower emissions. However, shifting the weight compositions does not show a significant effect on the total carbon footprint of the fleet. The largest observation is seen in scenario A, while the lowest in seen in scenario D. For the sustainable development scenarios, the differences between the main scenario and high and low case moves towards zero during the simulation period.

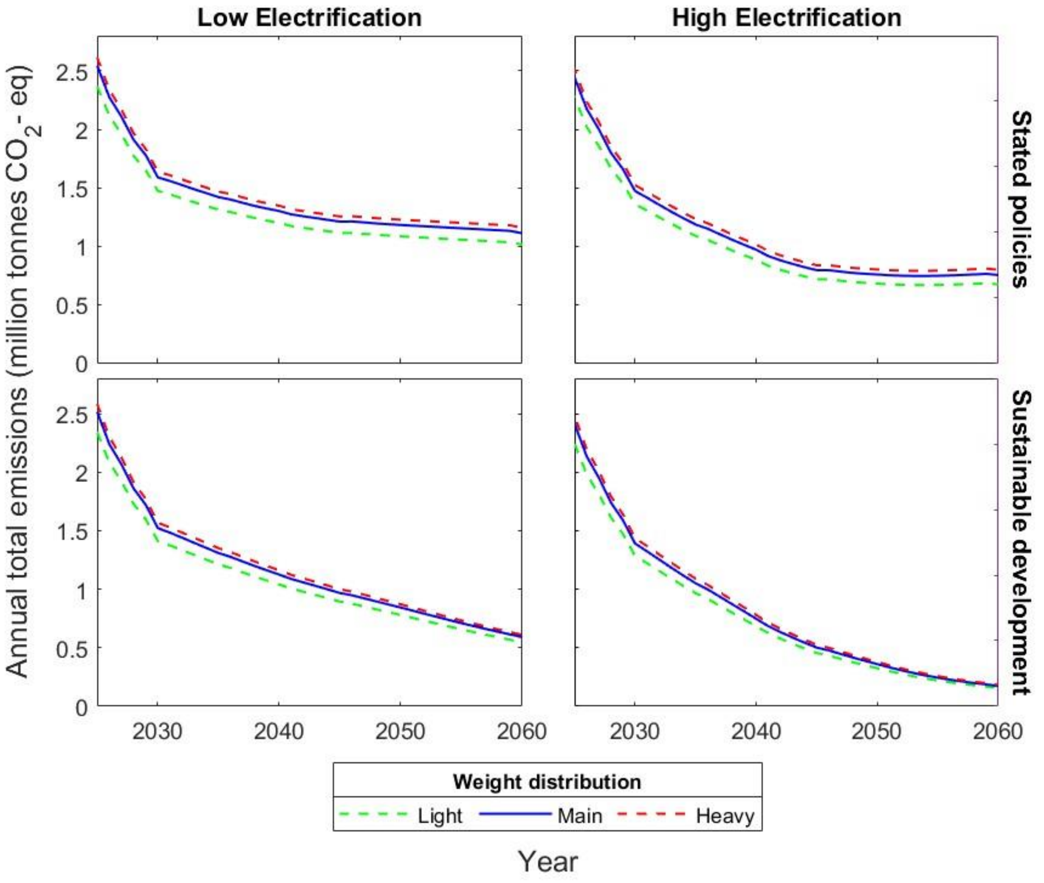

Figure 51: Annual fleet emissions for sensitivity scenarios of weight class distribution 2025 – 2060.

Since the lighter distribution consists of lighter lorries, the emissions from the vehicle cycle should be lower for this scenario, which is consistent with the results. Likewise, the heavier distribution consists of heavier lorries, with higher vehicle cycle emissions. Moreover, the fuel/electricity consumption is higher for heavier lorries, and lower for lighter ones. However, the differences between the main, low and high scenario are quite modest. This could be explained by that the overall changes in the weight distribution sensitivity analysis are not large enough to have a significant impact on a fleet basis.

What needs to be considered is that the model is based on vehicle activity, with added average loads and as such the main, low and high scenarios do not represent the same freight activity. For instance, in year 2040 the main case has a freight activity of 47 billion tkm, the low case 40 billion tkm (- 15 %) and the high case 50 billion tkm (+ 6 %). Consequently, to achieve the same freight activity as the main scenario, the high scenario would need fewer lorries. This would decrease the emissions. On the other hand, the low scenario would need more lorries to achieve the same freight activity, which would increase the emissions. This reasoning suggests that the differences in emissions between the scenarios should be smaller than shown in the results. By this logic, it is also possible that a very light fleet would have higher emissions than a corresponding heavier fleet, although that is not possible to conclude from this sensitivity analysis[39]. To reach a conclusion, a parameter matching the fleet towards freight activity, and not only vehicle activity, would have to be implemented in the model.

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[39] This would also depend on the load factors for the different vehicles, which in this study are assumed the same for all lorries,

7. Discussion and conclusion

In this chapter the research questions are discussed based on the findings in chapters 4 and 5, as well as the presented simulation results and analysis in chapter 6, followed by conclusions. Lastly, potential improvements and suggestions for future research are presented.

7.1. Design of long-term scenarios

Research question 1: How can long-term scenarios be formulated to describe shifts in Sweden's heavy-duty lorry fleet composition and size?

Long-term scenarios for the Swedish heavy-duty lorry fleet were designed by reviewing literature (primarily prognoses and reports by authorities, research articles and policy) and using the prospective LCA methodology presented in section 2.2. The most interesting parameters to investigate in scenarios, with regards to the development of the fleet, were decided to be the electrification rate, biofuel share and transport demand. These parameters are discussed below, based on the findings in chapter 4.

While the number of electrified heavy-duty lorries on the road is currently limited, the literature reviewed in chapter 4 suggests that electrification of the heavy-duty lorry fleet is necessary to achieve the national climate goals and could take off in the coming years. The findings also suggests that electrification should be prioritised over biofuels, to achieve the transition towards a fossil-free fleet. The potential developments for long-term electrification, presented in section 4.1.1, translates into an increasingly larger share of BEVs over time in the simulations. However, electrification also include the potential expansion of PHEVs and FCEVs. Therefore, in practice the estimated shares allocated to BEVs in the electrification scenario should also include these alternative electrification pathways (although literature suggests that the expansion of FCEVs lies further ahead in time). Moreover, the findings point towards that electrification would not occur evenly distributed across the fleet, as assumed in the simulations. Instead, lorries predominantly covering short distance transports are likely to be electrified prior to longer distance transports. Similarly, heavier lorry segments could be expected to be electrified later than lighter segments. Another important factor to consider with regards to the chosen electrification scenarios is the need for infrastructure development. While the electrification scenarios were primarily based on prognoses by vehicle manufacturers and governmental scenarios considering this to varying degrees, investigating the need for infrastructure development that these scenarios would incur was beyond the scope of this study. As proper infrastructure is a prerequisite to achieve a wide-scale expansion of BEVs, the plausibility of the selected scenarios should be further investigated.

Regarding the biofuel shares in diesel, reviewed in section 4.2, the future is especially uncertain. One the one hand, the mandate for emission reductions for liquid fuels has been in action since 2018 and reports by authorities claim that it is essential in reaching the milestone climate target for the transport sector in 2030, and suggest increased shares for 2030 onwards. On the other hand, the mandate is currently paused at the 2022 levels and there are suggestions to lower the mandated reductions. One such possibility could be that the mandate is lowered to the EU minimum levels, which is the assumption for the low case of the biofuel share sensitivity analysis. If the reduction levels would be resumed according to current legislation, there are still uncertainties associated with the main biofuel scenario in the model due to the current limitations imposed by fuel quality legislations and standards, that could restrict the share of biofuels possible to mix with fossil diesel. Moreover, the required amount of biodiesel raises concerns about security of supply and the indirect land use change impact of biodiesel. One important aspect to consider is Sweden's ambition to act as a role-model for other countries in their own transitions towards fossil free transport sectors. As mentioned, Sweden uses almost 1/3 of the global supply of HVO, which raises the questions: 1) if Sweden was to increase the reductions in the mandate, would the supply of biofuels be able to increase to cover the demand, and 2) would the supply be enough for other countries also trying to decarbonise their transport sector? These questions are not covered by this study, but need to be considered as they point to uncertainties in the future amount of biofuels used by heavy-duty lorries. In future research, the estimated energy consumption of biofuels in this study could be utilised to investigate the plausibility of such a development with regards to supply concerns. Moreover, this study focused solely on biofuels. In a further development of the model, it would be desirable to also implement other renewable fuels, for instance electro-fuels, which could act as alternatives to biofuels. However, as mentioned in section 3.6.2, vehicles using electro-fuels require between 5 – 6 times more electricity than directly electrified vehicles such as BEVs.

The literature findings suggest that the transport demand is one of the primary drivers impacting emissions for heavy-duty transport. As mentioned, the development of the transport demand of the fleet is dependent on the economic development and, as for the other scenario parameters, there are significant uncertainties tied to the long time period of the simulation. The vehicle activity of the Swedish heavy-duty lorry fleet, in the unit vehicle kilometres, was found to be a suitable measure of the transport demand. However, the energy consumption of the lorries was found to be dependent on lorry weight, and as such average loads were assumed for each baseline vehicle. Aside from uncertainties regarding the total vehicle activity of the fleet, there are uncertainties regarding the relative share that is supplied by Swedish-registered lorries as opposed to by foreign ones. It is possible that this share may change over time, whereas it was kept constant in the model. A constant share was assumed to make the results over time more comparable - for instance, had the shares of the vehicle activity supplied by foreign lorries been assumed to rise over the time period, this would lower the emissions by Swedish lorries as they would carry out a smaller share of transports within Swedish borders. Moreover, potential future transport efficiency measures would affect the transport demand, which was not investigated in the study. For instance, route optimisation measures leading to higher load factors (i.e., transports would be filled with goods to a higher degree) could decrease the overall distances covered by the fleet. To account for potential transport efficiency measures, the model would have to be based on freight activity, rather than vehicle activity, to match the lower distances resulting from efficiency improvements with higher loads.

Conclusively, BEVs are a promising pathway towards decarbonisation of heavy-duty lorry transport and the expansion of these vehicles could take off in the near future. As such, scenarios for different electrification rates are a suitable way to consider a shift of the fleet's composition. The future of biofuels is uncertain due to the paused mandate on emission reductions for liquid fuels and the announced reduced levels. Meanwhile, some actors claim that the mandate is crucial to reach the milestone climate target in 2030. As such, the uncertainty of the mandate is important to consider when creating scenarios – for instance by utilising sensitivity analysis. Prognoses on future vehicle activities can be suitable to act as basis for formulating scenarios of the transport demand. However, the impact of varying loads should be considered when estimating the carbon footprint, to capture variances in the energy consumption. Lastly, when formulating long-term scenarios all parameters include inherent uncertainties which cannot be avoided but should be identified and discussed.

7.2. Carbon footprint impacts

Research question 2: How will scenarios for the transformation of the Swedish heavy-duty lorry fleet impact its carbon footprint over time?

The results indicate that a high electrification rate of the fleet yields the most significant decrease in total emissions, with up to 80 % from 2025 to 2045 when the national climate goal is to be reached, even in the case of a less ambitious background system development such as the stated policies scenario. A high biofuel share, as demonstrated in the biofuel sensitivity analysis, could potentially yield lower total emissions than the scenario with high electrification and a background system evolution in line with sustainable development. However, as will be discussed below, at the current time the biofuel high case seems unlikely to occur.

Consequently, the emissions reductions achieved through a high electrification rate are found to be greater than the increases in emissions due to 1) the higher vehicle cycle emissions associated with BEVs as compared to ICEVs, 2) the continuously increasing transport demand and 3) the higher emissions associated with the stated policies scenario as compared to the sustainable development scenario. However, the results show that the second and, third point does not hold true past year 2054, when the emissions for the high electrification and stated policies scenario surpasses the emissions in the low electrification and sustainable development scenario, and then continues to increase. This suggests that climate change mitigations in the background systems, beyond the effects of stated policies, are necessary to keep emissions down long-term, as the transport demand increases. However, higher transport efficiencies, which improve the load factor, could act as a mitigating measure to the increasing transport demand.

The main results and sensitivity analysis further suggest that complementing the electrification of the fleet with biofuels is necessary to reduce emissions in line with national climate targets. As such the future of the reduction mandate is a vital factor for the GHG emissions reductions of the fleet, both short term (until 2030) and long-term, regardless of electrification rate. As the mandated reduction levels are currently paused, it is uncertain whether the assumed biofuel shares until 2030 will be reached. This is further exacerbated by the uncertainties associated with the fuel quality legislations and standards. Owing to these two points, it is also possible to argue that the high case of the sensitivity analysis can be deemed unlikely to occur, which reinforces the importance of electrification as a pathway to decarbonise the fleet. Should the reduction mandate remain paused, or as recently announced be reduced to lower levels similar to those assumed in the low case scenario in this study, there would be a significant impact on the fleet emissions. This impact would be exacerbated if the low biofuel share is accompanied by a low electrification rate of the fleet – in which case, the total emissions in 2045 are seen to match the estimated main scenario emissions in 2025 (around 2.25 million tonnes CO_2-eq and 2.5 million tonnes CO_2-eq, respectively).

While emissions reductions between 50 – 80 % occur between years 2025 – 2045 depending on scenario, none of the scenarios reach zero emissions until year 2045 or anytime during the simulated period. This suggests that further measures than what is included in the main scenarios are necessary to reach the national climate goal on time. This could include increasing transport efficiency, increasing the electrification rate above the simulated high scenario, a higher use of biofuels, improving recycling processes of batteries for BEVs and utilising carbon capture and storage (CCS) in the vehicle and fuel cycle processes. Implementation of other renewable fuels, such as electro-fuels, could also be a potential measure. However, if the levels in the mandate for emission reductions for liquid fuels is lowered, incentives for use of other renewable fuels would also decrease.

Conclusively, a high electrification rate of the fleet seems to be the most important factor to maximise reductions of the GHG emissions of the fleet, although climate mitigation scenarios for the fuel and vehicle cycles are important to push emissions down and keep them down long-term. Moreover, the use of biofuels (or other renewable fuels) is seen to be a crucial complement to electrification in order to reduce emissions, before the fleet is fully electrified.

7.3. Impact on demand for fuels, electricity, and batteries

Research question 3: How will scenarios for the transformation of the Swedish heavy-duty lorry fleet impact demand of fuels, electricity for charging, and batteries over time?

The results indicate that between years 2025 – 2060 a low and high electrification rate could reduce the fleet-wide energy demand for propulsion with 43 % and 64 %, respectively, and significantly impact the demand of different energy carriers. As only ICEVs and BEVs are considered in the model, the difference in total energy demand between the electrification scenarios can be explained by the lower specific energy consumption of BEVs. It is possible that additional powertrains will be introduced to the fleet, such as FCEVs, which could impact the fleet's energy demand. Moreover, a few hybrids and plug-in hybrids already exist within the fleet, which are not considered in the model. Should the potential additional powertrains have a similar specific energy consumption to BEVs, the total energy demand would remain more or less unchanged. On the other hand, if the specific energy consumption is closer to the one for ICEVs the impact of the electrification rate on the total energy demand could be reduced.

The electrification scenarios also affect the demand of different energy carriers. The result suggest that a high electrification rate could enable a reduction of the fleet’s demand of fossil fuels to zero around 2055, regardless of the development of the biofuels shares. Since the future shares of biofuels is uncertain in terms of both political forces and supply (as explained in chapter 3 and 4), a high electrification rate could have the potential to reduce the impact of future outcomes of the biofuel demand and at the same time terminate the dependency on fossil fuels in the long-term. However, a higher electrification rate and the following increase in electricity demand of the fleet, will require adequate developments of infrastructure for charging and power supply, which were not investigated in this study.

In the main scenarios the highest demand of biofuels is 7 TWh, reached in 2030 in the low electrification scenario, which can be compared to the 17 TWh of biodiesel use in 2020 for the whole transport sector in Sweden (as shown in the background chapter 3.3.4). If the passenger car fleet were to be electrified more rapidly than the heavy-duty lorry fleet, more biodiesel could potentially be available to the latter and facilitate an emission reduction despite a lower electrification rate. Furthermore, the biofuel scenario has a considerable impact on the fossil fuel demand, especially if the fleet would evolve in line with the low electrification scenario, since more ICEVs would remain in the fleet (and a potential reduction in biofuel use would be compensated by a higher fossil fuel demand). However, in practice other renewable alternative fuels could be used, thus avoiding a higher fossil fuel demand despite decreasing biofuel demand. This highlights the importance of fuel options for ICEVs, to reduce the fleet’s fossil fuel demand regardless of electrification rate.

As expected, the battery capacity demand, and the related demand of critical materials, increases with higher electrification rates as more BEVs are introduced to the fleet. However, it is possible to argue that the simulation results overestimate the future demand as ICEVs may not exclusively be replaced by BEVs. For instance, replacement with PHEVs or FCEVs could result in a lower battery demand of the fleet than simulated, although this could increase the demand of other resources such as biofuels, electro-fuels and hydrogen. Moreover, it is possible that recycling processes for BEV batteries could be improved during the investigated time period, which would lower the demand of virgin raw materials. The demand of critical raw materials could also be changed if other battery chemistries, with different material requirements than the NMC622 used in the model, would be employed for the BEVs in the fleet. In addition, if the energy density increases over time the overall material demand per kWh battery could be lower and thereby decrease the demand of critical materials. However, critical materials for batteries and their potential shifts over time were not covered in this study. Furthermore, the potential expansion of other renewable fuels could contribute to a lower demand for batteries. On the other hand, the batteries for BEVs in the model are not assumed to be replaced during a vehicle’s lifetime. If this would be required, the simulation results could be underestimated. Consequently, it is possible that the simulation overestimates the battery capacity and material demands as long as the BEVs in the fleet do not require battery replacement during their lifetime.

Conclusively, the fleet’s total energy demand can be reduced by up to 64 % depending on electrification rate, despite increasing transport demand. A high electrification rate could also result in almost no demand of fossil fuels around 2055, whereas an earlier phase-out would require additional renewable fuels. For a lower electrification rate, a phase out of fossil fuels is not achieved during the simulation time period which highlights the need for complementation by other renewable fuels. For instance, by a higher share of biofuels, that show considerable potential to reduce the fleet’s future fossil fuel demand, especially at lower electrification rates. The fleet’s annual battery capacity demand (and related material demand), strongly depend on the electrification rate. The scenarios could be both higher and lower than what is estimated in the results; higher if replacement batteries are necessary during the lifespan, and lower if in the battery capacities in the model are overestimated.

7.4. Potential improvements and recommendations for future research

- As mentioned in section 2.4.2, no replacement of the lithium-ion battery was considered in the model. However, as the results show, the battery is a hotspot for GHG emissions connected to the BEV production. As such, it would be desirable to investigate the effects of a potential battery replacement. It would also be beneficial to investigate possible future developments of battery energy densities and recycling potentials, as these developments could potentially lower the battery weights and virgin raw material demand.

- The weight and material estimation for the baseline vehicles in the model should be regarded as rough estimates and were heavily dependent on the scalable LCI provided by Wolff et al. (2020). It would have been beneficial to expand the research on the vehicle material composition to confirm the estimations. Potential shifts in materials over time (for instance due to lightweighting measures) could also affect the results but were not considered in the study.

- Another potential improvement would be to consider that different segments of the heavy-duty lorry fleet can be expected to become electrified at different paces, depending on typical distances covered, type of transport (for instance urban, regional, and long-haul), and lorry weight.

- In future research, it would be desirable to create a similar model which considers other alternative powertrain configurations, for instance PHEVs and FCEVs, as well as other renewable fuels. Thereby, a broader range of possible pathways for a decarbonised fleet, and their potential effects on the carbon footprint, could be covered.

- The plausibility of the assumed electrification rates and biofuel shares, with regards to the estimated electricity and biofuel demand, should be investigated. This could be done by analysing the potential infrastructure and biofuel supply developments that would be necessary to meet the demands estimated in this study. This would also elaborate on the need for other, alternative measures to decarbonise the fleet.

- It would be interesting to investigate the effects on the carbon footprint of the fleet through transport efficiency measures, such as optimising transport routes This could be done by further developing the model by implementing freight activity as a governing parameter, which would also enable a more accurate investigation on the influence of the weight distribution.

References

Andersson, Öivind, and Pål Börjesson. 2021. ‘The Greenhouse Gas Emissions of an Electrified Vehicle Combined with Renewable Fuels: Life Cycle Assessment and Policy Implications’. *Applied Energy* 289:116621. doi: 10.1016/J.APENERGY.2021.116621.

Arvidsson, Rickard, Anne Marie Tillman, Björn A. Sandén, Matty Janssen, Anders Nordelöf, Duncan Kushnir, and Sverker Molander. 2018. ‘Environmental Assessment of Emerging Technologies: Recommendations for Prospective LCA’. *Journal of Industrial Ecology* 22(6):1286–94.

Basma, Hussein, Yannis Beys, and Felipe Rodríguez. 2021. ‘Battery Electric Tractor-Trailers in the European Union: A Vehicle Technology Analysis’.

Bennett, Sean. 2016. *Heavy Duty Truck Systems*. 6th ed. Boston, USA: Cengage Learning.

Bisinella, V., T. H. Christensen, and T. F. Astrup. 2021. ‘Future Scenarios and Life Cycle Assessment: Systematic Review and Recommendations’. *International Journal of Life Cycle Assessment* 26(11):2143–70.

Burke, Andrew, and Hengbing Zhao. 2017. *Fuel Economy Analysis of Medium/Heavy-Duty Trucks: 2015-2050* .

Buysse, Claire, Miller, Josh. 2021. ‘Transport Could Burn up the EU’s Budget’. Retrieved 23 January 2023 (https://theicct.org/transport-could-burn-up-the-eus-entire-carbon-budget/).

Chumchal, C., and D. Kurzweil. 2017. ‘Lead-Acid Battery Operation in Micro-Hybrid and Electrified Vehicles’. Pp. 395–414 in *Lead-Acid Batteries for Future Automobiles*. Elsevier Inc.

Cunanan, Carlo, Manh-Kien Tran, Youngwoo Lee, Shinghei Kwok, Vincent Leung, and Michael Fowler. 2021. ‘A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles’. *Clean Technologies* 3(2):474–89.

Dagens Nyheter. 2023. ‘Så Mycket Kan Reduktionsplikten Sänkas’. Retrieved 27 April 2023 (https://www.dn.se/sverige/strid-hardnar-sa-mycket-kan-reduktionsplikten-sankas/).

Delgado, Oscar, Josh Miller, Ben Sharpe, and Rachel Muncrief. 2016. *Estimating the Fuel Efficiency Technology Potential of Heavy-Duty Trucks in Major Markets around the World*.

Delgado, Oscar, Rachel Muncrief, and Felipe Rodríguez. 2017. ‘Fuel Efficiency Technology in European Heavy-Duty Vehicles: Baseline and Potential for the 2020–2030 Timeframe’. Retrieved 11 May 2023 (https://theicct.org/publication/fuel-efficiency-technology-in-european-heavy-duty-vehicles-baseline-and-potential-for-the-2020-2030-timeframe/).

Directive (EU) 2018/2001. n.d. ‘Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources’.

Drivkraft Sverige. n.d. ‘Beräkningsfaktorer’. Retrieved 26 April 2023 (https://drivkraftsverige.se/fakta-statistik/berakningsfaktorer/).

Dunn, Jessica, Margaret Slattery, Alissa Kendall, Hanjiro Ambrose, and Shuhan Shen. 2021. ‘Circularity of Lithium-Ion Battery Materials in Electric Vehicles’. *Environmental Science and Technology* 55(8):5189–98. doi: https://doi.org/10.1021/acs.est.0c07030.

Energigas Sverige. 2022. ‘Vätgas Hjälper Transportjätte Att Ställa Om’. *Tidningen Energigas,* September 26.

European Commission. 2019. *Bodies and Trailers - Development of CO2 Emissions Determination Procedure*.

European Commission. 2020. *Determining the Environmental Impacts of Conventional and Alternatively Fuelled Vehicles through LCA*. Brussels, BE.

European Commission. 2023a. ‘Proposal for a Regulation of the European Parliament and of the Council Amending Regulation (EU) 2019/1242’.

European Commission. 2023b. ‘Questions and Answers: Revision of the CO2 Emission Standards for Heavy-Duty Vehicles’. Retrieved 16 February 2023 (https://ec.europa.eu/commission/presscorner/detail/en/qanda_23_763).

European Commission. n.d.-a. ‘EU Classification of Vehicle Types’. Retrieved 23 January 2023 (https://alternative-fuels-observatory.ec.europa.eu/general-information/vehicle-types).

European Commission. n.d.-b. ‘Reducing CO_2 Emissions from Heavy-Duty Vehicles’. Retrieved 31 January 2023 (https://climate.ec.europa.eu/eu-action/transport-emissions/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en).

European commission, and Joint Research Center. 2020. *JEC Well-to-Tank Report v5 Well-to-Wheels Analysis of Future Automotive Fuels and Powertrains in the European Context*. Luxembourg.

European Environment Agency. 2019. ‘1.A.3.b.i-Iv Road Transport 2019 — European Environment Agency’. Retrieved 26 April 2023 (https://www.eea.europa.eu/publications/emep-eea-guidebook-2019/part-b-sectoral-guidance-chapters/1-energy/1-a-combustion/1-a-3-b-i/view).

European Environment Agency. 2022. *Transport and Environment Report 2021 Decarbonising Road Transport — the Role of Vehicles, Fuels and Transport Demand*. Copenhagen, DK.

Everett, Bob, Stephen Peake, and James Warren. 2023. *Energy Systems and Sustainability*. 3rd ed. Oxford : Oxford university press.

Fossilfritt Sverige. 2020. *Färdplan För Fossilfri Konkurrenskraft Fordonsindustrin - Tunga Fordon*.

Government Offices of Sweden. 2021a. *I En Värld Som Ställer Om- Sverige Utan Fossila Drivmedel 2040 (SOU 2021:48)*. Klimat- och närlingslivdepartementet.

Government Offices of Sweden. 2021b. *Regler För Statliga Elvägar (SOU 2021:73)*.

Government Offices of Sweden. 2022. 'Satsning På Laddinfrastruktur Genom Klimatklivet'. Retrieved 15 April 2023 (https://www.regeringen.se/pressmeddelanden/2022/11/satsning-pa-laddinfrastruktur-genom-klimatklivet/).

Government Offices of Sweden. n.d. 'Mål För Transportpolitiken'. Retrieved 23 November 2022 (https://www.regeringen.se/regeringens-politik/transporter-och-infrastruktur/mal-for-transporter-och-infrastruktur/).

HBEFA. 2019. *Update of Emission Factors for HBEFA Version 4.1*.

Hildermeier, Julia, Andreas Jahn, Regulatory Assistance Project, and Felipe Rodríguez. 2020. 'Electrifying EU City Logistics - An Analysis of Energy Demand and Charging Cost'.

Hill, Nikolas, John Norris, Felix Kirsch, and Craig Dun. 2015. *Light Weighting as a Means of Improving Heavy Duty Vehicles' Energy Efficiency and Overall CO2 Emissions Heavy*.

ILZSG SECRETARIAT. 2023. 'The Potential Impact of Hybrid and Electric Vehicles on Lead Demand-Update 4'.

International Energy Agency. 2017. *The Future of Trucks*.

International Energy Agency. 2019. *World Energy Outlook 2019*.

International Energy Agency. 2020. *Global EV Outlook 2020 Entering the Decade of Electric Drive?*

International Energy Agency. 2022. *World Energy Outlook 2022*.

International Energy Agency. 2023. *Global EV Outlook 2023 Catching up with Climate Ambitions*. Paris.

IVA. 2019. *Resurseffektivitet Inom Livsmedelstransporter*.

Javaid, Amjad, E. Essadiqi, Boyd Davis, and S. Bell. 2003. 'Final Report on Scrap Management, Sorting and Classification of Aluminum'. doi: 10.13140/RG.2.2.30171.98089.

Jing, Liang, M. El-Houjeiri Hassan, Jean-Christophe Monfort, Adam R. Brandt, Mohammad S. Masnadi, Deborah Gordon, and Joule A. Bergerson. 2020. 'Carbon Intensity of Global Crude Oil Refining and Mitigation Potential'. *Nature Climate Change* 10:526–32.

Klimat- och näringslivsdepartementet. 2017. 'Klimatlag (2017:720)'.

Klimatmärkning för mat. 2010. 'Klimatpåverkan Från Livsmedelstransporter- Underlag till Klimatcertifiering'.

Lakshminarayanan, P. A., and Avinash Kumar Agarwal. 2020. *Design and Development of Heavy Duty Diesel Engines*. Singapore: Springer Nature Singapore Ptc Ltd.

Lane, Ben. 2006. *Life Cycle Assessment of Vehicle Fuels and Technologies*. London, UK.

Law, Karen, Michael D. Jackson, and Michael Chan. 2011. *European Union Greenhouse Gas Reduction Potential for Heavy-Duty Vehicles*.

Link, Steffen, and Patrick Plötz. 2022. 'Technical Feasibility of Heavy-Duty Battery-Electric Trucks for Urban and Regional Delivery in Germany—A Real-World Case Study'. *World Electric Vehicle Journal 2022, Vol. 13, Page 161* 13(9):161. doi: 10.3390/WEVJ13090161.

Mareev, Ivan, Jan Becker, and Dirk Uwe Sauer. 2018. 'Battery Dimensioning and Life Cycle Costs Analysis for a Heavy-Duty Truck Considering the Requirements of Long-Haul Transportation'. doi: 10.3390/en11010055.

Masnadi, Mohammad S., Hassan M. El-Houjeiri, Dominik Schunack, Yunpo Li, Jacob G. Englander, Alhassan Badahdah, Jean-Christophe Monfort, James E. Anderson, Timothy J. Wallington, Joule A. Bergerson, Deborah Gordon, Jonathan Koomey, Steven Przesmitzki, Inês L. Azevedo, Xiaotao T. Bi, James E. Duffy, Garvin A. Heath, Gregory A. Keoleian, Christophe McGlade, D. Nathan Meehan, Sonia Yeh, Fengqi You, Michael Wang, and Adam R. Brandt. 2018. 'Global Carbon Intensity of Crude Oil Production'. *Science* 361(6405):851–53.

Matzer, Claus, Konstantin Weller, Martin Dippold, Silke Lipp, Martin Röck, Martin Rexeis, and Stefan Hausberger. 2019. *Update of Emission Factors for HBEFA Version 4.1*.

Mendoza Beltran, Angelica, Brian Cox, Chris Mutel, Detlef P. van Vuuren, David Font Vivanco, Sebastiaan Deetman, Oreane Y. Edelenbosch, Jeroen Guinée, and Arnold Tukker. 2020. 'When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment'. *Journal of Industrial Ecology* 24(1):64–79. doi: 10.1111/jiec.12825.

Miljöfordon. 2017. 'Så Fungerar Etanollastbil'. Retrieved 3 February 2023 (https://www.miljofordon.se/lastbilar/saa-fungerar-etanollastbil/).

MIT Energy Initiative. 2019. *Insights into Future Mobility*.

Mobility Sweden. 2023. 'Databas Nyregistreringar'. Retrieved 10 May 2023 (https://mobilitysweden.se/statistik/databas-nyregistreringar).

Morfeldt, Johannes, Simon Davidsson Kurland, and Daniel J. A. Johansson. 2021. 'Carbon Footprint Impacts of Banning Cars with Internal Combustion Engines'. *Transportation Research Part D: Transport and Environment* 95:102807. doi: 10.1016/J.TRD.2021.102807.

Morfeldt, Johannes, and Daniel J. A. Johansson. 2022. 'Impacts of Shared Mobility on Vehicle Lifetimes and on the Carbon Footprint of Electric Vehicles'. *Nature Communications* 13(1). doi: 10.1038/s41467-022-33666-2.

Morfeldt, Johannes, Jörgen Larsson, David Andersson, Daniel Johansson, Johan Rootzén, Cecilia Hult, and Ida Karlsson. 2023. 'Consequences of Adopting National Consumption-

Based Climate Targets alongside the Territorial Commitments under the Paris Agreement'. doi: 10.21203/rs.3.rs-2687300/v1.

Naturvårdsverket. n.d. 'Sveriges Klimatmål Och Klimatpolitiska Ramverk'. Retrieved 1 May 2023 (https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/sveriges-klimatarbete/sveriges-klimatmal-och-klimatpolitiska-ramverk/).

Network for Transport Measures. n.d. 'Road Cargo Transport Baselines Sweden'. Retrieved 2 May 2023 (https://www.transportmeasures.org/en/wiki/evaluation-transport-suppliers/road-transport-baselines-sweden/).

Nikowitz, Michael. 2016. *Advanced Hybrid and Electric Vehicles*. Springer International Publishing AG Switzerland.

Nordic Energy Research. 2021. *Nordic Clean Energy Scenarios - Solutions for Carbon Neutrality*.

O'connell, Adrian, Nikita Pavlenko, Georg Bieker, and Stephanie Searle. 2023. *A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels*.

Regulation (EU) 2019/. 1242. 'Of the European Parliament and of the Council of 20 June 2019 Setting CO2 Emission Performance Standards for New Heavy-Duty Vehicles Entered , (L 198/202 25.7.2019)'.

Rodriguez, Felipe, and Ben Sharpe. 2018. *Market Analysis of Heavy-Duty Commercial Trailers in Europe*.

Sacchi, Romain, Christian Bauer, and Brian Cox. 2021. 'Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium? The Heavy-Duty Vehicles'. *Environmental Science and Technology* 55(8):5224–35. doi: 10.1021/ACS.EST.0C07773/ASSET/IMAGES/LARGE/ES0C07773_0007.JPEG.

Scania. 2018. *The Pathways Study: Achieving Fossil-Free Commercial Transport by 2050*.

Scania. 2021. *Battery Electric vs Diesel Driven*.

Scania. n.d.-a. 'Facts and Figures'. Retrieved 10 May 2023 (https://www.scania.com/group/en/home/about-scania/scania-in-brief/facts-and-figures.html).

Scania. n.d.-b. 'Location'. Retrieved 16 May 2023 (https://supplier.scania.com/about-scania/locations/).

Serrano-Guevara, Oscar S., and Jose I. Huertas. 2022. 'Greenhouse Gas Emissions Reduction from Fuel Switching in Heavy Duty Vehicles and Its Application in the International Carbon Market'. *2022 International Symposium on Electromobility, ISEM 2022*. doi: 10.1109/ISEM55847.2022.9976866.

Shepherd, S. P. 2014. 'A Review of System Dynamics Models Applied in Transportation'. *Transportmetrica B* 2(2):83–105.

Sigle, Sebastian, and Robert Hahn. 2022. ‘Energy Consumption Comparison of Current Powertrain Options in Autonomous Heavy Duty Vehicles (HDV)’. *2022 2nd International Conference on Sustainable Mobility Applications, Renewables and Technology, SMART 2022*. doi: 10.1109/SMART55236.2022.9990489.

SIKA. 2004. *PM 2004:7 Transportarbetets Utveckling, Redovisning Av Tidsserier Samt Metoder För Beräkning Av Transportarbetet.*

Smallbone, Andrew, Boru Jia, Penny Atkins, and Anthony Paul Roskilly. 2020. ‘The Impact of Disruptive Powertrain Technologies on Energy Consumption and Carbon Dioxide Emissions from Heavy-Duty Vehicles’. *Energy Conversion and Management: X* 6. doi: 10.1016/J.ECMX.2020.100030.

Sveriges Riksdag. 2022a. ‘Pausad Höjning Av Reduktionsplikten För Bensin Och Diesel 2023’. Retrieved 27 April 2023 (https://www.riksdagen.se/sv/dokument-lagar/arende/betankande/pausad-hojning-av-reduktionsplikten-for-bensin_H901MJU31).

Sveriges Riksdag. 2022b. ‘Transportsektorns Klimatmål’. Retrieved 15 February 2023 (https://lunduniversityo365-my.sharepoint.com/:w:/r/personal/so7765to-s_lu_se/_layouts/15/Doc.aspx?sourcedoc=%7BF74476E4-9120-412A-ADB5-8C52B4FA09FC%7D&file=Exjobb.docx&action=default&mobileredirect=true).

SWECO. 2021. *Carbon Intensity and Primary Energy Factors- Report to the Swedish Energy Agency.*

Swedish Energy Agency. 2021a. *Drivmedel 2020-ER 2021:29.*

Swedish Energy Agency. 2021b. *Statens Energimyndighets Föreskrifter Om Hållbarhetskriterier För Biodrivmedel Och Biobränslen-STEMFS 2021:7.*

Swedish Energy Agency. 2021c. *Utvärdering Av Skattereduktion För Rena Och Höginblandade Flytande Biodrivmedel- ER 2021:9.*

Swedish Energy Agency. 2022a. ‘Drivmedel 2021- ER 2021:29’.

Swedish Energy Agency. 2022b. *Kontrollstation För Reduktionsplikten 2022 Delrapport 1 Av 2- ER 2022:07.*

Swedish Energy Agency. 2023a. *Energiläget 2022- ET 2022:09.*

Swedish Energy Agency. 2023b. ‘Klimatpremien’. Retrieved 15 April 2023 (https://www.energimyndigheten.se/klimat--miljo/transporter/transporteffektivt-samhalle/klimatpremie/).

Swedish Energy Agency. 2023c. ‘Reduktionsplikt’. Retrieved 27 April 2023 (https://www.energimyndigheten.se/fornybart/hallbarhetskriterier/reduktionsplikt/).

Swedish Energy Agency. 2023d. *Scenarier Över Sveriges Energisystem 2023 Med Fokus På Elektrifieringen 2050- ER 2023:07.*

Swedish Energy Agency. 2023e. ‘Växthusgasberäkning’. Retrieved 20 April 2023 (https://www.energimyndigheten.se/fornybart/hallbarhetskriterier/hallbarhetslagen/fragor-och-svar/vaxthusgasberakning/).

Swedish Environmental Protection Agency. 2021a. ‘Inrikes Transporter, Utsläpp Av Växthusgaser’. Retrieved 23 November 2022 (https://www.naturvardsverket.se/data-och-statistik/klimat/vaxthusgaser-utslapp-fran-inrikes-transporter/#:~:text=Utsl%C3%A4ppen%20av%20v%C3%A4xthusgaser%20fr%C3%A5n%20l%C3%A4tta,kraftigaste%20%C3%B6kningen%20under%202000%2Dtalet.).

Swedish Environmental Protection Agency. 2021b. ‘Sveriges Utsläpp Och Upptag Av Växthusgaser’. Retrieved 22 November 2022 (https://www.naturvardsverket.se/data-och-statistik/klimat/sveriges-utslapp-och-upptag-av-vaxthusgaser/).

Swedish Environmental Protection Agency. 2023. ‘Når Sverige de Nationella Klimatmålen?’ Retrieved 27 April 2023 (https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/sveriges-klimatarbete/nar-sverige-de-nationella-klimatmalen/).

Swedish Environmental Protection Agency. n.d.-a. ‘Beräkna Direkta Utsläpp Från Förbränning’. Retrieved 26 April 2023 (https://www.naturvardsverket.se/vagledning-och-stod/luft-och-klimat/berakna-klimatpaverkan/berakna-direkta-utslapp-fran-forbranning/).

Swedish Environmental Protection Agency. n.d.-b. ‘Biogena Koldioxidutsläpp Och Klimatpåverkan’. Retrieved 2 May 2023 (https://www.naturvardsverket.se/amnesomraden/klimatomstallningen/omraden/klimatet-och-skogen/biogena-koldioxidutslapp-och-klimatpaverkan/).

Swedish Transport Administration. 2020a. ‘Prognos För Godstransporter 2040 – Trafikverkets Basprognoser 2020’. Retrieved 15 February 2023 (http://trafikverket.diva-portal.org/smash/get/diva2:1442798/FULLTEXT03.pdf).

Swedish Transport Administration. 2020b. *Scenarier För Att Nå Klimatmålet För Inrikes Transporter*.

Swedish Transport Administration. 2021. *Disaggregering Av Prognos För Godstransporter 2040 till Bansek, EVA, Sampers/Samkalk Och TEN Tec - Trafikverkets Basprognoser 2016*.

Swedish Transport Administration. 2022a. *Transporters Fyllnadsgrad- Exempel Från Näringslivet*.

Swedish Transport Administration. 2022b. *Trender i Transportsystemet*.

Swedish Transport Administration. 2023a. ‘Bärighetsklasser (BK) På Vägar Och Broar’. Retrieved 5 May 2023 (https://bransch.trafikverket.se/for-dig-i-branschen/vag/bk--barighetsklasser-pa-vagar-och-broar/).

Swedish Transport Administration. 2023b. ‘Sveriges Första Permanenta Elväg’. Retrieved 2 May 2023 (https://www.trafikverket.se/vara-projekt/projekt-i-orebro-lan/sveriges-forsta-permanenta-elvag/).

Swedish Transport Agency. 2013. ‘Lastbil’. Retrieved 23 January 2023 (https://www.transportstyrelsen.se/sv/vagtrafik/fordon/fordonsregler/lastbil).

Swedish Transport Agency. 2020. ‘Bruttoviktstabeller’. Retrieved 14 April 2023 (https://www.transportstyrelsen.se/sv/vagtrafik/Yrkestrafik/Gods-och-buss/Matt-och-vikt/viktbestammelser/Bruttoviktstabeller/).

Swedish Transport Agency. 2021. ‘Modulsystemet’. Retrieved 12 April 2023 (https://www.transportstyrelsen.se/sv/vagtrafik/Yrkestrafik/Gods-och-buss/Matt-och-vikt/langd-och-breddbestammelser/Modulsystemet/).

Thonemann, Nils, Anna Schulte, and Daniel Maga. 2020. ‘How to Conduct Prospective Life Cycle Assessment for Emerging Technologies? A Systematic Review and Methodological Guidance’. *Sustainability (Switzerland)* 12(3). doi: 10.3390/su12031192.

TRACCS. 2013. ‘Download Section for Public Data’. Retrieved 2 May 2023 (https://traccs.emisia.com/index.php).

Transport Analysis. 2013. ‘Fordon 2013’. Retrieved 23 January 2023 (https://www.trafa.se/globalassets/statistik/vagtrafik/fordon/2022/fordon-2021-220304.pdf).

Transport analysis. 2015. ‘Transportarbete 1950–2002’. Retrieved 23 February 2023 (https://www.trafa.se/globalassets/statistik/transportarbete/transportarbete-1950-2002.pdf).

Transport analysis. 2019. *Styrmedel for Tunga Miljövänliga Lastbilar (Rapport 2019:2)*.

Transport Analysis. 2020. *Vägfordonsflottans Utveckling till År 2030*.

Transport Analysis. 2022a. ‘Fordon 2021’. Retrieved 23 January 2023 (https://www.trafa.se/globalassets/statistik/vagtrafik/fordon/2022/fordon-2021-220304.pdf).

Transport Analysis. 2022b. ‘Körsträckor Med Svenskregistrerade Fordon’. Retrieved 2 February 2023 (https://www.trafa.se/vagtrafik/korstrackor/).

Transport Analysis. 2022c. ‘Lastbilstrafik 2021’. Retrieved 23 January 2023 (https://www.trafa.se/globalassets/statistik/vagtrafik/lastbilstrafik/2021/lastbilstrafik-2021.pdf).

Transport Analysis. 2022d. ‘Trafikarbete På Svenska Vägar’. Retrieved 2 February 2023 (https://www.trafa.se/vagtrafik/trafikarbete/).

Transport analysis. 2022. ‘Transportarbete’. Retrieved 23 January 2023 (https://www.trafa.se/ovrig/transportarbete/).

Transport Analysis. 2022e. ‘Transportarbete i Sverige 2000–2021’. Retrieved 23 January 2023 (https://www.trafa.se/globalassets/statistik/transportarbete/transportarbete-2021-2022-10-04.pdf).

Transport Analysis. 2022f. ‘Utländska Lastbilstransporter i Sverige’. *Utländska Lastbilstransporter i Sverige*. Retrieved 14 February 2023 (https://www.trafa.se/vagtrafik/utlandska-lastbilar/).

Transport Analysis. 2023a. ‘ Detailed Excerpt on Scrappage of Heavy-Duty Lorries from the Swedish Vehicle Registry (“Fordonsregistret”) for the Years 2017-2021’.

Transport Analysis. 2023b. ‘Fordon 2022’. Retrieved 23 January 2023 (https://www.trafa.se/globalassets/statistik/vagtrafik/fordon/2022/fordon-2021-220304.pdf).

Transport Analysis. 2023c. ‘Lastbilstrafik’. Retrieved 18 March 2023 (https://www.trafa.se/vagtrafik/lastbilstrafik/).

Volvo Group. n.d. ‘Our Production Facilities’. Retrieved 10 May 2023 (https://www.volvogroup.com/en/about-us/organization/our-production-facilities.html).

Volvo Trucks. 2018. ‘Emissions from Volvo’s Trucks’.

Volvo Trucks. n.d. ‘Lastbilar’. Retrieved 28 March 2023 (https://www.volvotrucks.se/sv-se/trucks.html).

VTI. 2018. *Svenskregistrerade Tunga Lastbilars Trafikarbete i Sverige Revidering Av Indata till Avgasmodellen HBEFA Avseende Trafikarbetets Fördelning Inom Segment*.

Wang, Guihua, Lewis Fulton, and Marshall Miller. 2022. ‘UC Davis White Papers Title The Current and Future Performance and Costs of Battery Electric Trucks: Review of Key Studies and A Detailed Comparison of Their Cost Modeling Scope and Coverage Permalink Https://Escholarship.Org/Uc/Item/8zj9462h Publication Date Data Availability’. doi: 10.7922/G2D50K9T.

Wolff, Sebastian, Moritz Seidenfus, Karim Gordon, Sergio Álvarez, Svenja Kalt, and Markus Lienkamp. 2020. ‘Scalable Life-Cycle Inventory for Heavy-Duty Vehicle Production’. *Sustainability (Switzerland)* 12(13). doi: 10.3390/su12135396.

Yan, Shiyu, Kelly de Bruin, Emer Dennehy, and John Curtis. 2021. ‘Climate Policies for Freight Transport: Energy and Emission Projections through 2050’. *Transport Policy* 107:11–23. doi: 10.1016/J.TRANPOL.2021.04.005.

Zacharof, Nikiforos, Georgios Fontaras, Theodoros Grigoratos, Biagio Ciuffo, Oscar Delgado, and J. Felipe Rodriguez. 2017. ‘Estimating the CO2 Emissions Reduction Potential of Various Technologies in European Trucks Using VECTO Simulator’. *SAE Technical Paper*.

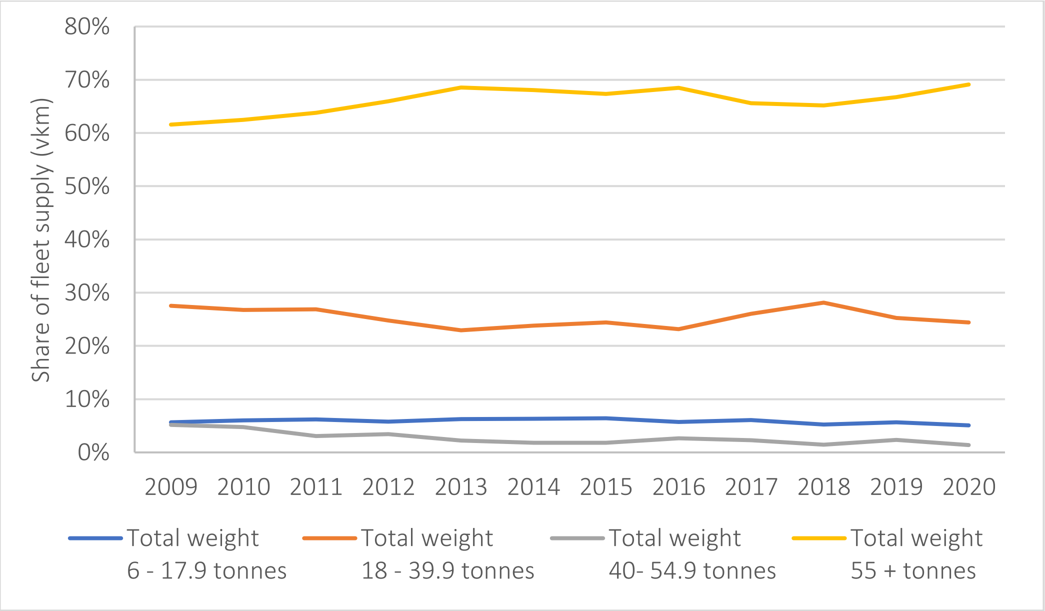
A. Additional statistics

i. Weight distribution of the fleet

In the model, estimations on the shares of the total fleet supply (% of mileage in vkm) per weight class are based on estimations by VTI (2018). In this segment, estimates based on statistics are presented as comparison.

The statistics on transports by Swedish-registered heavy-duty lorries demonstrate the distances covered by lorries with varying maximum permissible weights (Transport Analysis 2023). The weight classes in the statistics were processed to match the weight classes in this study. Thereafter the shares of the total fleet mileage per weight class were calculated, see results in appendix figure 1. It should be noted that the statistics only include heavy-duty lorries with a *maximum load* exceeding 3.5 tonnes (Transport Analysis 2023). The definition of a heavy-duty lorry is a lorry with a *maximum permissible weight* exceeding 3.5 tonnes, meaning that the statistics exclude the lightest heavy-duty lorries (Transport Analysis 2023). Moreover, the statistics represent transport with Swedish-registered lorries both within Swedish borders and abroad, whereas this study only considers transport within Swedish borders (Transport Analysis 2023).

According to the authors' processing of the statistics, the heaviest lorries, with maximum permissible weights above 55 tonnes, contributed to a majority of the distances covered between 2009 and 2020, ranging from between 62 to 69 % of the total distances. The group with the second largest contribution to the traffic covers lorries with a maximum permissible weight between 18 – 39 tonnes and has amounted to between 23 – 28 % of the distances in recent years.



Appendix figure 1: Share of the total yearly fleet mileages per weight class between years 2009 – 2020. Based on statistics by Transport Analysis (2023).

The final shares of contribution per vehicle class were calculated as the mean of the respective shares between years 2009 – 2020 and are presented in appendix table 1. For comparison, the shares estimated based on the report by VTI (2018) are also included.

Appendix table 1:Assumed share of the yearly fleet supply per weight class in the model.

Total weight (tonnes)	**Share of total fleet supply based on statistics (%)**	**Share of total fleet supply based on estimations by VTI (%)**
> over 3.5 – 17.9	6.0	11.4
18 – 39.9	25.0	29.8
40 – 54.9	1.0	33.0
55 +	68.0	25.8

B. Development of baseline vehicles

i. Determination of weight classes and baseline vehicle weights

The gross combined vehicle weight (GCVW) of a Swedish heavy-duty lorry vehicle train can range from between right above 3.5 tonnes up to 74 tonnes (Swedish Transport Agency 2013, 2020). Therefore, the fleet was divided into four weight classes to account for variations in material demand for different lorry sizes, as well as variations in fuel consumption/km. The weight class groups were chosen to obtain a moderately even division of the fleet with regards to weight:

- > over 3.5 – 17.9 tonnes
- 18 – 39.9 tonnes
- 40 – 54.9 tonnes
- 55 + tonnes

A representative weight for each weight class was chosen based on findings in literature, presented in the next section, and are displayed in appendix table 2.

Appendix table 2: Representative lorry weights for each selected weight class.

Weight class (tonnes)	Gross combined vehicle weight (tonnes)
>Over 3.5 – 17.9	12
18 – 39.9	28
40 – 54.9	44
55 +	60

ii. Literature findings on curb, tractor, and trailer weights

To estimate the weight of the major components of the lorries, three weight parameters were investigated in literature: the curb weight, tractor weight and trailer/body weight.

- The *curb weight* is the weight of the vehicle in its entirety, excluding cargo and driver (Bennett 2016).
- The *tractor* is the power unit of the lorry, and consists of the powertrain components, cab, and belonging structural components (chassis, suspension etc), wheels, tires, braking system etc (Wolff et al. 2020).
- The *body* is the container with load (Bennett 2016). If the lorry pulls a trailer, the trailer consists of the body as well as the structural components beneath (chassis, suspension etc.), wheels, tires and braking system (Sacchi et al. 2021).

The result from the literature review is shown in appendix figure 2 on the next page. It shows the source of the data, what kind of lorry configuration the data considers (rigid lorry or tractor-trailer), clarifies whether the data covers information on tractor plus body/trailer weight (TT) or only tractor weight (T). The gross combined vehicle weight rating (GCVWR) and the gross vehicle weight rating (GVWR) are presented. Here, the latter refers to the maximum weight of the tractor, body and load for a rigid lorry and maximum weight of tractor, one trailer and load for a tractor-trailer. The former includes the maximum possible weight of any vehicle train combination. The table also shows the curb weight of the tractor, body/trailer, and total curb weight. Additionally, the type of body considered is mentioned in the cases were this was presented. For the Volvo tractors, the respective model names are presented.

An overview of the literature sources is also presented in appendix table 3.

Appendix table 3: Overview of literature sources for curb, tractor, and trailer weights.

Source
(Sacchi et al. 2021)
(Matzer et al. (2019)
(Delgado et al. 2017)
(Law, Jackson, and Chan 2011)
(Hill et al. 2015)
(Volvo Trucks n.d.)[40]

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[40] Specifications for the Volvo tractors can be found at https://www.volvotrucks.se/sv-se/trucks.html.

Source	Rigid / Tractor-trailer	Data covers tractor + body/trailer (TT) or only tractor (T)	Gross combined vehicle weight (kg)	Gross vehicle weight (kg)	Curb weight tractor (kg),	Body/trailer (kg)	Total curb weight (kg)	Additional info
Sacchi et al. (2021)	Rigid	TT	3500	-	1313	496	1808	box body
	Rigid	TT	7500	-	2813	1063	3875	box body
	Rigid	TT	12000	-	4500	1700	6200	box body
	Rigid	TT	18000	-	5000	3210	8210	box body
	Rigid	TT	26000	-	6000	4396	10396	box body
	Tractor-trailer	TT	32000	-	7050	4583	11633	curtain-sider
	Tractor-trailer	TT	40000	-	7050	7491	14541	curtain-sider
	Tractor-trailer	TT	60000	-	7050	14762	21812	curtain-sider
Matzer et al. (2019)	Rigid	TT	5800	-	-	-	3680	-
	Rigid	TT	11000	-	-	-	6300	-
	Rigid	TT	13500		-	-	7660	-
	Rigid	TT	17200	-	-	-	9290	-
	Rigid	TT	25500	-	-	-	12370	-
	Rigid	TT	27000	-	-	-	12850	-
	Rigid	TT	32000	-	-	-	14250	-
	Rigid	TT	35500	-	-	-	15060	-
	Tractor-trailer	TT	18000	-	-	-	9620	-
	Tractor-trailer	TT	32000	-	-	-	14250	-
	Tractor-trailer	TT	39800	-	-	-	15870	-
	Tractor-trailer	TT	47000	-	-	-	16800	-
	Tractor-trailer	TT	60000	-	-	-	20370	-
Delgado et al. (2017)	Tractor-trailer	TT	40000	-	7000 - 8200	6200 - 7500	14000 - 15700	curtain-sider
Law et al. (2021)	Tractor-trailer	TT	40000	-	7000	5650		curtain-sider
Hill et al. (2015)	Rigid	TT	12000	-	-	-	6200 - 6350	box body
	Articulated	TT	40000	-	-	-	14550 - 15000	curtain-sider
	Articulated	TT	40000	-	-	-	14750	box body
Volvo website (n.d)	Rigid	T	15500	10000	3995 - 4220	-	-	FL 10 ton 4 cyl 4x2 luftfjädring bak FL 42 R 510A
	Rigid	T	16500	12000	6485 - 6560	-	-	FL 12 ton 4x4 bladfjädring bak FL 44 R 812L
	Rigid	T	16500	14000	5440 - 5510	-	-	FL 14 ton 4x4 bladfjädring bak FL 44 R 814L
	Rigid	T	21000	18000	5060 - 5370	-	-	FL 18 ton 4x2 luftfjädring bak FL 42 R 818A
	Rigid	T	32000	18000	5490 - 5855	-	-	FE 4x2 jämnlast bladfjädring FE 42 R L
	Rigid	T	32000	25300	6685 - 6985	-	-	FE 6x2 jämnlast luftfjädring bak FE 62TR A
	Rigid	T	44000	18000	6635 - 7125	-	-	FH 4x2 jämnlastare luftfjädrad FH 42R 3A
	Tractor-trailer	T	32000	18000	5745 - 5765	-	-	FE 4x2 semi luftfjädring bak FE 42 T A
	Tractor-trailer	T	44000	24000	7595 - 7665	-	-	FH 6x2 tag semidragare luftfjädrad FH 62T T3A
	Tractor-trailer	T	44000	24000	7695 - 7730	-	-	FH 6x2 pusher semidragare luftfjädrad FH 62T P3A
	Tractor-trailer	T	44000	18000	6535 - 6555	-	-	FH 4x2 semidragare luftfjädrad FH 42T 3A
	Tractor-trailer	T	64000	24000	8170 - 8195	-	-	FH16 6x2 pusher semidragare luftfjädrad FH 62T P6A
	Tractor-trailer	T	64000	24000	8865 - 8945	-	-	FH16 6x4 semidragare luftfjädrad FH 64T 6A
	Tractor-trailer	T	64000	24850	9570 - 9605	-	-	FH 8x4 Tridempusher-semidragare luftfjädrad FH 84T P3A

Appendix figure 2: Results from the literature review on heavy-duty lorry weights.

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iii. Estimation of baseline curb, tractor, and trailer weights

Based on the findings in the literature, the weights presented in appendix table 4 were decided for the baseline ICEVs. For BEVs, the corresponding weights were determined based on component masses, as presented in section iv.

Appendix table 4: Assumed curb weight, tractor weight and trailer weight for the baseline ICEVs.

Gross combined vehicle weight (tonnes)	Curb weight total (tonnes)	Tractor weight (tonnes)	Trailer weight (tonnes)
12	6.3	4600	1700
28	10.9	6461	4400
44	15.0	7500	7500
60	20.1	8337	11755

12 tonne lorry

The total curb mass was estimated based on findings in Hill et al. (2015), Sacchi et al. (2021) and Matzer et al. (2019). The tractor and body/trailer weights were based on those presented in Sacchi et al. (2021) and as such a box-body was assumed. The tractor weight was checked against the tractor weights (for rigid lorries) for similar weight spans within the Volvo tractors[41] and deemed reasonable.

28 tonnes lorry

The tractor and body/trailer weights were based on the findings in Sacchi et al. (2021), although scaled by a factor of 28 / 26 = 1.077 since the lorry in Sacchi et al. (2021) has a GCVW of 26 tonnes. As such a box-body was assumed. The tractor weight was checked against the tractor weights (for rigid lorries) for similar weight spans within the Volvo tractors and deemed reasonable. The total curb weight was acquired by adding the tractor and body/trailer weight. The assumed curb weight is somewhat lower than for similar lorries in Matzer et al. (2019).

44 tonnes lorry

The tractor weight was based on the findings in Delgado, Muncrief, et al. (2017), Law, Jackson, and Chan (2011), Sacchi et al. (2021) and the Volvo tractors with a GCVW of 44 tonnes. The trailer weight was based on the estimates in Delgado, Muncrief, et al. (2017), Law et al. (2011) and Sacchi et al. (2021) which all assumed curtain-side trailers. The total curb weight was acquired by adding the tractor and trailer weight. The trailer was assumed to consist of a 13.6 metre module, based on the European module system for lorries (Swedish Transport Agency 2021).

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[41] All specifications for the Volvo tractors are found on https://www.volvotrucks.se/sv-se/trucks.html.

60 tonnes lorry

The tractor weight was based on a mean value of the tractor weights for the 64 tonnes Volvo tractors (adjusted by a factor of 60 / 64 = 0.9375) and the estimate in Sacchi et al. (2021). The trailers for the 60 tonnes lorry were assumed to consist of one 13.6 metre module and one 7.8 metre module (both curtain-siders) based on to the European module system for lorries (Swedish Transport Agency 2021).The weight for the 13.6 metre module was assumed to be the same as the trailer for the 44 tonnes lorry. The weight for the 7.8 metre module was estimated by scaling down the weight for the 13.6 metre module based on length (7.8 / 13.6 = 0.57). As such the total trailer weight was estimated to 7500 + 7500 * 0.57 = 11775 kg.

iv. Estimation of component weights

Tractor component weights

To estimate the component weights of the tractor, a scalable life cycle inventory for N3[42] lorries created by Wolff et al. (2020) was used. A disclaimer is that this inventory was created for a tractor-trailer configuration specifically, and not a rigid lorry vehicle configuration (Wolff et al. 2020). The 12 tonne and 28 tonnes tractors in this study are conceptually thought of as rigid lorries and their curb, tractor and body weights were influenced by literature on rigid lorries. However, they are not explicitly regarded as rigid lorries and as evident in appendix figure 4, the weights of a tractor for a trailer-tractor and rigid lorry can overlap. As the aim of this study is to capture the bigger picture, rather than conduct a proper life cycle analysis, using the scalable life cycle inventory by Wolff et al. for all lorries was considered sufficient.

The total estimated tractor weights presented in appendix table 3 were divided over the various tractor components, based on the relative contribution of each component to the total tractor weight as in Wolff et al. (2020). This applied to all components except for the engine. The engine weight was estimated based on the findings in Sacchi et al. (2021), which are partly based on the inventory in Wolff et al. (2020). The reason for not using the relative contribution of the engine as for the other components, was that this caused the engine size to seemingly be underestimated for the lightest and heaviest lorry when comparing with real life examples of engines by Volvo Trucks.

The relative contributions of each tractor component, as percentage of the total weight (excluding engine), is presented in appendix table 5. The resulting component weights are presented in appendix table 6.

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[42] Lorries with a gross vehicle weight / gross combined vehicle weight over 12 tonnes.

Appendix table 5: The calculated relative contributions of the tractor components to the total tractor weight (excl. engine).

Tractor (excl. engine)	
Component	**Relative contribution (weight- %)**
Cabin	22 %
Frame	14 %
Suspension	25 %
Tires & Wheels	10 %
Others	13 %
Exhaust	7 %
Diesel Tank	1 %
Transmission	4 %
Lead-acid Battery	1 %
Retarder	1 %
Oil	1 %
Coolant	1 %

Appendix table 6: The calculated tractor component weights for the baseline ICEVs.

Component weights (kg)	**12t lorry**	**28t lorry**	**44t lorry**	**60t lorry**
Cabin	898	1156	1378	1464
Frame	553	712	849	901
Suspension	1036	1334	1590	1689
Tires & wheels	427	549	655	695
Others (glider)	535	688	821	871
Engine	518	1208	1238	1686
Exhaust	275	354	422	449
Diesel tank	33	43	51	55
Transmission	154	198	236	250
Lead-acid battery	58	75	89	95
Retarder	53	68	81	87
Oil	23	30	36	38
Coolant	35	45	54	57
Total	**4600**	**6461**	**7500**	**8337**

For the BEVs, the glider components (cabin, frame, suspension, tires, wheels, and others) as well as the lead-acid battery were assumed to weigh the same as for the corresponding ICEVs. The weights of the transmission, retarder and coolant were estimated by using the same proportions between the components in the BEV and ICEV as in the LCI-inventory by Wolff et al. (2020). For example, the transmission of the BEV weighs about half of what the transmission for the ICEV weighs in the inventory. As such, the transmissions for the BEVs were estimated to weigh half of what the ICEV transmissions weighed.

The weights of the li-ion batteries were estimated by multiplying the assumed specific weight of the NMC622 battery packs with the assumed capacities:

200 kWh: 6.4496 kg/kWh * 200 kWh = 1290 kg

350 kWh: 6.4496 kg/kWh * 200 kWh = 2257 kg

625 kWh: 6.4496 kg/kWh * 200 kWh = 4031 kg

1000 kWh: 6.4496 kg/kWh * 200 kWh = 6450 kg

The weight of the electric machine was set to 860 kg for all BEVs (Wolff et al. 2020). The resulting weights of the tractor components of the BEVs are presented in appendix table 7.

Appendix table 7: The calculated tractor component weights for the baseline BEVs.

Component weights (kg)	12t lorry	28t lorry	44t lorry	60t lorry
Cabin	898	1156	1378	1464
Frame	553	712	849	901
Suspension	1036	1334	1590	1689
Tires & wheels	427	549	655	695
Others (glider)	535	688	821	871
Transmission	81	104	124	132
Lead-acid battery	58	75	89	95
Retarder	53	68	81	87
Coolant	35	45	54	57
Electric Machine	860	860	860	860
Battery Pack	1290	2257	4031	6450
Total	**5827**	**7849**	**10532**	**13301**

Trailer (and body) component weights

Since Wolff et al. (2020) only consider the tractor, the body/trailer weights were allocated to the various components based on the relative contribution of the components as in Sacchi et al. (2021). The calculated relative contributions of the components and the corresponding weight distributions are presented in appendix tables 8 and 9.

Appendix table 8: The calculated relative contribution of the trailer/body components to the total trailer/body weight.

Trailer/body	
Component	**Relative contribution (weight- %)**
Frame	35 %
Suspension	14 %
Wheels & tires	10 %
Brakes	5 %
Other	36 %

Appendix table 9: The calculated trailer component weights for the baseline vehicles.

Component weight (kg)	12t lorry	28t lorry	44t lorry	60t lorry
Frame	595	1540	2625	4121
Suspension	238	616	1050	1649
Wheels & tires	170	440	750	1178
Brakes	85	220	375	589
Other	612	1584	2700	4239
Total	***1700***	***4400***	***7500***	***11775***

v. Estimation of component material composition

The material compositions were estimated based on the LCI-inventory by Wolff et al. (2020). This was done by calculating the relative contribution (weight- %) of each material of a component, as presented in the LCI. The same composition for each component was assumed regardless of lorry size. This was done for all components except for the li-ion battery and lead-acid battery. The reason for this was that the LCI by Wolff et al. (2020) assumes a different battery chemistry for the li-ion battery (NMC111) than this study (NMC622), and that the LCI does not present the assumed material composition for the lead-acid battery. Data on the carbon footprints for these two components were thus added to the model on a component level, instead of on material level. Moreover, the body (i.e., the component containing the load) was not considered for the vehicle cycle, only the tractor and the trailer. The reason was the multitude of various body types and sizes (and therefore varying material consumption) that exist within the fleet, based on the findings in literature, see section 5.1.1.2.

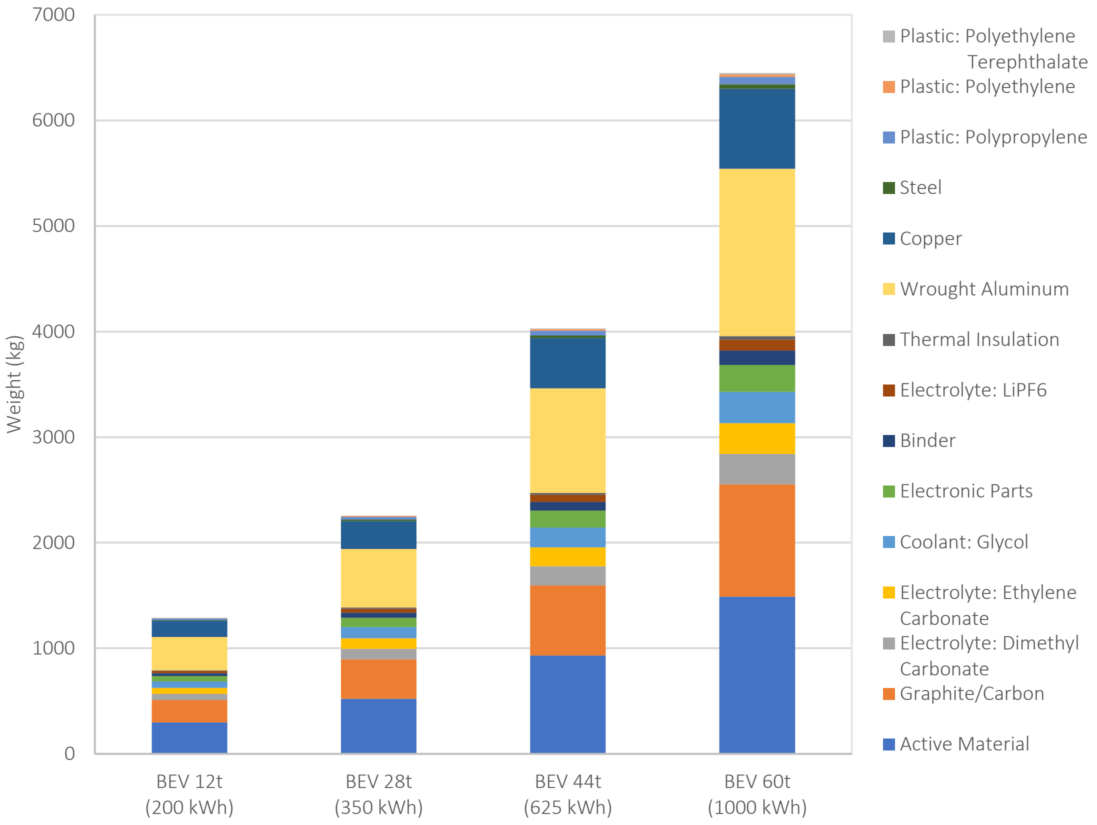
The calculated material weights are presented in Figure 28 and Figure 29 in the main report. Between 95 – 98 % of the baseline ICEVs' weights were estimated to consist of steel, cast iron, aluminium, rubber, and plastics. Between 96 – 98 % of the baseline BEVs' weights were estimated to consist of the same materials plus the battery pack. The aluminium composition was assumed to be 75 % cast aluminium and 25 % wrought aluminium, based on estimates for vehicles by Morfeldt et al. (2023, 2021) and weighted averages based on findings by Javaid et al. (2003). *Other* materials include platinum, ceramics, glass, organic material, magnesium, zinc, paint, lubricating oil, coolant and other non-specified materials in the LCI by Wolff et al. (2020). According to the calculations in this study, this category contributed to between 3 – 5 % of the total weight for the various ICEVs and between 2 – 4 % of the materials for the various BEVs. These materials were excluded from the carbon footprint calculations. Since they constituted to a small fraction of the total vehicle weights, the impact of these components on a lifecycle basis and fleet basis was considered omittable for the purpose of this study. Nonetheless, the exclusion of these components is a flaw in the study and lowers the calculated carbon footprint.

The battery pack materials for the NMC622 battery as assumed by Morfeldt et al. (2023, 2021) are specified by weight percentage in appendix table 10 and by resulting weights for the various battery capacities in appendix figure 3. The batteries are assumed to have a $LiNi_{0.6}Co_{0.2}Mn$

$_{0.2}$O2 cathode, synthetic graphite anode and N-Methyl-2-pyrrolidone solvent (Morfeldt et al. 2023, 2021). Note that these material estimations were not used for carbon footprint calculations, as these were calculated on a component basis for the li-ion battery.

Appendix table 10: The relative contribution of the li-ion battery pack. Estimated *by* (Morfeldt et al. 2023, 2021).

Battery materials	*weight- %*
Active Material	23.1 %
Graphite/Carbon	16.5 %
Electrolyte: Dimethyl Carbonate	4.5 %
Electrolyte: Ethylene Carbonate	4.5 %
Coolant: Glycol	4.6 %
Electronic Parts	4.0 %
Binder	2.1 %
Electrolyte: $LiPF_6$	1.6 %
Thermal Insulation	0.5 %
Wrought Aluminum	24.6 %
Copper	11.8 %
Plastic: Polypropylene	1.1 %
Steel	0.6 %
Plastic: Polyethylene	0.4 %
Plastic: Polyethylene Terephthalate	0.2 %



Appendix figure 3: Material weights for the li—ion batteries.

C. Transport demand

i. Vehicle activity estimations

Prognoses for vehicle activity within Swedish borders are presented in appendix table 11. These were estimated by the Swedish Energy Agency and acquired through Helen Lindblom (the Swedish Transport Administration) [43].

Appendix table 11: Prognosis for vehicle activity within Swedish borders 2018 – 2050.

Year	**Vehicle activity (Billion vkm)**	**Change compared to year 2018 (%)**
2018	4.9	-
2030	5.3	+ 8.16
2035	5.5	+ 12.24
2040	5.8	+ 18.37
2045	6.0	+ 22.50
2050	6.3	+ 28.47

The share of the vehicle activity supplied by foreign lorries within Swedish borders was assumed to be 20 %, which was the mean value of findings in statistics for years 2016 – 2021 (Transport Analysis 2022f)[44].

As such the vehicle activity for Swedish heavy-duty lorries within Swedish borders was assumed to be 80 % of 4.9 billion vkm in 2018, i.e., 3.9 billion vkm. The same changes over time as presented in appendix table 11 was assumed.

ii. Freight activity calculations

The freight activity for a certain time period can be calculated by multiplying the total vehicle activity during the time period with the average payload (SIKA 2004). Thereby, the annual freight activity for a specific weight class w_c was calculated by multiplying the annual total vehicle activity for the fleet with the share supplied by weight class w_c and the average payload for weight class w_c. See appendix equation (1).

$$Freight\ activity_{w_c} = vehicle\ activity_{fleet} \cdot \%\ of\ activity_{w_c} \cdot average\ payload_{w_c} \quad (1)$$

Thereafter, the total freight activity was calculated as the sum of the freight activities for the weight classes.

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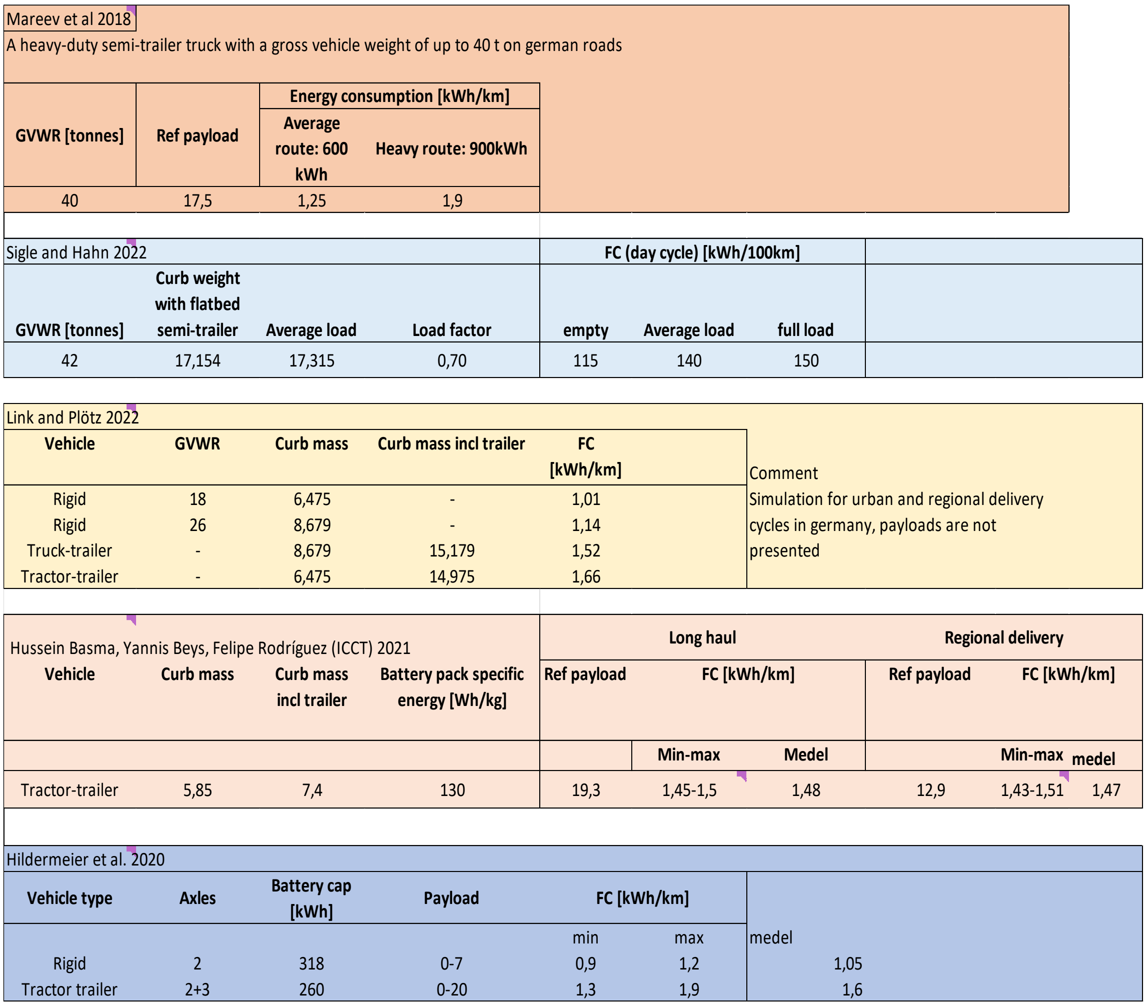
[43] Personal communication (email), 18 April 2023.

[44] The statistics only cover heavy-duty lorries with a maximum load > 3.5 tonnes and, as such, does not include the lightest heavy-duty lorries. This was deemed a good enough approximation for the study.

D. Literature findings on energy consumption

Literature findings on energy consumption is presented in appendix figures 4 and 5 for BEVs and ICEVs, respectively. An average energy consumption was calculated for each baseline vehicle by matching the literature vehicle data with the model's baseline vehicle characteristics such as GCWR, curb weight, payload, tractor and trailer configuration.

i. BEV



Mareev et al 2018

A heavy-duty semi-trailer truck with a gross vehicle weight of up to 40 t on german roads

GVWR [tonnes]	Ref payload	Energy consumption [kWh/km]	
		Average route: 600 kWh	Heavy route: 900kWh
40	17,5	1,25	1,9

Sigle and Hahn 2022				FC (day cycle) [kWh/100km]		
GVWR [tonnes]	Curb weight with flatbed semi-trailer	Average load	Load factor	empty	Average load	full load
42	17,154	17,315	0,70	115	140	150

Link and Plötz 2022

Vehicle	GVWR	Curb mass	Curb mass incl trailer	FC [kWh/km]	Comment
Rigid	18	6,475	-	1,01	Simulation for urban and regional delivery cycles in germany, payloads are not presented
Rigid	26	8,679	-	1,14	
Truck-trailer	-	8,679	15,179	1,52	
Tractor-trailer	-	6,475	14,975	1,66	

Hussein Basma, Yannis Beys, Felipe Rodríguez (ICCT) 2021

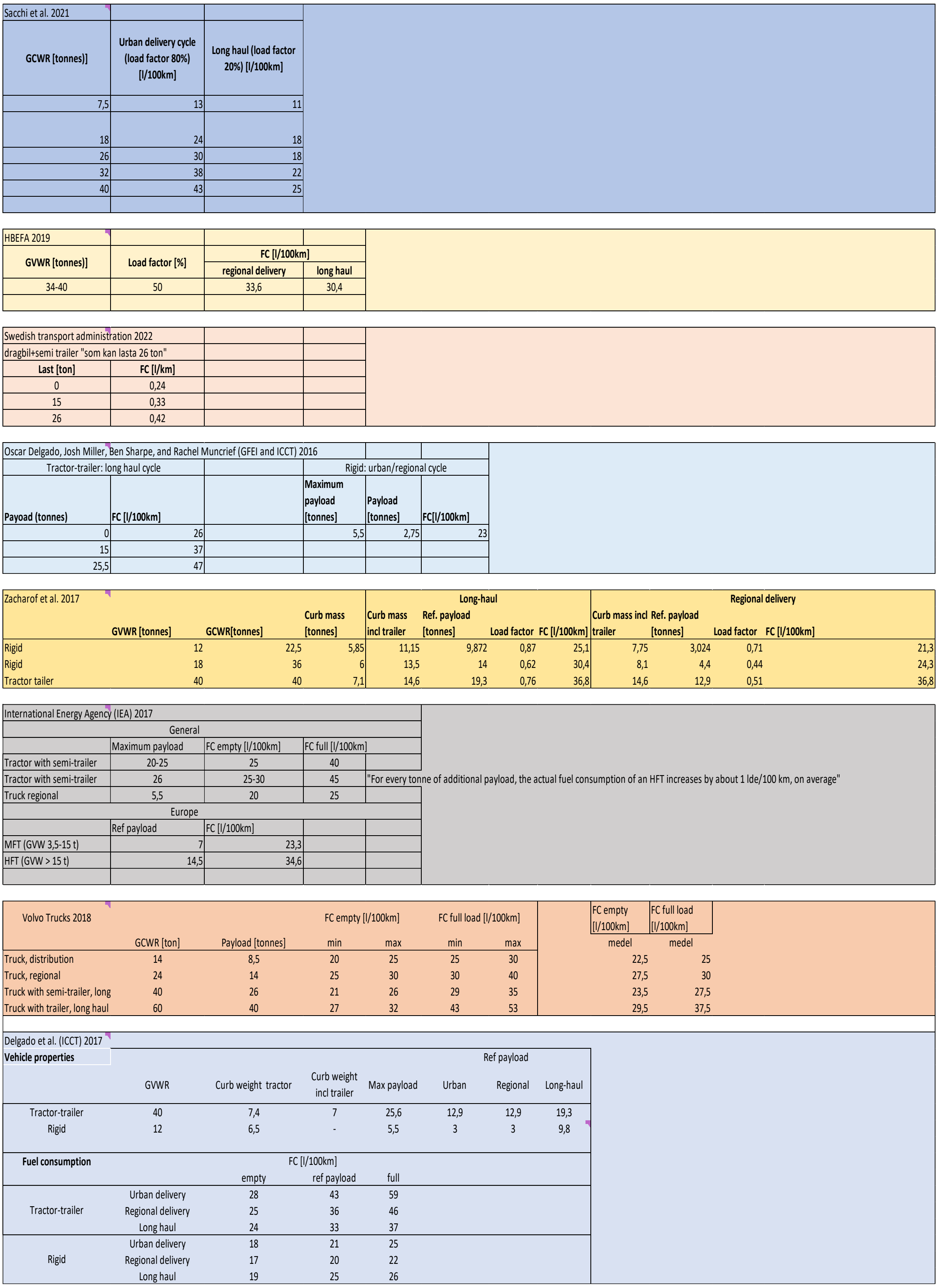
Vehicle	Curb mass	Curb mass incl trailer	Battery pack specific energy [Wh/kg]	Long haul			Regional delivery		
				Ref payload	FC [kWh/km]		Ref payload	FC [kWh/km]	
					Min-max	Medel		Min-max	medel
Tractor-trailer	5,85	7,4	130	19,3	1,45-1,5	1,48	12,9	1,43-1,51	1,47

Hildermeier et al. 2020

Vehicle type	Axles	Battery cap [kWh]	Payload	FC [kWh/km]		
				min	max	medel
Rigid	2	318	0-7	0,9	1,2	1,05
Tractor trailer	2+3	260	0-20	1,3	1,9	1,6

Appendix figure 4: Literature findings on electricity consumption for BEVs.

ii. ICEV



Sacchi et al. 2021

GCWR [tonnes)]	Urban delivery cycle (load factor 80%) [l/100km]	Long haul (load factor 20%) [l/100km]
7,5	13	11
18	24	18
26	30	18
32	38	22
40	43	25

HBEFA 2019

GVWR [tonnes)]	Load factor [%]	FC [l/100km]	
		regional delivery	long haul
34-40	50	33,6	30,4

Swedish transport administration 2022

dragbil+semi trailer "som kan lasta 26 ton"

Last [ton]	FC [l/km]
0	0,24
15	0,33
26	0,42

Oscar Delgado, Josh Miller, Ben Sharpe, and Rachel Muncrief (GFEI and ICCT) 2016

Tractor-trailer: long haul cycle			Rigid: urban/regional cycle		
Payoad (tonnes)	FC [l/100km]		Maximum payload [tonnes]	Payload [tonnes]	FC[l/100km]
0	26		5,5	2,75	23
15	37				
25,5	47				

Zacharof et al. 2017

				Long-haul				Regional delivery			
	GVWR [tonnes]	GCWR[tonnes]	Curb mass [tonnes]	Curb mass incl trailer	Ref. payload [tonnes]	Load factor	FC [l/100km]	Curb mass incl trailer	Ref. payload [tonnes]	Load factor	FC [l/100km]
Rigid	12	22,5	5,85	11,15	9,872	0,87	25,1	7,75	3,024	0,71	21,3
Rigid	18	36	6	13,5	14	0,62	30,4	8,1	4,4	0,44	24,3
Tractor tailer	40	40	7,1	14,6	19,3	0,76	36,8	14,6	12,9	0,51	36,8

International Energy Agency (IEA) 2017

General				
	Maximum payload	FC empty [l/100km]	FC full [l/100km]	
Tractor with semi-trailer	20-25	25	40	
Tractor with semi-trailer	26	25-30	45	"For every tonne of additional payload, the actual fuel consumption of an HFT increases by about 1 lde/100 km, on average"
Truck regional	5,5	20	25	

Europe		
	Ref payload	FC [l/100km]
MFT (GVW 3,5-15 t)	7	23,3
HFT (GVW > 15 t)	14,5	34,6

Volvo Trucks 2018

			FC empty [l/100km]		FC full load [l/100km]		FC empty [l/100km]	FC full load [l/100km]
	GCWR [ton]	Payload [tonnes]	min	max	min	max	medel	medel
Truck, distribution	14	8,5	20	25	25	30	22,5	25
Truck, regional	24	14	25	30	30	40	27,5	30
Truck with semi-trailer, long	40	26	21	26	29	35	23,5	27,5
Truck with trailer, long haul	60	40	27	32	43	53	29,5	37,5

Delgado et al. (ICCT) 2017

Vehicle properties

					Ref payload		
	GVWR	Curb weight tractor	Curb weight incl trailer	Max payload	Urban	Regional	Long-haul
Tractor-trailer	40	7,4	7	25,6	12,9	12,9	19,3
Rigid	12	6,5	-	5,5	3	3	9,8

Fuel consumption

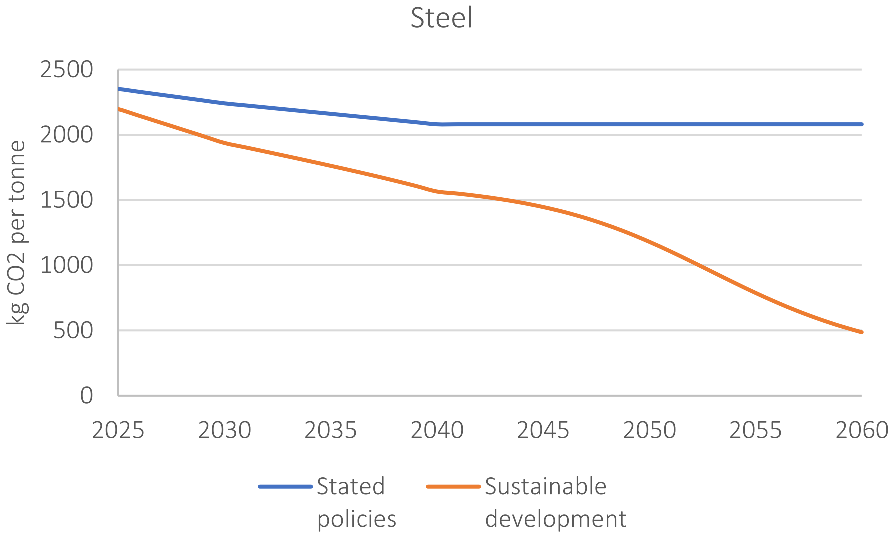
		FC [l/100km]		
		empty	ref payload	full
Tractor-trailer	Urban delivery	28	43	59
	Regional delivery	25	36	46
	Long haul	24	33	37
Rigid	Urban delivery	18	21	25
	Regional delivery	17	20	22
	Long haul	19	25	26

Appendix figure 5: Literature findings on fuel consumption for ICEVs.

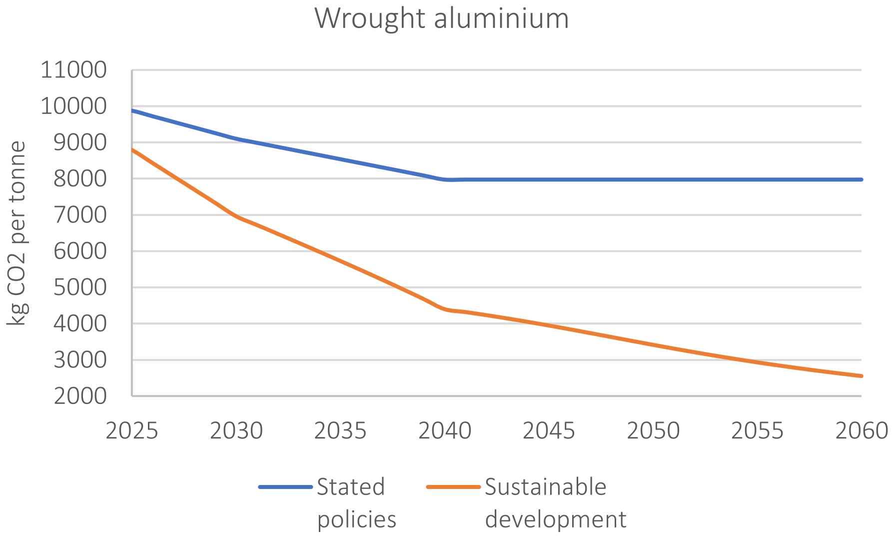
E. Literature LCA data for vehicle cycle

i. Materials

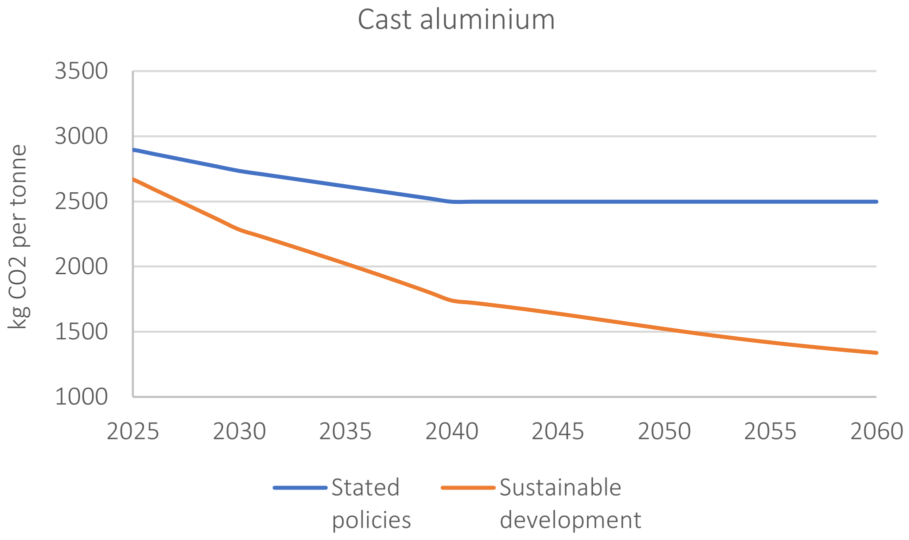
The assumed carbon intensities for steel, wrought aluminium, cast aluminium, cast iron, rubber, average plastics and copper are estimates by Morfeldt et al. (2023, 2021). These are presented in appendix figure 6 – appendix figure 12 below.



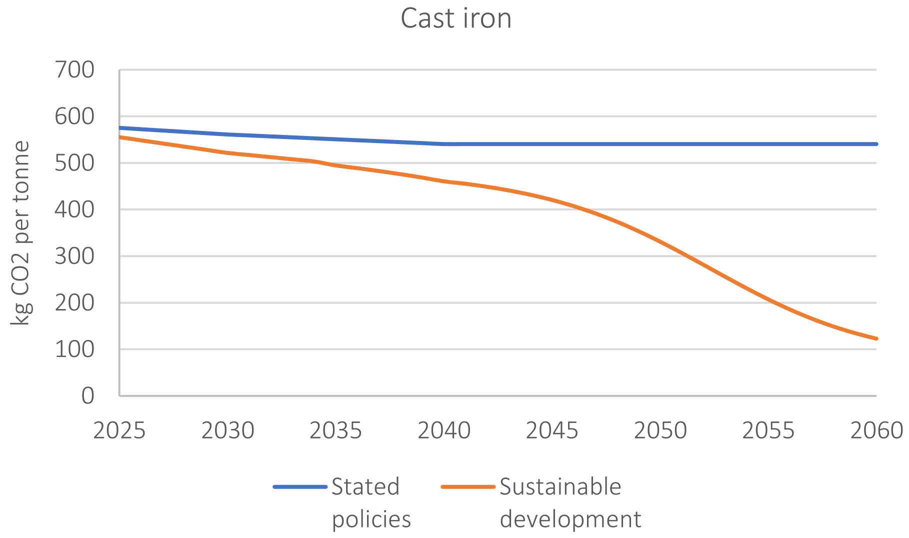
Appendix figure 6: Carbon intensities for steel 2025 – 2060.
Based on estimates by Morfeldt et al. (2023, 2021).



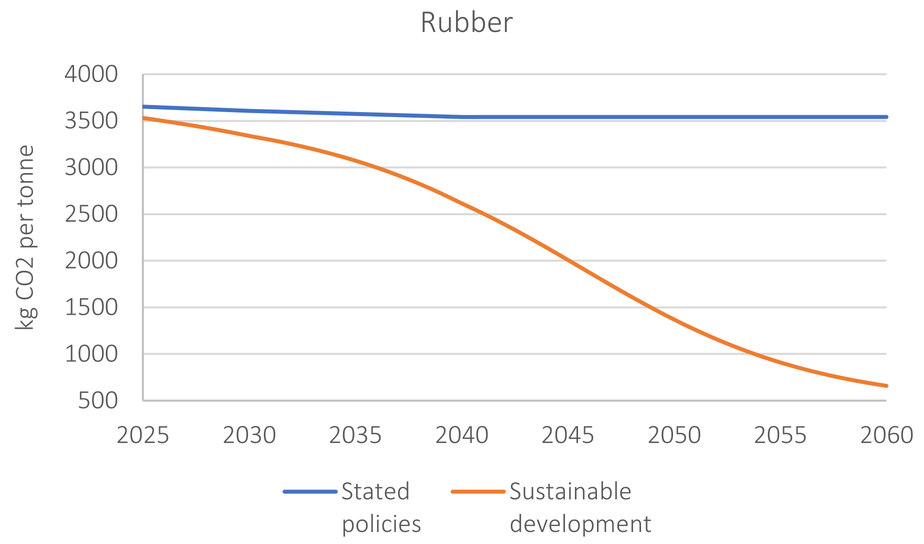
Appendix figure 7: Carbon intensities for wrought aluminum 2025 – 2060.
Based on estimates by Morfeldt et al. (2023, 2021).



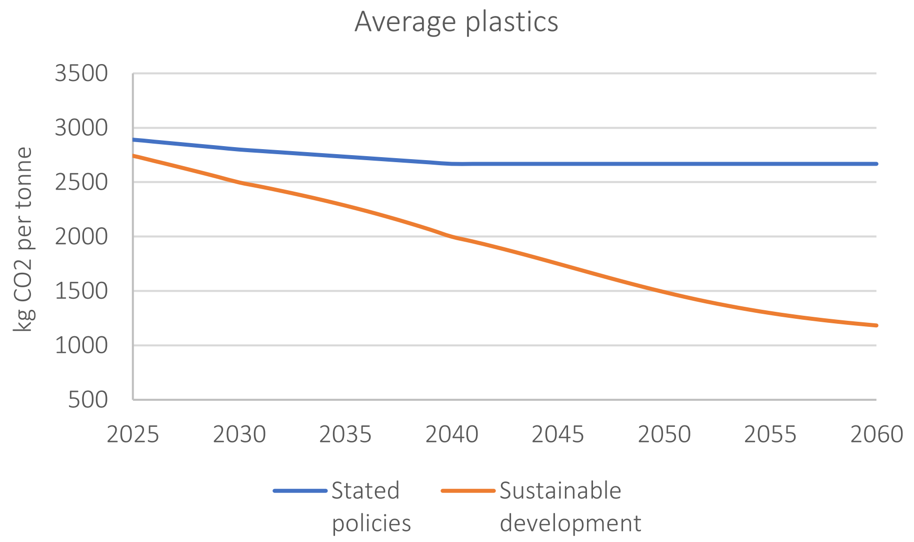
Appendix figure 8: Carbon intensities for cast aluminum 2025 – 2060. Based on estimates by Morfeldt et al. (2023, 2021).



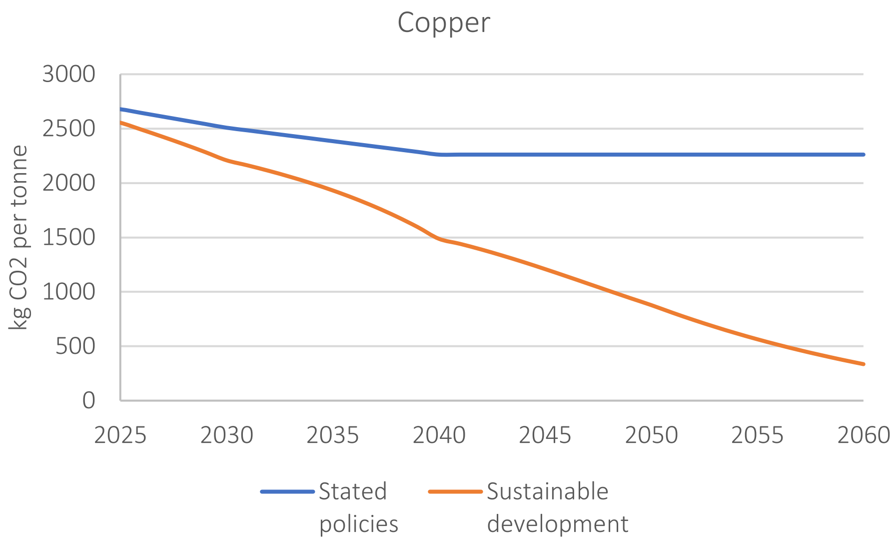
Appendix figure 9: Carbon intensities for cast iron 2025 – 2060. Based on estimates by Morfeldt et al. (2023, 2021).



Appendix figure 10: Carbon intensities for rubber 2025 – 2060.
Based on estimates by Morfeldt et al. (2023, 2021).



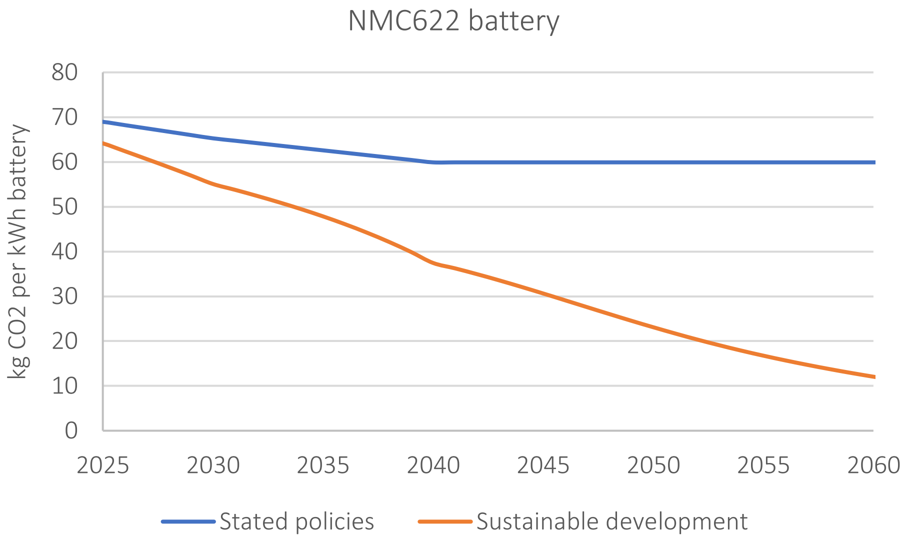
Appendix figure 11: Carbon intensities for average plastics 2025 – 2060.
Based on estimates by Morfeldt et al. (2023, 2021).



Appendix figure 12: Carbon intensities for copper 2025 – 2060.
Based on estimates by Morfeldt et al. (2023, 2021).

ii. Li-ion battery

The assumed carbon intensities for the NMC622 li-ion battery were acquired from Morfeldt et al. (2023, 2021) and are presented in appendix figure 13.



Appendix figure 13: Carbon intensities for NMC622 batteries 2025– 2060.
Based on estimates by Morfeldt et al. (2023, 2021).

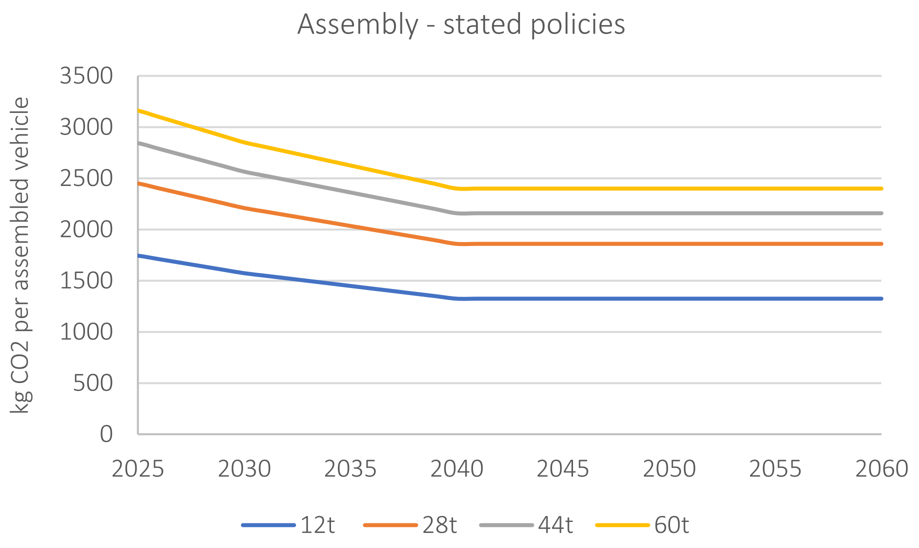
iii. Lead-acid battery

As no prospective LCA-data was found for the lead-acid battery, the carbon intensity was kept constant over the simulated time period regardless of background scenario. Based on estimates by Wolff et al. (2020), the carbon intensity was assumed to be 4.53 kg CO_2e per kg lead acid-battery.

iv. Assembly and disassembly

For the assembly process, the GHG emissions as presented by Wolff et al. (2020) was used as a base (2916 kg CO_2 per assembled vehicle) which was scaled based on tractor weight of the baseline vehicles in this study.[45] The same amount of GHG emissions were assumed for ICEVs and BEVs, such as in Wolff et al. (2020) and Morfeldt et al. (2021). Thereafter, the same percentual annual decrease of the GHG emissions connected to the assembly process as presented in (Morfeldt et al. 2023, 2021) was used. This approach was taken as the absolute GHG emissions for assembly in Morfeldt was given for a passenger car, not a heavy-duty lorry.

The assumed carbon intensities for the assembly process are presented in appendix figures 14 and 15 below.



Appendix figure 14: Carbon intensities for assembly in stated policies scenario. Based on estimates by Morfeldt et al. (2023a, 2021).

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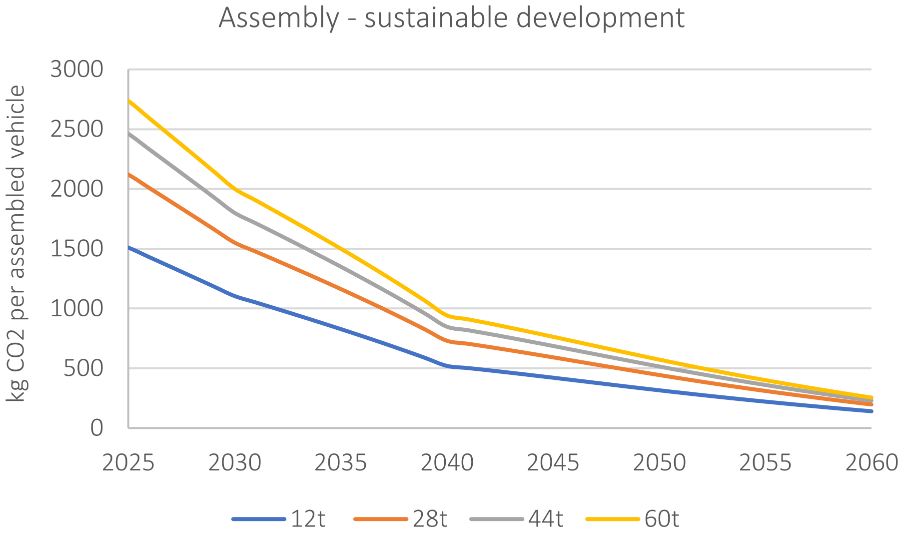
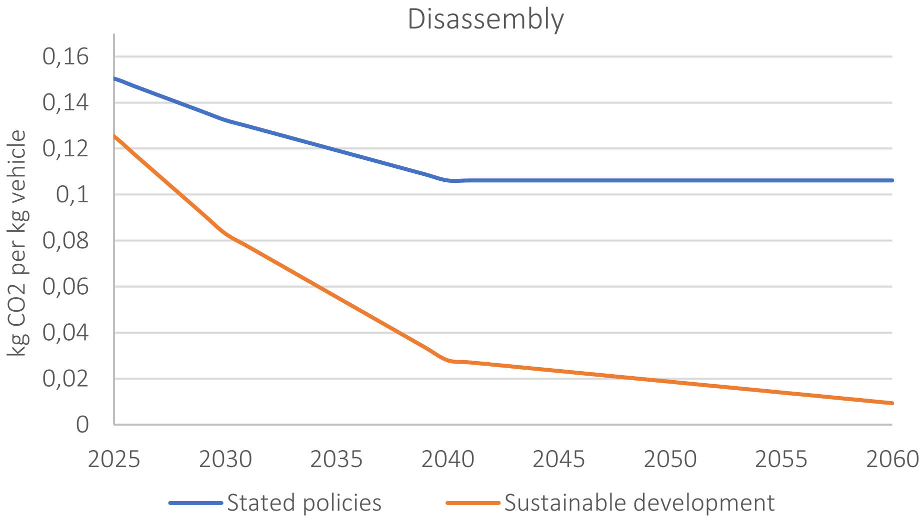
[45] The scaling factor was estimated by dividing the tractor weights of the ICEV baseline vehicles in this study with the tractor weight of the ICEV in Wolff et al. (2020).



Appendix figure 15: Carbon intensities for assembly in sustainable development scenario. Based on estimates by Morfeldt et al. (2023a, 2021).

The assumed carbon intensities for the disassembly process are presented in appendix figure 16 below, based on estimates by Morfeldt et al (2023, 2021). Unlike for the assembly process, the estimates for the disassembly process were given per kg vehicle and could as such be used directly in the model.



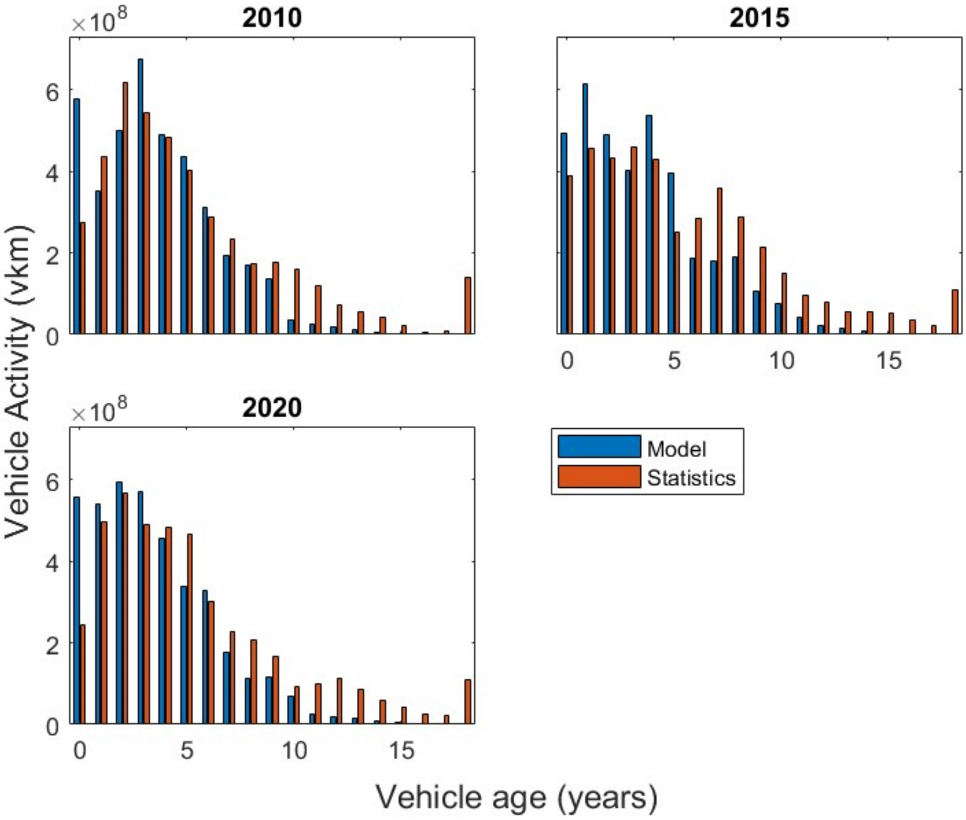
Appendix figure 16: Carbon intensities for disassembly 2025– 2060. Based on estimates by Morfeldt et al. (2023a, 2021).

F. Vehicle fleet turn-over model

i. Model verification

Appendix figure 17 shows a comparison of the supplied kilometres per age group of the fleet as estimated by the model and as presented in statistics[46], for years 2010, 2015 and 2020. The last bar seen for the statistics in the figure represents the sum of the supply from vehicle ages older than 18 years, as these are aggregated in the statistics.

As can be seen, the model tends to underestimate the supply contribution from the older vehicles, which is compensated by a larger supply from new sales.



Appendix figure 17: Comparison of model output and statistics for vehicle activity per age group

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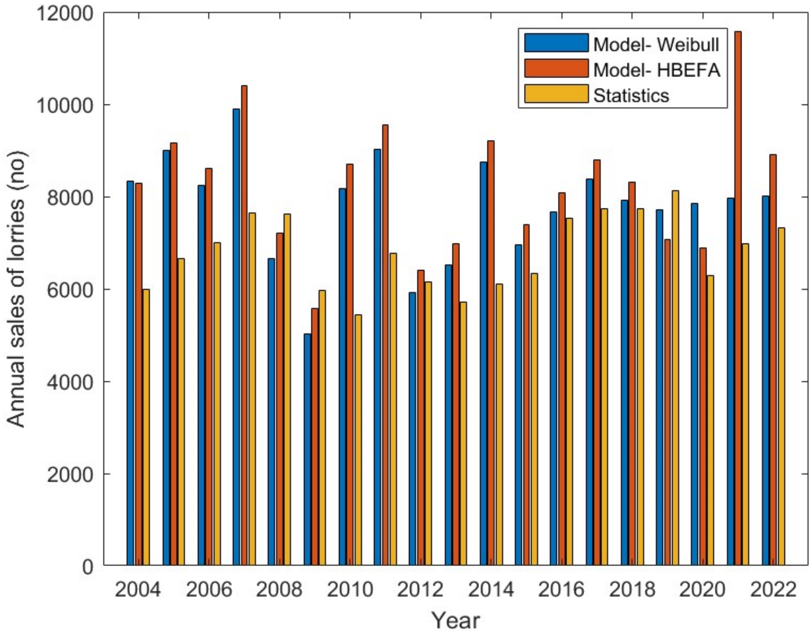
[46] (Transport Analysis 2022b)

Appendix figure 18 displays a comparison of the annual new sales of lorries presented in statistics[47] and the model output when using the two considered survival probability curves mentioned in section 2.5.1. It can be observed that the model tends to overestimate the number of new sales. The survival probability based on HBEFA lifespan curves result in slightly higher estimations than the Weibull distribution (based on statistics for scrappage). The overestimation by the model could be explained by that second-hand sales are not accounted for, instead all sales are assumed to be new sales.



Appendix figure 18: Comparison of model output and statistics for annual sales of lorries 2004 – 2022

ii. Annual supply and new sales per powertrain

This section presents model outputs on the annual supply per powertrain as well as the annual number of new sales per powertrain, depending on electrification scenario. Appendix figure 19 shows the annual vehicle activity and in appendix figure 20 the new sales.

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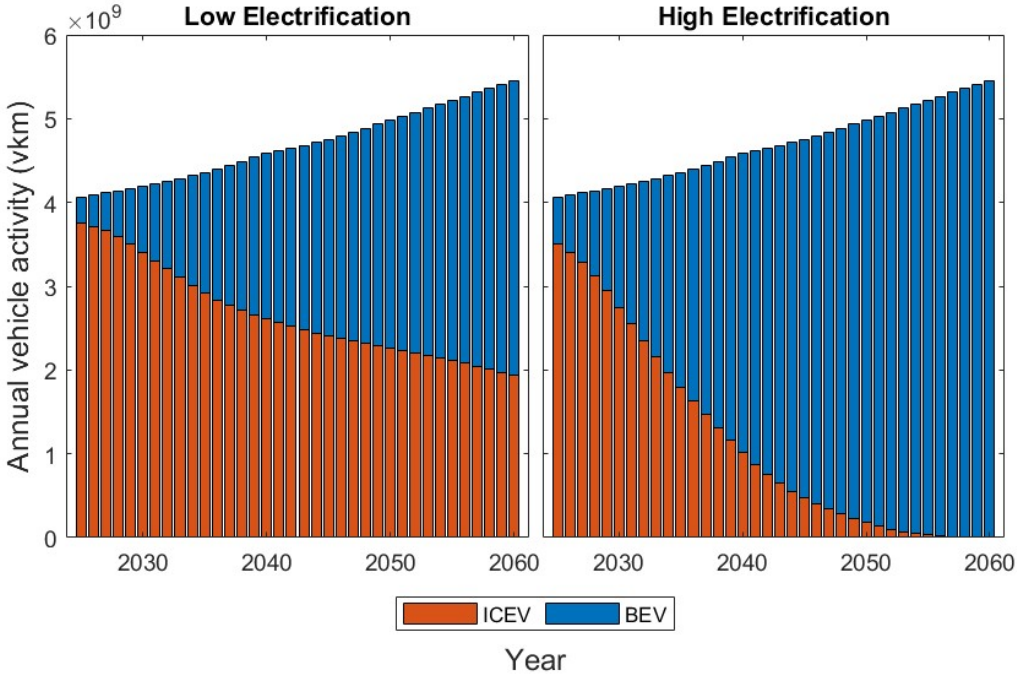
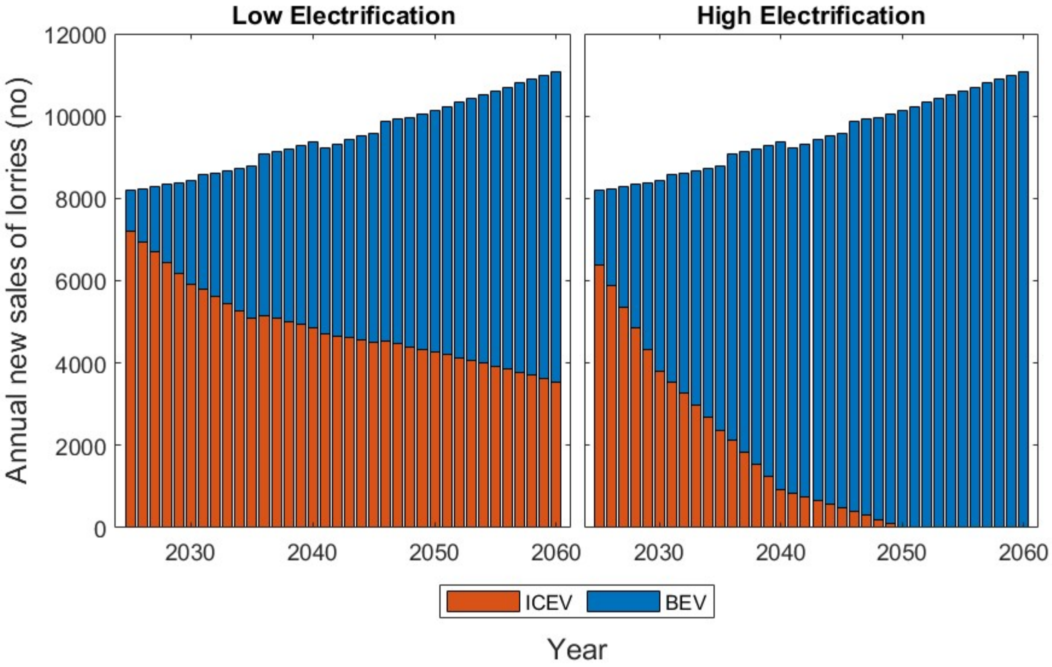
[47] Source for statistics 2004-2012 (Transport Analysis 2013)
Source for statistics 2013-2022 (Transport Analysis 2023b)



Appendix figure 19: Annual supply of vkm per powertrain 2025 – 2060.

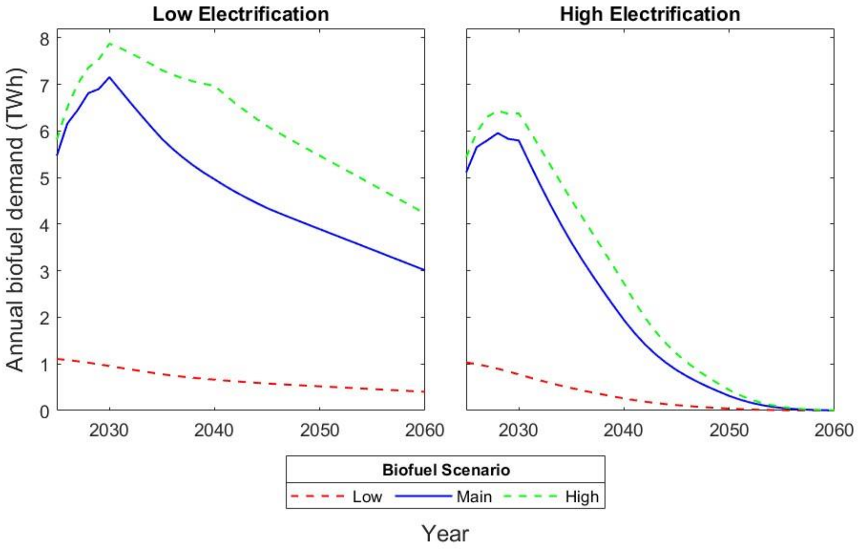


Appendix figure 20: Annual new sales of lorries per powertrain 2025 – 2060.

G. Additional scenario simulation results

i. Biofuel sensitivity analysis: Biofuel demand

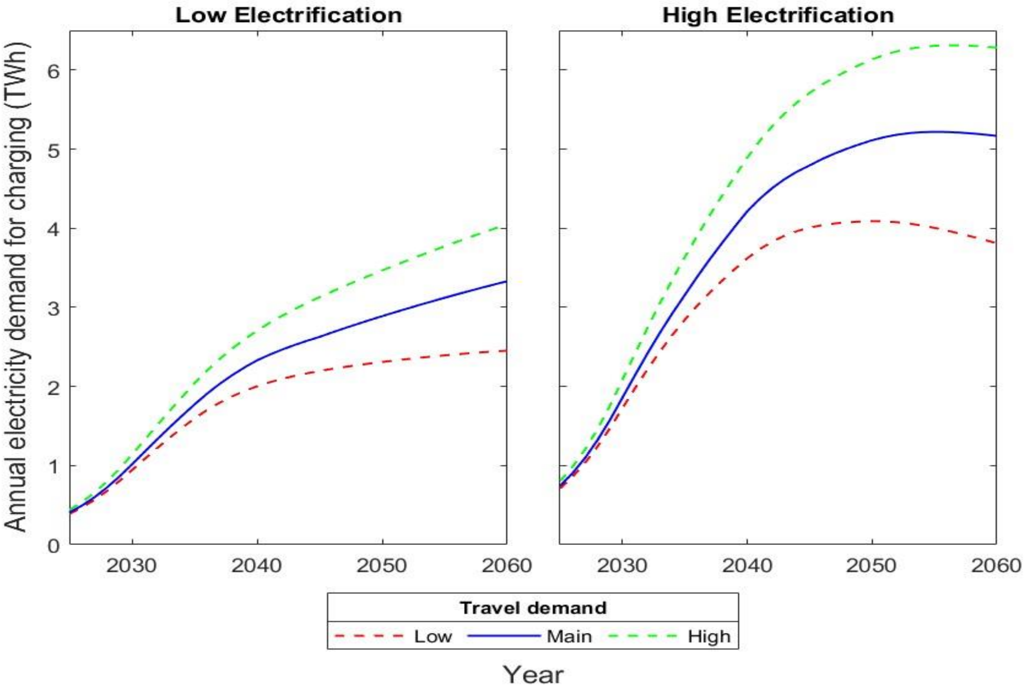
A sensitivity analysis of the biofuel scenario's impact on biofuel demand is displayed in appendix figure 21.



Appendix figure 21: Sensitivity analysis for biofuel demand.

ii. Transport demand sensitivity analysis: Electricity demand

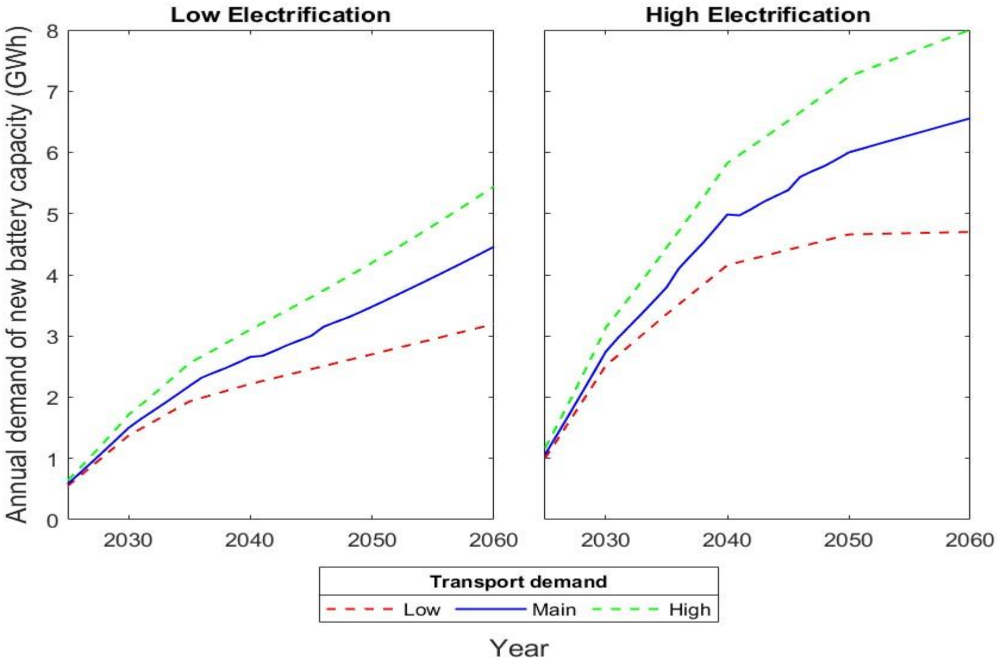
A sensitivity analysis of the travel demands impact on the electricity demand is displayed in appendix figure 22.



Appendix figure 22: Sensitivity analysis of transport demand

iii. Transport demand sensitivity analysis: Battery demand

A sensitivity analysis of the travel demand's impact on annual battery demand is displayed in appendix figure 23.

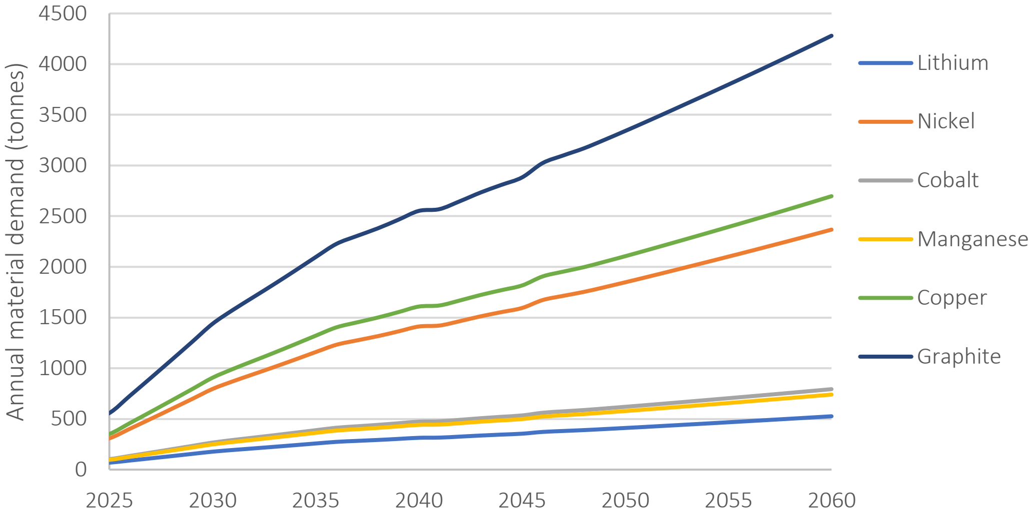


Appendix figure 23: Sensitivity analysis of annual battery demand for BEVs year 2025– 2060.

H. Material demand for NMC622 batteries

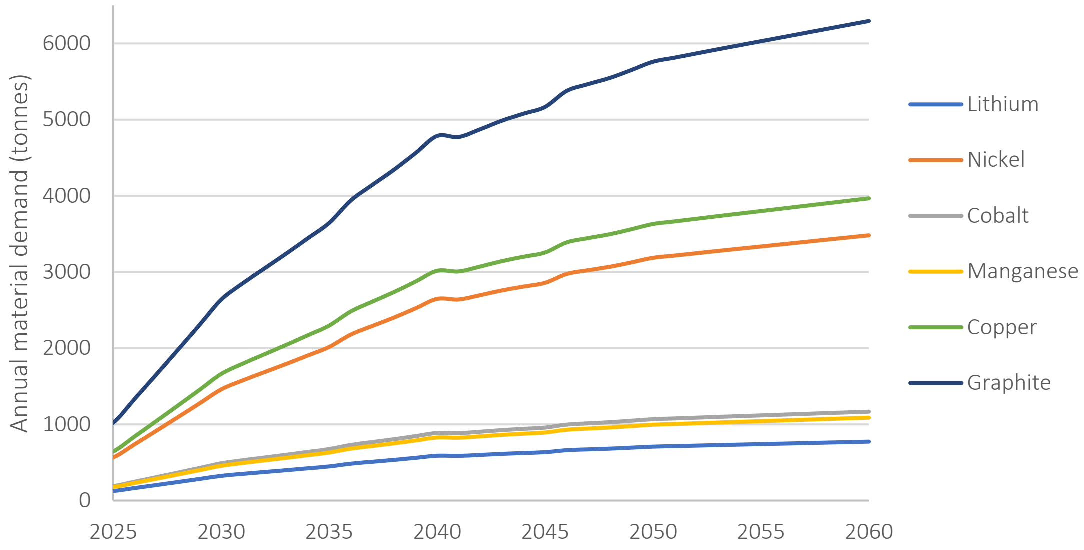
To gain a perception of the corresponding battery material demand for the fleet, the battery capacity demand from the simulation was multiplied by material demand estimations on battery metals for a NMC622 li-ion battery. The material estimations in kg/kWh were acquired from Dunn et al. (2021) and are presented in appendix table 12.

The estimated annual material demand for batteries in the low electrification scenario is displayed in appendix figure 24.



Appendix figure 24: Estimated material demand for batteries in the low electrification scenario.

The estimated annual material demand for batteries in the high electrification scenario is displayed in appendix figure 25.



Appendix figure 25: Estimated material demand for batteries in the high electrification scenario.

Appendix table 12. Material demand for NMC622 batteries (excluding aluminium). Source: Dunn et al. (2021).

Material	**kg/kWh**
Lithium	0.118
Nickel	0.531
Cobalt	0.178
Manganese	0.166
Copper	0.605
Graphite	0.960