Life Cycle Assessment of Electric Road Systems

– Climate impact in comparison with battery electric vehicles, biogas vehicles and fuel cell electric vehicles

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Sammandrag

En tredjedel av Sveriges årliga växthusgasutsläpp kommer idag från transportsektorn, vilket innebär att stora förändringar behöver ske om målet om nettonollutsläpp vid 2045 ska nås. En viktig åtgärd som diskuteras i denna kontext är en ökad elektrifiering och en lösning som har möjlighet att bidra i denna omställning är elvägssystem, där elfordon laddas dynamiskt. En typ av konduktiv elvägsteknik utvecklas av företaget Elonroad, vars lösning innehåller fyra huvudsakliga komponenter: skena, avtagare, ombordladdare och matarstation. För att avgöra om elvägar har möjlighet att bidra till utsläppsmålen undersöker denna studie klimatpåverkan från Elonroads elvägsteknik genom en livscykelanalys av de fyra komponenterna. Resultaten kombineras sedan med data från tidigare studier kring klimatpåverkan från elfordon, biogasfordon och bränslecellsfordon gällande både lastbilar och personbilar. Detta för att jämföra klimatpåverkan mellan fordonsslagen ur ett livscykelperspektiv. Slutligen används resultaten från livscykelanalysen i en fallstudie på Stockholms busslinje fyra.

Resultaten visar att en skena ger upphov till en klimatpåverkan om 2 590 kg CO_2-ekv, en avtagare 200 kg CO_2-ekv ekv, en ombordladdare 1 370 kg CO_2-ekv och en matarstation 153 000 kg CO_2-ekv, samt att hotspots är aluminium i skenan och spänningsomvandlaren i ombordladdaren. I jämförelsen mellan fordonsslagen visar resultaten att elvägsfordon har en betydligt lägre påverkan från livscykelsteget fordonsproduktion jämfört med stationärt laddade elfordon, då elvägar möjliggör en minskad batterikapacitet. Variabeln med störst påverkan på utfallet i jämförelsen är användningsgraden av elvägen, vilken avgör hur stor del av påverkan som tillskrivs vardera fordon. För tunga transporter, uttryckt i gram CO_2-ekv per tonkilometer, innebär en användninggrad över 428 fordon per dag att elvägsfordon har lägst klimatpåverkan bland de studerade fordonsslagen. Bränslecellsfordon med vätgas producerad via ångreformering av naturgas har högst påverkan, följt av biogasfordon med flytande biogas och därefter elfordon laddade stationärt. Lägst påverkan efter elvägsfordon med hög användningsgrad har bränslecellsfordon med vätgas från elektrolys. För personbilar, uttryckt i gram CO_2-ekv per fordonskilometer, krävs en användningsgrad över 4 780 fordon per dag för att elvägsfordon ska prestera bäst. Högst påverkan har bränslecellsfordon med vätgas från ångreformering av naturgas, följt av motsvarande med vätgas från elektrolys och därefter biogasfordon med komprimerad biogas. Lägst påverkan efter elvägsfordon med hög användningsgrad har elfordon med stationär laddning. Resultaten från fallstudien av Stockholms busslinje fyra visar att elvägar kan minska de årliga utsläppen från 1 480 ton CO_2-ekv/år med nuvarande system av biogas- och biodieselbussar till 480 ton CO_2-ekv /år. Vid en övergång till elbussar med stationär laddning kan en reduktion till 802 ton CO_2-ekv /år nås.

Nyckelord

Elvägssystem, Elonroad, livscykelanalys, laddskena, matarstation, avtagare, ombordladdare, klimatpåverkan, global uppvärmningspotential, lastbil, personbil, buss.

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Life Cycle Assessment of Electric Road Systems -
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Abstract

One third of Sweden's total annual greenhouse gas emissions originate from the transport sector today and great changes are thus needed in order to reach the net zero emission target by 2045. One of the most important measures discussed is an increased electrification of the transport sector and a solution with potential to contribute to this transition is electric road systems (ERS), where vehicles are charged dynamically. A conductive ERS technology is currently being developed by the company Elonroad, offering a solution involving four main components: rail, pick-up, on-board charger and feed-in station. This study investigates climate impact from Elonroad's ERS solution by conducting a life cycle assessment of the four components. Results from the life cycle assessment are also combined with findings in previous studies on fuel cell electric vehicles, battery electric vehicles and vehicles fuelled with biogas for both heavy-duty vehicles and passenger cars. This in order to compare climate impact between the renewable transport solutions from a life cycle perspective. Lastly, the results from the life cycle assessment of the ERS are used in a case study on the public transport bus line 4 in Stockholm.

It is found that one rail contribute to emissions of 2 590 kg CO$_2$-eq, one pick-up of 200 kg CO$_2$-eq, one OBC of 1 370 kg CO$_2$-eq and one feed-in station of 153 000 kg CO$_2$-eq, with hotspots being aluminium used in the rail and DC/DC converter used in the on-board charger. In the comparison between the propulsion systems it is seen that the ability for the ERS vehicles to downsize the battery reduces life cycle emissions from vehicle production significantly. The variable influencing the climate performance the most is the utilisation rate, determining how many vehicles sharing the environmental burden. For heavy-duty vehicles assessed in gram CO$_2$-eq per tonne kilometre, it is seen that above a utilisation rate of 428 vehicles/day the ERS vehicles have the lowest climate impact amongst the studied propulsion systems. Fuel cell electric vehicles using hydrogen from steam methane reforming of natural gas have the highest impact, followed by biogas vehicles using liquefied biogas and then battery electric vehicles. Lowest impact after ERS vehicles with a high ERS utilisation rate has fuel cell electric vehicles using hydrogen from electrolysis. For passenger cars assessed in gram CO$_2$-eq per vehicle kilometre, a utilisation rate of 4 780 vehicles/day is required for ERS vehicles to perform the best. The highest impact is seen for fuel cell electric vehicles using hydrogen from steam methane reforming of natural gas, followed by the corresponding but with hydrogen from electrolysis and then vehicles fuelled with compressed biogas. Lowest impact after ERS with a high utilisation rate has the battery electric vehicle. In the case study of Stockholm bus line 4 it is seen that ERS can reduce annual emissions from 1 480 tonne CO$_2$-eq /year with today's system of biogas and biodiesel buses to 480 tonne CO$_2$-eq /year with ERS. If instead transitioning to stationary charged electric buses a reduction to 802 tonne CO$_2$-eq /year is seen.

Keywords

Electric road systems, Elonroad, life cycle assessment, rail, feed-in station, pick-up, on-board charger, climate impact, global warming potential, articulated lorry, lower medium car, bus.

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Preface

This master thesis has been written as a last part of the MSc in Environmental Engineering at Lund University, Faculty of Engineering, LTH. The thesis was written during the spring semester of 2022 by Ebba Söderström and Emanuel Bengtsson, where both authors participated equally to the work. The thesis was written in collaboration with the company Elonroad and Examiner of the thesis was Max Åhman at the department of Technology and Society, Environmental and Energy Systems Studies.

We would like to thank our supervisor Pål Börjesson for great feedback, positive spirit and valuable advice during the journey. It is inspiring how precise and smart answers you deliver on both detailed and general questions.

To our supervisor at Elonroad, Johan Teleman, thank you for prioritising our weekly meetings, making Tuesdays the highlight of the week. Your engagement and genuine interest in the subject have really been appreciated and motivating for our continuous work.

To Elonroad and all employees at the company, thank your for your patience with all our questions and your pedagogic approach when explaining the technology. Last but not least, thanks for all delicious ”fredagsfika” and great community around the lunch tables.

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Lund, June 2022

Ebba Söderström & Emanuel Bengtsson

Abbreviations

AADT - Annual average daily traffic

AC - Alternating current

AD - Anaerobic digestion

CNG - Compressed natural gas

CO_2-eq - Carbon dioxide equivalent

BEV - Battery electric vehicle

BEV-ERS - Battery electric vehicle using electric road systems

BG - Biogas

CCS - Carbon capture and storage

DC - Direct current

EPD - Environmental product declaration

EPDM - Ethylene propylene diene M-class

ERS - Electric road systems

FAME - Fatty acid methyl ester

FCEV - Fuel cell electric vehicle

FCEV-electrolysis - Fuel cell electric vehicle fuelled with hydrogen from electrolysis

FCEV-SMR - Fuel cell electric vehicle fuelled with hydrogen from SMR

FU - Functional unit

GHG - Greenhouse gas

GWP - Global warming potential

HDV - Heavy-duty vehicle

HVO - Hydrogenated vegetable oil

IC - Integrated circuit

ICEV-CBG - Internal combustion engine vehicle fuelled with compressed biogas

ICEV-LBG - Internal combustion engine vehicle fuelled with liquefied biogas

LCA - Life cycle assessment

LNG - Liquefied natural gas

OBC - On-board charger

PCB - Printed circuit board

PM - Particulate matter

PWB - Printed wiring board

RME - Rapeseed methyl ester

SI - Spark-ignition

SMR - Steam methane reforming

Tkm - Tonne kilometre

TTW - Tank-to-wheel

Vkm - Vehicle kilometre

WTT - Well-to-tank

WTW - Well-to-wheel

Contents

1 Introduction

1.1 Background

The global average temperature has increased with one degree compared to pre-industrial levels and due to anthropogenic activities climate change is occurring at an unprecedented pace. To prevent the temperature increase and the irreversible effects that come with it, emissions of greenhouse gases (GHGs) contributing to climate change have to decrease. In the Paris agreement the EU states that global warming should be kept well below two degrees by drastically decreasing the emissions of GHGs to the atmosphere (European Commission 2022). The concrete action of this has in Sweden led to the decision of a net zero emission target for greenhouse gases by 2045 (Regeringskansliet 2020). Today, one third of Sweden's total annual GHG emissions originate from the transport sector. As a stepping stone towards achieving the net zero goal, the government has decided that emissions from the transport sector shall decrease by 70% to 2030 compared to the 2010 level. This will according to a governmental official investigation be attained by phasing out fossil fuels and steering towards an electrified transport sector, combined with an increased transport efficiency and a transition towards renewable fuels (Elvägsutredningen 2021). The Swedish Transport Administration states in their report *Scenarier för att nå klimatmålet för inrikes transporter* that the single most important part of the transition in order to reach the 2030 reduction goal is an increased electrification of the transport sector (Trafikverket 2020). An increased attention is also paid on reducing traffic work and planning for a decreased traffic density in the future as measures to reach the emission targets (Klimaträttsutredningen 2022).

Electrification has to this point mainly been focused on batteries and hybrid solutions supplying desired range for a vehicle. Another solution with potential to contribute to an increased electrification is electric road systems (ERS), where vehicles are charged in motion. An implementation of this technology could allow for a reduced battery size, an increased transport efficiency as a consequence of the dynamic charging, as well as a reduced demand for stationary charging infrastructure (Elvägsutredningen 2021).

The technology is not yet commercialised and there are a limited number of studies and life cycle assessments (LCAs) on ERS. Conducting an LCA is therefore of interest in order to evaluate if and under what circumstances the ERS technology may contribute to the goal of reduced emissions from the transport sector. Such a study is also of interest for comparison of the environmental performance between different renewable transport solutions. Besides ERS and battery electric vehicles (BEVs) using stationary charging, two other renewable solutions pointed out as possible alternatives to fossil-based transports are fuel cell electric vehicles (FCEV) and internal combustion engine vehicles (ICEVs) using biofuels. Amongst biofuels used in Sweden today, biogas is reported to have one of the best GHG performances (Energimyndigheten 2021a), which therefore is of relevance to include in a comparison between the previous mentioned propulsion systems. Out of the mentioned technologies, both FCEVs and ERS are by the Swedish Transport Administration pointed out as important solutions in order to meet the net zero emission goal, but are expected to play a more important role after 2030 due to the novelty of the technologies (Trafikverket 2020).

1.2 Aim and research questions

The aim of this study is to perform a life cycle assessment on an electric road system developed by the company Elonroad in Lund and to compare climate impact between vehicles using the ERS and other renewable transport solutions. The studied impact category is climate change and the result from the LCA will be used together with previous studies on fuel cell electric vehicles, battery electric vehicles using stationary charging and vehicles fuelled with biogas. By performing a sensitivity analysis this study aims to understand if and under what circumstances ERS is advantageous to the other listed renewable solutions, from a life cycle perspective. As a last part, the results from the LCA of the ERS will be used in a case study on the public transport bus line number 4 in Stockholm. The case study will be based on a previous study investigating the traffic conditions of the line. The aim will be fulfilled by answering the following research questions:

- From a life cycle perspective, what climate impact does the different components of Elonroad's electric road system have?

- What climate impact from heavy-duty vehicles and passenger cars is found in previous studies examining fuel cell electric vehicles, battery electric vehicles charged with stationary charging infrastructure and vehicles fuelled with biogas?
- Based on the results from the life cycle assessment and the literature review, how does climate impact differ between the four propulsion systems and what parameters have the largest impact on the result?
- What climate impact does the electric road system from Elonroad have if applied to the public transport bus line 4 in Stockholm compared to current system and a system with stationary charged battery electric buses?

1.3 Electric road systems

One path towards an electrified transport sector is via ERS, which is a technology where vehicles are charged dynamically, i.e. in motion. This in contrast to the dominant charging technology of today for electric vehicles in the form of stationary charging with conventional charging points. With ERS, the electricity may be transferred to the vehicle in several different ways and these can be summarised into four main categories: conductive overhead, conductive rail, conductive on side and inductive (Elvägsutredningen 2021).

In Sweden there are at present four pilot projects together covering all mentioned solutions except the conductive on side of the road. Outside Sandviken the conductive overhead technology is tested, using catenary wires and a pantograph on the vehicles. This is comparable to how trains, trolley buses and trams have been driven for more than 100 years. The conductive rail solution is being tested at two places, Lund and Arlanda, however with different designs. In Visby, the inductive solution with wireless power transfer is developed (Elvägsutredningen 2021).

All solutions tested in Sweden come with their pros and cons, differing in e.g. power transfer capability, voltage level, flexibility towards vehicle type, billing system and impact on existing road and its maintenance (Elvägsutredningen 2021). As a consequence of different power transfer capability, the electrification rate is also varying, i.e. how much of the road that is electrified (Natanaelsson et al. 2021). Furthermore, the environmental impact will also differ between the ERS types, which is discussed further in section 1.4.2.

In this study Elonroad's ERS technology is examined. Elonroad is a start-up company in Lund founded by Dan Zethraeus in 2014, developing a solution of the conductive rail system. The company currently focuses on two different products where one is the dynamic charging solution, with a market today targeting closed-loop systems such as ports. The ambition is to up-scale this and implement it on highways and in cities to be able to charge vehicles in motion. The solution is currently being tested in Lund as a pilot project. The other product is an automated stationary charging solution where the rails are used in for example terminals to replace stationary chargers.

This ERS is based on the conductive rail technology, where a 30 cm wide and 5 cm thick rail is submerged into an existing road in the middle of a lane. The rails are 9.2 m long and are connected in series to reach desired length. Electricity is supplied from the grid to the rails via feed-in stations, in which incoming alternating current (AC) level is lowered and then converted to direct current (DC) used in the rails. The system voltage in the rails is set to 600 V DC, with possibility to increase up to 800 V DC. Approximately one feed-in station per kilometre electric road is needed.

To be able to transfer electricity to the vehicle, a pick-up is mounted underneath the vehicle. The pick-up automatically connects the vehicle to the rail by adjusting its arm vertically and horizontally. Depending on the number of sliding contacts, 150 or 300 kW may be transferred. For the vehicle to be able to receive electricity from the electric road, an on-board charger (OBC) also needs to be installed in the vehicle to match the DC voltage levels between rail and vehicle battery.

The rails are divided in segments of 1 m, offering the possibility to activate only the part that is being covered by a vehicle and thus increasing the security. It is possible to implement the technology in electrified highways, for public transports, in closed loop systems such as ports or as stationary parking chargers. In this report the ERS focus is on highways or larger roads and on public transport in terms of a city bus line in Stockholm.

Elonroad's ERS technology and its components are visualised in figure 1. In addition to the components already described, a cloud service managing billing and communication between vehicle, rail and Elonroad's server will also be used as seen in figure 1. This is however not fully developed yet and is therefore not considered in this study.

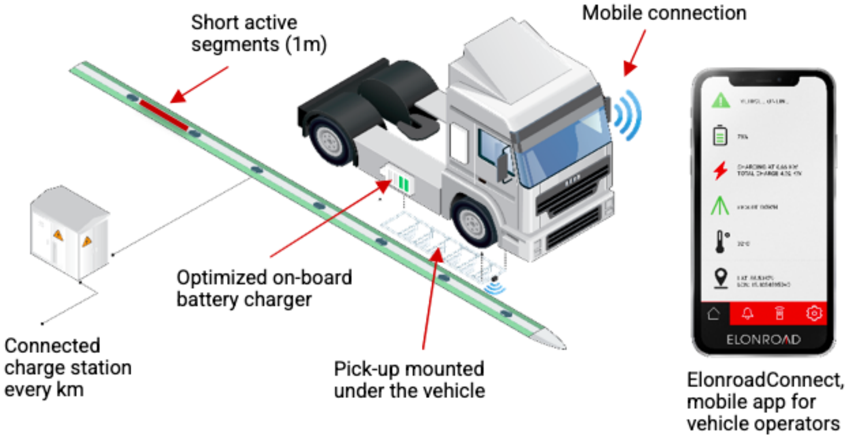


Figure 1: Overview of Elonroad's ERS components. Picture from Elonroad.

A visualisation of the rail submerged into the asphalt is shown in figure 2.

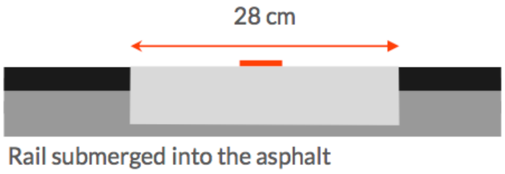


Figure 2: Cross section of road with rail submerged into the asphalt. Picture from Elonroad.

1.4 Previous studies

There are several previous studies examining the ERS technologies from different perspectives, both economically, environmentally and technically. However, non of them investigating climate impact in detail and in comparison with other renewable propulsion systems from a life cycle perspective. This section aims to summarise important findings from previous works useful and relevant to this study. In Sweden the Swedish Transport Administration have been assigned the task from the government to investigate prerequisites and plan for an implementation of electric roads, which is presented in a report by Natanaelsson et al. (2021). Results and important assumptions from this report is presented in section 1.4.1, followed by a review of other relevant studies in coming section regarding different environmental aspects.

1.4.1 ERS scenario by The Swedish Transport Administration

In the report by Natanaelsson et al. (2021), analysing how a possible implementation of ERS could be performed in Sweden, it is described that 2 000 km of electric roads are planned to be in operation by 2030 and an additional 1 000 km by 2035, thus a total of 3 000 km by 2035. This is in two directions, meaning that the total length of the system will be 6 000 km. The initially intended 2 000 km are the largest E-roads and highways in Sweden with the highest traffic density, complemented with 1 000 km strategic routes between ports and terminals. The report is focused on heavy-duty transports as it predicts that these are the only vehicles that will use the ERS at an early stage. Important parameters and assumptions made by Natanaelsson et al. (2021) will be described onwards, thus focusing on heavy-duty vehicles (HDVs).

The fundamental parameter when determining the performance of an ERS is the utilisation rate and how many vehicles are sharing the investment, both concerning GHG emissions and economy. The utilisation rate is dependent on the traffic density of the specific road and the share of these vehicles utilising the ERS. Natanaelsson et al. (2021) have made estimations for both parameters, expressed in annual average daily traffic (AADT). This is a measure of how many vehicles passing a certain road segment per day on average, based on the total traffic volume during a year. It accounts for traffic in both directions and may represent either a point or an entire road network (Trafikverket 2015). When evaluating a road network as in this case with an electric road system, the AADT is dependent on which roads that are included in the network, reducing the AADT value if roads with low traffic volume are added to the system.

In the report by Natanaelsson et al. (2021) a heavy-duty AADT for the entire system of 3 000 km is presented for different years between 2030 and 2040, based on a linearly increased traffic volume from today's level. An AADT for HDVs using the ERS at the different years is then derived from an assumption on the share of all vehicles that will use the ERS, including both Swedish and foreign vehicles. The derived AADT values by Natanaelsson et al. (2021) is presented in table 1. The default case in their report is the higher value, named ”AADT HDV using ERS” in the table. There is also an assumption on a low case, where the low case is 50% of the identified AADT using ERS. As can be seen in table 1, at 2040 it is assumed that 25% of all HDVs are using the ERS, whilst the share is lower before that.

Table 1: Annual average daily traffic (AADT) in vehicles/day for heavy-duty vehicles (HDVs) in total respectively using ERS for a system of 3 000 km electric roads. Data from Natanaelsson et al. (2021).

	2030	**2033**	**2035**	**2037**	**2040**
Total AADT HDVs	3 100	3 500	3 750	4 150	4 400
AADT HDVs using ERS	345	676	896	973	1 088
AADT HDVs using ERS (low case)	172	338	448	486	544

Serving as basis for the derived AADT values is a survey study included in the report, investigating driving patterns and how much of the total travelled distance during a year that a truck is driving on the 3 000 km network. Natanaelsson et al. (2021) assumes that trucks driving 40% or more of their total annual driving distance on the road network will have incentive to use the ERS. Among these vehicles, the result from the survey shows that 60% of their total driving distance will occur on the road network analysed.

Another factor influencing both performance and design of the ERS infrastructure is the so called electrification rate. This term refers to the fraction of a certain road distance with ERS that actually is electrified, i.e. that is equipped with rails as in the case of Elonroad. Different ERS technologies are able to transfer different amount of power to a vehicle and the ERS needs to provide the vehicle with enough energy to both be able to drive on the electric roads continuously but also a certain distance outside the ERS network with energy from the battery (Natanaelsson et al. 2021). This parameter is further studied by Domingues-Olavarría (2018), investigating the cost efficiency of different electrification rates. It was found that the lowest system cost was reached at 50% electrification rate. This value of 50% is further motivated by Elvägsutredningen (2021), pointing out that several studies have come to a similar conclusion that around 50% is an optimal rate. Of the four technologies examined by Natanaelsson et al. (2021), it is described that the inductive will need an electrification rate of 100%, the conductive catenary 35%, the conductive at road (not being Elonroad's) 67 & and Elonroad's conductive at road 60%. The choice of electrification rate does also affect other components such as OBC, feed-in station and battery size, since it influences how much energy that needs to be transferred during a certain distance to provide enough energy to the vehicle.

In the report, Natanaelsson et al. (2021) make an economical analysis of a possible ERS implementation of any of the technologies. The conclusion is that it might be socio-economically beneficial, dependent on future development of other factors such as the greenhouse gas reduction mandate, fuel prices, user fee and battery technology development. An estimation of the GHG reduction potential for ERS is also performed.

The possible reduction of emissions from the HDV fleet with an implementation of ERS depends on the level of the reduction mandate. The report concludes that emissions from HDVs at year 2040 could be reduced by 9-18% with a low level of the reduction mandate. With a more ambitious level of the mandate the corresponding reduction is 3-7%. In the short term, biofuels are pointed out as important and cost efficient alternatives together with stationary charging (Natanaelsson et al. 2021).

1.4.2 Environmental aspects

Natanaelsson et al. (2021) have as already mentioned included an estimation of the reduction potential, however for the entire transport sector and not on individual vehicle level. A rough estimation on emissions, not considering the entire life cycle, is also made by Pettersson et al. (2017). The comparison does only involve the omitted tailpipe emissions with a transition to electric vehicles.

In a study by Haugen, Paoli, Cullen, Cebon and Boies (2021), different energy pathways for transports are investigated in terms of energy efficiency and GHG emissions regarding vehicles with low emissions (BEVs and FCEVs). ERS is included in the comparison of heavy-duty vehicles and it was found that ERS reached the highest energy efficiency, out-competing BEV and FCEV independent on electricity or hydrogen production pathway. The CO_2 emissions in g CO_2/km is modelled as a function of electricity mix, including alternatives such as production of electricity and hydrogen from both electrolysis and steam methane reforming, as well with as without carbon capture and storage (CCS). The results show that with a renewable electricity grid ERS has the lowest impact. Given an average global electricity mix, both BEVs and FCEVs fuelled with electricity respectively hydrogen produced from natural gas seem marginally advantageous, amplified further if using the CCS technology.

Nordin (2020) have made a review of existing LCAs where the three different ERS technologies overhead catenary, conductive rail and inductive are compared. The author states that there are a limited number of studies on the field, making it difficult to assess the technologies fairly. The report also focuses on the comparison between an ordinary road and an electric road, from construction to operation. Since maintenance and operation are the main contributors in terms of GHG emissions when only studying the life cycle of an ordinary road, it is important to consider how an ERS technology will affect this (Nordin 2020).

In a report by Taljegard, Thorson, Odenberger and Johnsson (2020) examining CO_2 emissions and cost for ERS in Sweden and Norway, effects from large-scale implementation were analysed. The study found that if 25% of the total E- and N-road length in Sweden and Norway were electrified, 35% of all travelled vehicle kilometres in both countries could be electrified and 70% of the traffic specifically on these roads. With ERS on 40% of the E- and N-roads, GHG emissions is found to be reduced by 36% for light-duty vehicles and 55% for heavy-duty vehicles compared to existing system. However under the circumstances that emissions from ERS transports are assumed to be zero.

Schulte and Ny (2018) have made a comparison between ERS and current diesel system for freight transports from a simplified model of a catenary overhead ERS. In the report it is seen that with wind power electricity, ERS performs better than a diesel system in 11 of 18 impact categories studied. With a European electricity mix the impact is instead higher in 12 of the 18 categories. The GHG performance is however still better with a European mix, but worse than diesel with a coal-based production. A large contributor is the copper used in the catenaries, causing a greater impact in toxicity categories and metal depletion independent of electricity mix. The payback time in terms of GHG compared to a diesel system was also examined as a function of the number of trucks using it per day. With a Nordic electricity mix, break-even is reached in about three to four years with 1 000 trucks/day under ten years with 500 trucks/day. Another factor discussed is the lock-in effect with ERS due to its long lifetime, motivating the need of holistic research on both environmental as economical aspects before investing and implementing the technology on large-scale. From the results in the study the authors conclude that ERS might be an important factor in the electrification transition in order to reach sustainable transports, but with recommendation to compare the ERS also with other alternatives such as BEV and FCEV trucks.

Several other studies on different ERS technologies such as dynamic wireless charging have come to a similar conclusion regarding its potential in reducing climate impact from transports, especially compared to today's conditions with fossil-based fuels in ICEVs (Limb et al. 2019; Bi et al. 2019; Connolly 2016; Plötz, Gnann, Jochem, Yilmaz & Kaschub 2019; Gustavsson, Hacker & Helms 2019).

There is one study comparing the three different ERS concepts in terms of impact per km road, conducted by Balieu, Chen and Kringos (2019). Impact from construction, maintenance during winters and rehabilitation is considered, where all three technologies seems to imply a greater impact compared to an ordinary road per km constructed road. Even though no detailed investigation on exact material composition is performed, the results indicate marginally lower GHG emissions for the conductive rail compared to the inductive technology and highest for the overhead catenary. For the construction phase it is assumed in the study that the conductive rail only is consisting of steel in a quantity of 5 tonnes per km road.

A previous master thesis by Nádasi (2017) did investigate the impact from construction of the same three different electric road types via development of a SimaPro model. It does however only focus on the ERS life cycle infrastructure and not the use phase. It is pointed out ERS technologies without copper cables, i.e. the conductive rail, seem to be advantageous in terms of climate impact.

More impact categories are discussed in the literature review by Nordin, Hellman, Genell, Gustafsson and Andersson-Sköld (2020). Even though electric vehicles have no particle emissions (PM10 and PM2.5) during driving unlike the combustion engines, progresses in particle filter technology have diminished this difference. However, there is a possible source of PM10 particles from the conductive rail due to wear of the contact material between vehicle and rail. In addition, particles from wear of tyres, brakes and the road surface will remain relatively unchanged with ERS. It is also concluded that since ERS probably will be constructed on large roads with high vehicle velocities, a decreased noise level is not to expect since the engine noise is not dominating at these velocities. However, a question regarding additional noise from the conductive rail is raised. Lastly, electromagnetic fields are discussed in the study as an important factor to consider if implementing ERS.

Bi, Keoleian and Ersal (2018) have examined the implementation of wireless charging for an electric bus network at bus stops, similar to a solution with ERS, accounting for e.g. battery downsizing and its effects. An optimisation of how the charging infrastructure should be implemented is made and the results show that optimal siting compared to non-optimal siting may decrease life cycle costs with 13%, GHG emissions with 8% and energy demand with 8%. A similar study was earlier performed by Bi, Song, De Kleine, Chris Mi and Keoleian (2015) comparing plug-in and wireless charging for electric buses. The results indicates that the battery can be downsized with 27-44% with a wireless solution, decreasing the total bus weight and thus also the fuel consumption. There is also a potential of reducing climate impact compared to a plug-in solution, depending on charging efficiency. Another factor discussed is the effect of charging during daytime instead of during nighttime as for plug-in. This could imply additional load on the electricity grid during peak time, but could be beneficial from a GHG perspective if the daytime electricity mix is less carbon intense than that during nights.

Another aspect affected by an ERS implementation is the energy consumption, investigated by Márquez-Fernández, Bischoff, Domingues-Olavarría and Alaküla (2022) together with the need of charging infrastructure and system cost. It is concluded that an ERS have the potential of reducing the energy consumption from HDVs due to a lighter vehicle as a consequence of a downsized battery compared to a system without an ERS. It is on the contrary seen that passenger cars instead may increase their consumption, a result of that a longer travel distance is chosen in favour of travelling on electric roads. Furthermore, it is estimated that around 30 000 charging points of high power would be required for passenger cars in Sweden without an implementation of ERS, and 12 500 for HDVs. To put this in a context, there were 824 manned service stations 2018 in Sweden (Márquez-Fernández et al. 2022).

Despite the fact that many studies point towards a potential for ERS to contribute in reducing GHG emissions from transports compared to today's system, no detailed analysis investigating climate impact from the ERS technology in relation to other renewable transport solutions has been performed. This is what this study aims to investigate, as previously described.

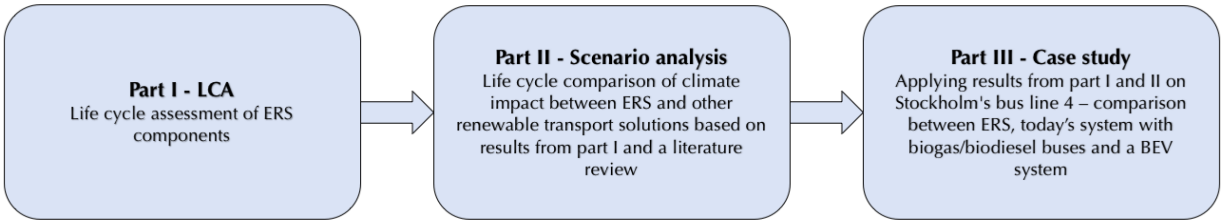
2 Method

This study is divided into three parts and the methodology for each part is in this chapter described briefly as an overview. General assumptions and limitations valid through the entire report are also described in this section but for simplicity and comprehension, details connected to each part is further described in its separate section.

In part I, a life cycle assessment is conducted on Elonroad's electric road system with climate change as impact category, with purpose to answer research question one in section 3.6.4. In addition to rail, the ERS solution also includes pick-up, on-board charger and feed-in station. Data for this are based on primary data from Elonroad and their upstream vendors when available, complemented with generic data on life cycle emissions from constituent materials. In order to maintain clearness and usefulness for remaining parts of the report as well as for future studies, results from this part are presented for each of the four components (rail, pick-up, on-board charger and feed-in station) and not aggregated further. The ERS is in part I investigated from cradle to installation, including upstream processes, manufacturing, transports and installation. End-of-life is excluded, which is further motivated in section 2.2.

In part II a scenario analysis based on a literature review is carried out, comparing results from previous studies examining climate impact from BEVs using stationary charging, ICEVs with biogas and FCEVs with hydrogen. This part aims at answering research question two and three. By also using results from part I, the four different renewable transport solutions are thereafter compared quantitatively in terms of global warming potential (GWP). Results from part I are in this case combined with assumptions concerning use phase conditions of the ERS to be able to make a relevant comparison. The four renewable transport solutions are compared for both heavy-duty vehicles and passenger cars, with a functional unit (FU) of g CO_2-equivalents (CO_2-eq) per tonne kilometre and g CO_2-eq per vehicle kilometre respectively. Furthermore, a sensitivity analysis is performed to evaluate influence of key assumptions on the final result. One example of a key parameter is the utilisation rate, since the total impact from the ERS is shared between the total amount of travelled vehicle kilometres or tonne kilometres. Other important parameters are hydrogen production pathways, emission factors from electricity generation, battery size and battery production CO_2-intensity.

Part III is a case study where results from part I are applied on bus line 4 in Stockholm, based on a scenario defined in a previous master thesis, *There is a new road in town*, by Jakobsson & Lindström (2021). Climate impact from Elonroad's ERS implemented on this bus line is then compared with both current system of biogas and biodiesel buses and a system with BEV buses charged stationary in order to be able to answer research question four. In part III a qualitative discussion regarding overhead catenary system used in trolley buses is also included.



Part I - LCA
Life cycle assessment of ERS components

Part II - Scenario analysis
Life cycle comparison of climate impact between ERS and other renewable transport solutions based on results from part I and a literature review

Part III - Case study
Applying results from part I and II on Stockholm's bus line 4 – comparison between ERS, today's system with biogas/biodiesel buses and a BEV system

Figure 3: Overview of method and the three different parts.

2.1 Assumptions

There are several assumptions made throughout the study and most of them are described when occurring. However, some of them being more general are described in this section. One initial assumption is that the ERS as designed today by Elonroad will be the technology that is implemented in the future and thus is to be evaluated in terms of climate impact and compared to other alternatives. The production is yet only on pilot project level and an up-scaling is required to be able to produce large quantities. This implies that there are uncertainties regarding both future conditions of production chains as well as exact design of components and a commercial implementation.

The report is focused on production and implementation of ERS in Sweden, due to Elonroad having their production site in Lund and an existing plan for implementation of the technology in Sweden. Therefore, data reflecting Swedish conditions are used to largest possible extent throughout the report. However, to properly asses the actual materials used in the ERS technology, the geographical coverage is not limited to Sweden as the upstream vendors are not only Swedish. Thus, European data are used for material and components bought from European vendors, but also for generic data if no primary or Swedish data exist. Swedish electricity mix with an emission factor of 26 g CO_2-eq/kWh (Energimyndigheten 2021b) is used in part I for the manufacturing process. Swedish fuel data on biogas, hydrogen and electricity generation are also used in part II and III where the different propulsion systems are compared. This to reflect how an ERS would perform compared to the other propulsion systems in a Swedish context.

2.2 Limitations

The study is delimited to evaluate only climate impact quantitatively, but other environmental effects of relevance are treated qualitatively to put the results in a broader context. Even if a larger picture with more environmental issues is included in a discussion, it is not intended to replace and fully compensate for a more detailed LCA concerning these aspects. Regarding ERS as a concept, this work is only considering the conductive rail solution by Elonroad, meaning that it is not by definition comprehensive for other types of ERS technology.

End-of-life has been excluded in this study with respect to uncertainties regarding how the ERS components and its constituent materials will be treated after decommissioning. Elonroad has not decided on a final strategy for this yet and there are great variations in recyclability of different materials. As a consequence, impact from end-of-life treatment is also excluded for other parts such as vehicles. Furthermore, since no large-scale ERS exists, operation and maintenance conditions are assessed based on currently available research and by input from Elonroad. These prerequisites will likely be different once a commercial implementation is realised. For example, the cloud service that will be part of the system in a future implementation is not considered in this study due to uncertainties and since it is not fully developed.

3 Part I - Life cycle assessment

In this first part of the study climate impact from Elonroad's electric road system will be evaluated from a life cycle perspective. The impact from each unique component required in an ERS will be investigated separately and the components included in the LCA are the following:

- Rail unit of 9.18 m
- Pick-up
- On-board charger (OBC)
- Feed-in station

Starting with a general description of the method and associated parts in a life cycle assessment, the components presented above are then described, investigated and assessed individually in separate sections. The results are after that presented separately for each of the four components.

3.1 Method

Format and procedure of a life cycle assessment are specified in the ISO standard 14044 (International Organization of Standardization (ISO) 2006). This study is not conducted strictly according to the framework described in the standard, but the LCA part of the study follows the general procedure and consequently some of the parts from the standard are utilised and presented below in this method chapter. Elonroad's core product is the rail and there is a difference between the four investigated products regarding both degree of fabrication by Elonroad and technology readiness level. The rail is more or less a finished product but the final design of both pick-up, OBC and feed-in station is yet to be decided. In addition, it is not clear whether Elonroad themselves will produce the pick-up, OBC and feed-in station in the future or only focus on the rail. As a consequence, the analysis of the rail is performed more thoroughly than the analysis of the other three components as these are related to more uncertainties.

To evaluate climate impact of the four components, each type of material needs to be individually assessed, e.g. in terms of mass and then related to an emission factor in kg CO_2-eq/kg material. Since there is a combination of raw material and finished goods in the construction of the ERS components, the methodology for deriving these values will differ. Furthermore, due to the ordering and usage of finished products it is of importance to comprise not only the emissions occurring at the production site of Elonroad, but also from all upstream vendor processes. For confidential reasons all upstream vendors are assigned an individual number, which is used throughout the report to represent the vendor instead of its name. Numbering of vendors and their corresponding emissions factor are found in appendix. In the report, vendor numbers are mentioned where suitable and are therefore not mentioned in numerical order.

As far as it is possible and reasonable, all material used in the four components is reduced to its most elemental form, being for example aluminium, steel or a certain type of plastic. This is independent of the degree of prefabrication, meaning that aluminium could still comprise a finished product ordered by Elonroad. If it is not possible to reduce to one element, for example due to higher complexity, a component may be seen as a material in itself. As a consequence, the term "material" depicts both raw material and finished products.

A general principle applied is that material with either a high mass contribution or with a high complexity are described in more detail in the main report regarding assumptions and data acquisition. Detailed values and additional assumptions are found in appendix A.1, continuously referred to in the text.

3.1.1 Product system

The product system to be studied is visualised in figure 4, consisting of four different components used in the ERS technology by Elonroad. The system depicts the conditions of today and will thus probably differ in a future up-scaled production and large-scale implementation.

Extraction and transport of raw material together with manufacturing and transport of constituent materials are upstream processes from Elonroad. It may be several vendors involved in these steps and the supply chains vary in complexity depending on which constituent material is investigated. Manufacturing is the process where Elonroad assembles the four different components of the ERS. As already mentioned, this process is most elaborated for the rail, followed by pick-up, OBC and feed-in station in descending order.

As seen in figure 4, all four components have the same life cycle stages with exception that the OBC and pick-up are not being transported after manufacturing. This is because it is assumed that the mounting of these components to the vehicle is made at the production site, which is the case today.

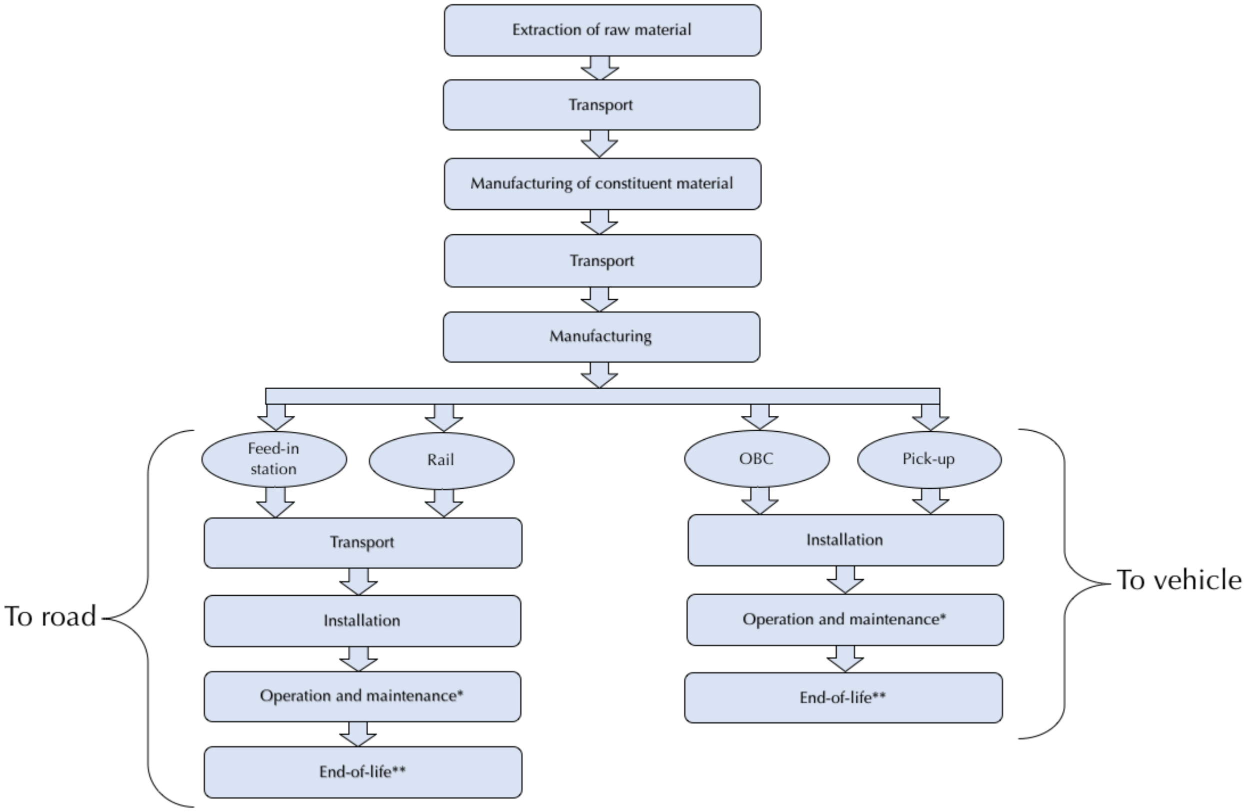


Figure 4: Life cycle stages of the four ERS components.
*Life cycle stage included in part II of the study.
**Life cycle stage excluded in the study.

3.1.2 Functional unit

The functional unit in part I of the study is one set of unique components needed for Elonroad's electric road system, being the following: rail, feed-in station, pick-up and OBC. The choice of functional unit is made with respect to comprehension and simplicity for as well upcoming parts in this study as future studies in the field.

3.1.3 System boundaries

Part I of the study is conducted with the system boundary cradle-to-installation, including all upstream processes, manufacturing at site, transport and installation of each component on its respective area of application. No cut-off has been applied in this part of the study meaning that all in going material and components have been assessed. In order to evaluate the conditions of the ERS as they are today, as new data as possible are gathered for emission factors. No data on emission factors older than 2015 are used. According to what was described in the method, section 2, the geographical coverage is limited to Europe as far as possible. This means that if no primary data exist from the specific upstream vendor or from a similar process, generic data depicting European conditions are used.

3.1.4 Allocation procedures

Allocation is avoided in all stages of the study except in the manufacturing process. Of the three components produced by Elonroad, emissions emerging from the energy use of the production facility has been allocated to the rail based on an energy usage allocation. As of today the OBC and pick-up are assembled by hand and no direct energy usage is related to it. Secondary energy usage in the form of heating of the manufacturing facility has been allocated to the rail. This since no distinction between the products was possible to obtain and since the number of rails produced greatly exceeds the number of OBCs and pick-ups produced in the facility.

3.1.5 LCIA methodology and types of impacts

The impact category considered quantitatively in this study is climate change, meaning that all LCI results are expressed in terms of generated greenhouse gas emissions. For this the IPCC baseline model for 100 years is used where all GHGs are translated to global warming potential (GWP_{100}) with unit kg CO_2-eq via characterisation factors. When Ecoinvent is used as a data source, the LCIA model IPCC 2013 and GWP 100a is chosen.

3.1.6 Types and sources of data

When possible and available, emission data are based on primary data supplied by upstream vendors or manufacturers of raw material and components used in the construction of the ERS. In cases were vendors are unable to provide sufficient data, data from environmental product declarations (EPDs) are used. In these cases, only the values representing cradle-to-gate emissions are taken. This means that the production phase is included but transport from gate to site, use phase, disposal and end-of-life are all excluded. Transport from gate to site are accounted for and calculated separately, why this is excluded. In EPDs where both fossil and other biogenic impacts are presented, only the fossil contribution is taken.

In cases were no relevant EPD is found, the Ecoinvent database is used. When working with Ecoinvent data, the chosen activity type is production, i.e. ”transforming activity”. Market datasets have not been considered since transports from gate to site is included in that set and this is considered individually. The database used is Ecoinvent version 3.8, released 2021, and the system model is set to ”allocation at the point of substitution”, former default allocation mode.

In most cases, emission data are received in kg CO_2-eq/kg material. Thus, the mass of material and components used in the products are needed to calculate the absolute amount of GHG emissions arose during the life cycle. Weight data are based on measurements on-site, theoretical weights from CAD models, information in data sheets from vendors and in some cases also estimations. Estimations are avoided when possible and generally only applied for material and components with low weight and low environmental significance.

3.2 Rail

The function of the rail is to supply the vehicles using it with DC current for propulsion. Electricity is transferred from the grid via a feed-in station to the rail. The rail consists of an aluminium profile onto which all components are mounted. Electric cables and network cables are used for power supply and software control, providing functions such as a billing system, load balance, access control and safety features. This is accompanied with printed circuit boards (PCBs) of various size and function. Material in the rail are e.g. different types of plastics and rubber, such as mylar, EPDM and silicone. These are used for electrical insulation, friction reduction and water-proofing. Other materials used are copper plates in different sizes and shapes to connect parts of the rail to one and other, also enabling electric transfer. Large steel plates are used together with the aluminium profile for robustness, further, various types of steel are used in screws and bolts used for interlinking the rail. The rail is submerged in the asphalt and the top layer has LED-lights illuminating only the part of the road segment that is electrified when a vehicle with a pick-up is passing over. As a safety measurement the rail is painted with a friction increasing paint on the top layer.

3.2.1 Material

There is a combination of different type of material and finished goods used in the construction of a rail. One rail weights 345 kg and an overview of the mass composition of the rail can be found in figure 5, the exact material composition of the rail is found in appendix in table A1. Each material used in the rail has a varying degree of prefabrication. Emissions related to the material with significant weight and higher complexity will be described in the coming paragraphs.

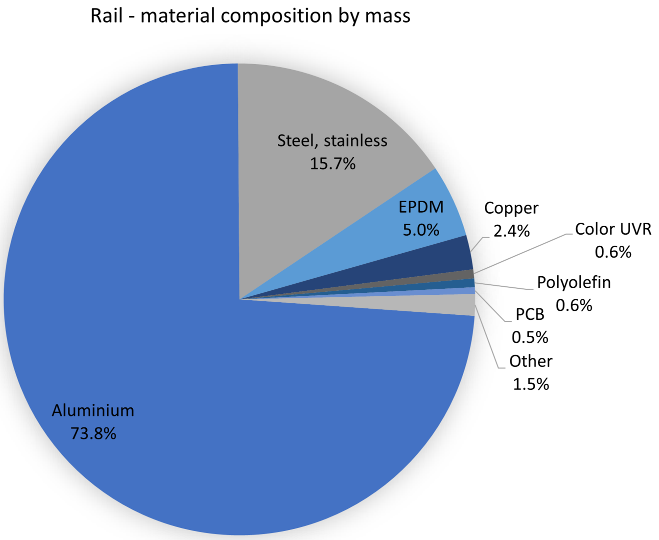


Figure 5: Material composition in rail expressed as percentage of the total mass of 345 kg.

3.2.1.1 Aluminium

Aluminium is bought from two different vendors with the majority coming from vendor 21 and emission factors related to all vendors are found in appendix A.1. Associated upstream emissions are reported directly from the vendor, including as well production of raw aluminium billet as extrusion and machining of profiles and then transport of these to Lund. The bulk of the emissions originate from production of raw aluminium ingot, which according to the vendor is assumed to be a European average of primary produced aluminium.

The remaining aluminium is bought from vendor 2. No primary data were available here and data were instead taken from an EPD for ”blank aluminium sheet”, performed by a reported upstream vendor earlier in the supply chain (Gesamtverband der Aluminiumindustrie e.V. 2020). However, this does not include the fabrication of the final aluminium component used in the rail. To account for the potential underestimation in this assumption, the machining process impact of 0.003 kg CO_2-eq/kg as given by vendor 21 is added as an approximation. Note the small fraction of the total impact coming from extrusion and machining, being 0.016 kg CO_2-eq/kg together, compared to 6.7 kg CO_2-eq/kg for the billet production.

3.2.1.2 Cables

As mentioned, the rail contains electrical components and various cables are used to allow data transfer and electricity distribution. Their mass contribution is relatively small, but are described due to their high material complexity. Electrical cables exist in different dimensions in the rail and are generally made up by a copper wire and PVC-coating. Climate impact has been estimated using the Ecoinvent dataset ”Cable production, unspecified, GLO”.

The network cables are treated similarly, but with the dataset for production of network cable category 5 in Ecoinvent. The rail contains both ribbon cables and flat flexible cables with plugs. Climate impact for all network cables in the rail has been determined using the Ecoinvent dataset ”Cable production, ribbon cable, 20-pin, with plugs, GLO”.

3.2.1.3 Copper

Various types of copper items from different vendors are used in the rail, consisting of either pure copper, nickel-plated copper alloy, silver-plated copper or tin-plated copper. As seen in table A1 in appendix most of them have a small mass contribution, except from pure copper constituting over two percent of the total rail mass. Climate impact of pure copper is taken from an LCA conducted by the International Copper Association (2018). The LCA comprises production of copper cathode in four continents during 2013, covering around 21% of the total global production that year. The reported value is 4.1 kg CO_2-eq/kg copper cathode. This is comparable to LCA data from European Copper Institute (2012) involving both copper tube, sheet and wire, where the latter has the highest impact with around 4.2 kg CO_2-eq/kg copper wire. With respect to the small mass contribution for the other copper materials, the altered impact from alloy and plating is assumed to be negligible and the same value is used for these as for pure copper.

3.2.1.4 EPDM

Around 17 kg of the synthetic rubber EPDM (ethylene propylene diene M-class) is used in one rail unit, mainly functioning as a rubber to embed the rail. The majority is from vendor 47 but due to lack of primary data life cycle emission data for this material are taken from an EPD for non-reinforced EPDM membranes for waterproofing (Inèdit Innovació SL 2018), with LCA results recalculated from kg CO_2-eq/m^2 to kg CO_2-eq/kg with given weight of 1.23 kg/m^2. The EPD concerns the Spanish company Firestone Building Products with its production in Spain, but is valid for the area of Europe.

3.2.1.5 Printed circuit boards

Components in the rail with small mass contribution but high complexity and potentially high environmental significance are the printed circuit boards. There are several different PCBs in the rail, with different functions. This is for example to communicate with the car, track which car is charging and how much power is being transferred, and to only activate the segment that is under a charging vehicle. A PCB usually contains several different components such as resistors, capacitors, diodes, transistors, integrated circuits (ICs), individually designed for the specific purpose. They can be either surface mounted or through-hole mounted (Vishay 2017). The PCBs in the rail are mostly surface mounted and contains numerous small components as the ones mentioned above. The components used in the PCBs are ordered from different vendors but designed and partly mounted by engineers at Elonroad. Due to time limitation and lack of detailed component data, climate calculations have not been performed component-wise for the specific PCBs used in the rail. However, since there are large differences in GHG performance between different components found on a PCB, the results are related to uncertainties. The difference in emissions is exemplified comparing the emission factor from the Ecoinvent dataset ”integrated circuit production, logic type” with that of the dataset ”capacitor production, for surface-mounting, GLO”: 1564 kg CO_2-eq/kg against 83 kg CO_2-eq/kg.

There are different types of PCBs per rail. With respect to how these are assessed in terms of climate impact, they are divided into two types. PCB type 1 denotes the largest and heaviest type used in the rail. The remaining types are aggregated and together denoted PCB type 2.

The total mass of PCB type 1 in the rail is 1.44 kg. The cards of type 1 enables the rail to be activated only in short segments under a vehicle and communicates with the data server. There are several different components such as integrated circuits and resistors on this type, most of them surface mounted. On each PCB of type 1 there are also 28 pieces of through-hole mounted resistors, with individual mass of 7 g. This means that 54% of the total PCB type 1 mass originates from from these transistors. Out of the available datasets for PCBs in Ecoinvent, there is no type corresponding to an mass fraction of 54% for transistors (Hischier et al. 2007). Due to that, these are treated separately with the Ecoinvent dataset ”transistor production, wired, big size, through-hole mounting, GLO", depicting transistors with an average weight of 6.34 g according to the dataset. For the remaining part being the PCB, the dataset "printed wiring board production, surface mounted, unspecified, Pb free, GLO" is utilised. The choice is made since it is assumed to be the most conforming set in terms of mass contribution from different components, comparing the PCB type 1 with the datasets described by Hischier et al. (2007).

The PCB type 2 includes different types of PCB with a total mass of 0.145 kg. The PCBs are all diverse in both size and complexity, but are all calculated with the Ecoinvent dataset "printed wiring board production, surface mounted, unspecified, Pb free, GLO", with the same reasoning as for PCB type 1. Details regarding total impact and calculations are found in appendix in table A3.

3.2.1.6 Stainless steel

Around 16% of the total rail weight is stainless steel, of which almost all is from vendor 2. The reported upstream vendor earlier in the supply chain have an EPD for hot finished structural hollow sections (Karlsson 2021) and this is used as an estimate for the GHG emissions. This value was chosen to not underestimate the climate impact since this product had the highest value compared to data from other EPDs by the same producer.

3.2.2 Transports

There are several transports involved in the process, originating from raw material, components and products being shipped throughout the supply chain. In addition, there are several actors and vendors involved being responsible for different parts along the life cycle, all with their trade secrets. Therefore, emissions from transports are estimated roughly with various assumptions and in general only including the route from vendor production facility to Elonroad in Lund. Furthermore, with a future up-scaled production transports are likely to differ from today's conditions.

For the aluminium from vendor 21, i.e. the majority of the total mass, data are supplied for a fully loaded truck driving from production site via interim storage to Lund. This accounts for 0.03 kg CO_2-eq/kg aluminium, to compare with 6.7 kg CO_2-eq/kg for production of the billet. The data is obtained directly from vendor 21.

Emissions originating from transport of the remaining material are determined with help of NTMcalc (Network for Transport Measures [NTM] n.d.) based on an assumed transport route. In NTMcalc, a truck with trailer 50-60 tonnes is chosen. The routes are approximated based on where the production site or headquarter of the vendor is situated, if that is known. Most of the vendors are situated in Sweden and have their production within Europe. When data are taken from an EPD, the transport route is set from the site that the EPD refers to. For details about this, see table A5.

3.2.3 Manufacturing

The rail is assembled and manufactured at the production site in Lund with the constituent material described earlier. The assembly is related to an energy usage in form of electricity, thus giving rise to GHG emissions. The exact electricity consumption is not known, but an estimation is made based on the total electricity consumption of the production site during a year. This is however an overestimation since all energy should not be entirely allocated to the rail assembly. Calculations and assumptions are presented in table 2. Since manufacturing of rails at present is project-based and to some extent is in research phase, the manufacturing speed is a rough approximation. A future optimised large-scale production will be different and most likely be more energy efficient that what is being estimated here.

Table 2: Estimated electricity consumption per rail from total electricity consumption during a year and assumed manufacturing speed.

Avg electricity consumption [kWh/month]	**Manufacturing speed [rails/month]**	**Electricity consumption per rail [kWh/rail]**
4192	10	419

3.2.4 Installation

The rail is submerged into the existing road to emerge at the same level as the asphalt. Thus, the installation of the rail requires pavement milling. Approximately 350*60 mm is milled, after which the rail is submerged and the air gap between the asphalt and the rail is filled up. There are two types of filling material used, both made of polymer modified bitumen, but with different elasticity due to different material composition. The bottom sealant layer is stiff whereas the top layer has high elasticity and functions as a sealant to fill the remaining area between bitumen and ground level. The volumes and weights needed per rail are presented in figure 3 and these are calculated from the aluminium profile layout in relation to the milled asphalt volume. The consumption of each material in kg/m^3 is given by the respective data sheet of the product. The processes, mass and materials required for installation are seen in 3. The data used to determined climate impact from this is found in appendix A.1.1.3. The installation process and its materials amounts to an impact of 159 kg CO_2-eq per rail.

Table 3: Material used for installation of rail as well as mass of milled asphalt.

Material	**Volume per rail [m^3]**	**Consumption [kg/m^3]**	**Mass [kg/rail]**
Bottom sealant	0.055	1700	93.0
Top sealant	0.011	1300	71.1
Total			**164**
Process		**Density [kg/m^3]**	
Pavement milling	0.19	1420	274

3.2.4.1 Transports related to installation

Transport of both sealant material and rail to installation point must also be included. Both polymer modified bitumen sealant products are transported from a vendor in Germany, assumed to be Baden-Württemberg as several materials treated before. The transported distance from factory will vary depending on installation site, which will be different for each individual rail. As an approximate, Örebro is chosen to represent an average. GHG emissions related to transport of one rail from Elonroad's factory to Örebro have been determined using NTMcalc (NTM n.d.), using the same settings as previously mentioned but for the route Lund-Örebro.

3.2.5 Operation and maintenance

The use phase of the entire ERS will involve both operational and maintenance measures. As mentioned, the main function of the rail is to supply vehicles with electricity. The electricity consumption and its impact will be investigated in the upcoming scenario analysis part, section 4.6.8. During operation the rail communicates with a data server aided by the PCBs and the electronic components in order to monitor and keep track of which vehicle is using the road and how much power is being transferred. The communication also enables the function of only activating the rail that is underneath a vehicle using the ERS. As a result, energy will be needed to keep the software control in operation. The energy use related to this is however difficult to estimate and is therefore excluded in the calculations. Once the system is commercialised and more data are available, it is recommended to investigate the impact of this further.

The maintenance part of the use phase relates to the lifetime and wear of components in the ERS. Elonroad predicts that the lifetime of one rail is 15 years and that no maintenance is needed during this time.

3.3 Pick-up

To facilitate power transfer between ERS and vehicles using it, a pick-up is mounted underneath the vehicle. The pick-up has an arm that operates both vertically and horizontally in order to follow the driver's path and ensure a continuous connection to the rail. Materials needed for the manufacturing are delivered to Elonroad, where all components are assembled and the pick-up is thereafter mounted onto the vehicle. The pick-up is primarily made of stainless steel, copper and polycarbonate. The design of the pick-up considered in this report is a design that is currently being updated, but the climate impact estimation is based on the current design. However, with an updated design it is likely that the material composition will change, resulting in an altered GHG performance.

3.3.1 Material

The pick-up is constructed on-site from several materials, each more or less prefabricated. Details of all materials can be found in Appendix table A6. An overview of the material composition is seen in figure 6. As for the rail, components such as screws are reduced to its in going material if possible. Main materials and more complex components are described in the upcoming sections.

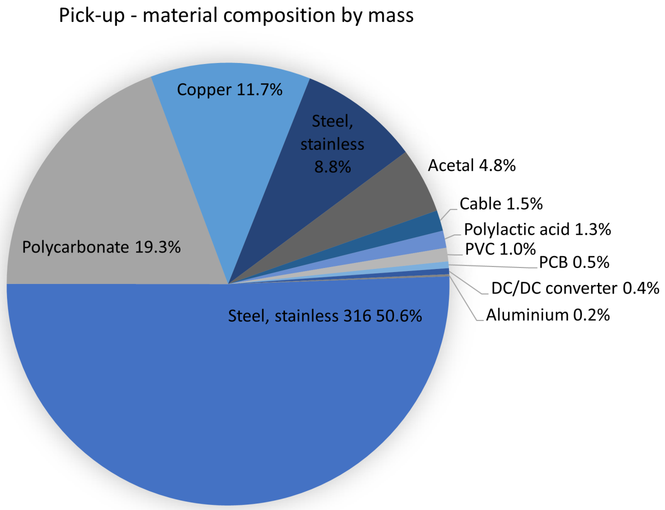


Figure 6: Material composition in the pick-up expressed as percentage of the total mass of 29 kg.

3.3.1.1 Stainless steel 316

The bulk of the material in the pick-up is stainless steel 316. Emission data for this material are taken from an EPD for welded and pickled stainless steel products of type 316L, produced in Norway (Øglænd System AS 2018). No primary data from vendors could be obtained for the stainless steel 316 used in the pick up, wherefore the Norwegian EPD data have been used. It is assumed representative since the product considered in the EPD is a ladder structure and the EPD includes both raw material production and the processing leading up to a finished product. Thus, the EPD is including processing of a metal structure similar to the one used for the pick-up. The material is related to emissions of 15.0 kg CO_2-eq. It is recommended that future studies examines this in more detail to determine its potential influence on the final result.

3.3.1.2 Polycarbonate

Polycarbonate accounts for 19% of the total mass. The GHG emissions have been evaluated using the Ecoinvent dataset ”Polycarbonate production, RER”.

3.3.1.3 Copper

The impact from copper used in the pick-up has been determined using the same EPD as for the copper in the rail (International Copper Association 2018). It has been assumed representative with the same arguments as for the rail.

3.3.2 Transports

Emissions from transport of all materials from vendors to Elonroad's site in Lund are approximated by assuming that the entire pick-up in terms of mass is transported from Baden-Württemberg in south Germany to Lund by truck. The calculation was performed with NTMcalc (NTM n.d.) with the same settings as for the rail. No detailed data concerning vendors were available as for the rail, why this assumption was made.

3.3.3 Manufacturing and installation

GHG emissions from manufacturing of the pick-up and the mounting onto the vehicle are assumed to be negligible and is thus excluded. Even if a small portion of the electricity consumption at the production site should be allocated to the pick-up, it is assumed that the rail is related to a significantly higher energy usage in the construction phase due to its complexity and higher mass.

3.3.4 Operation and maintenance

Due to the novelty of this component, it is difficult to predict maintenance needs during the lifetime. The pick-up is assumed to have an equally long lifetime as a vehicle, which is described further in part II. However, the contact material between rail and pick-up, a copper braid of 0.933 kg, will need to be exchanged approximately once a year due to wear. Additional emissions due to this exchange will be included in the upcoming scenario analysis in section 4.6.8.

3.4 On-board charger

The on-board charger enables and administers power transfer between rails and the battery of the vehicle. Since both the rail and the vehicle battery use DC, the objective of the OBC is to adjust the DC voltage. It is mounted onto the vehicle and consists of both electronic equipment and other materials. The exact design of the version of the OBC that will be produced at large-scale is not determined as of today. The current version is on prototype level, but is nevertheless used as a basis and reference in calculations. However, the main function of the OBC remain and it is likely that a revised design rather will result in a lower climate impact due to a more optimised design. Thus, the results should not be an underestimation.

The size and capacity of an OBC will differ depending on vehicle type and how much power that needs to be transferred from the rail, which is not yet determined. It is however expected that a passenger car will need an OBC capacity of approximately 70 kW and a truck a capacity of around 250-500 kW. The OBC design that the climate calculations are based has a capacity of 40 kW.

In general terms, the OBC consists of a DC/DC converter, electronic equipment and an enclosure which all components are encased in. The DC/DC converter is in turn made up of parts such as transistors, diodes, capacitors and inductors. Besides the converter, there are also an EMC filter, rectifiers, data cables, PCBs, fans and small parts as screws and bolts.

3.4.1 Material

As for the rail, raw material and finished goods are together used in manufacturing the OBC. In table A7 in appendix all material required for one on-board charger is presented, with varying degree of prefabrication for each element. An overview of the mass contribution per material is show in in figure 7. The emissions related to the material with highest mass or a high degree of complexity will be described in separate chapters.

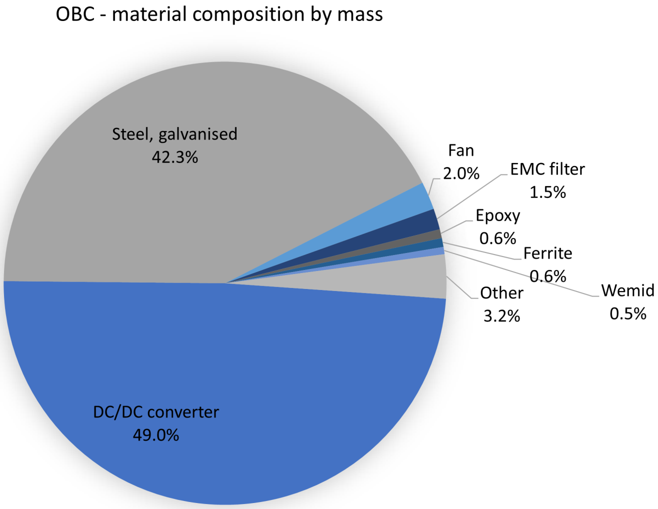


Figure 7: Material composition in the OBC expressed as percentage of the total mass of 59 kg.

3.4.1.1 DC/DC converter

The main component of the on-board charger in terms of mass is a DC/DC converter. This component is currently purchased as a finished product from a vendor, why it has not been possible to obtain a complete bill of material for this component. However, a number of studies have been conducted on climate impact of converters since this is a component found in most battery electric vehicles. In Ecoinvent a converter can be found were the value is based on a report examining a DC/DC converter of 4.8 kg and 3.5 kW (Habermacher 2011). The Ecoinvent data are given per kg converter. Applying the Ecoinvent dataset to the converter used in the OBC gives GHG emissions of 1 230 kg CO_2-eq for the converter with a mass of 28.5 kg. This is based on the assumption that the emissions scale linearly with increasing weight of the converter. However, the mass of the components in a converter does not scale linearly with increasing capacity since some components can remain unchanged in size whereas others need to be larger (Nordelöf, Alatalo & Ljunggren Söderman 2018). Thus, assuming that emissions would scale linearly with weight is most probably an overestimation of climate impact from the converter. Along with the ISO 14044 standard a conservative approach is however taken to rather overestimate than underestimate, why this value is chosen as a base case. To evaluate the influence of this assumption, a sensitivity analysis is performed where a lower value is used.

There is also one smaller DC/DC converter with a mass of around 300 g, which is treated and scaled similarly as the large one with respect to GHG emissions. These are summed up to 1 240 kg CO_2-eq, which is the value seen in appendix table A7. Furthermore, it is unclear what mass the large DC/DC converter will have in future designs, related to if an water- or air-cooled type is chosen since they differ in mass. It is likely that a lighter converter will be used, further motivating the assumption as a potential overestimation.

3.4.1.2 EMC filter

One EMC filter is used in the OBC and the function of this is to prevent electromagnetic disturbances that can occur in the circuit. The final design of the filter has not yet been determined and an estimation of size and components has therefore been made. This to have an indication of what climate impact the filter may be related to. The total mass of the examined filter is 0.9 kg but the exact composition of materials inside the casing made of stainless steel is unknown. Calculations and assumptions regarding the climate impact can be found in appendix A.1.3.1. The impact per component is determined to 6.04 kg CO_2-eq.

3.4.1.3 Fan

The OBC contains two fans, one smaller with a mass of around 300 g and a larger with a mass of 900 g. The combined mass of the fans accounts for around 2% of the total mass. Data for GHG emissions have been taken from Ecoinvent using the dataset "Fan production, for power supply unit, desktop computer, GLO".

3.4.1.4 Galvanised steel

The material with second largest mass contribution is galvanised steel, which constitutes around 43% of the total mass. The galvanised steel is mainly in form of an enclosure and it is bought from a vendor which has multiple manufacturing facilities in Europe. It has therefore been assumed that the steel in the enclosure has a corresponding impact as reported in the EPD by ArcelorMittal (2019) for their European production of galvanised steel. The EPD depicts double sided hot dipped galvanised steel with applications such as electrical cabinets and cable trays. However, it does not include the production of such equipment, only the cradle to gate production of 1 mm steel with 275 g/m^2 pure zinc metallic coating. No data have been found on GHG emissions related to the manufacturing stage between galvanised steel sheet and enclosure.

3.4.1.5 Rectifier

There are three rectifiers in the OBC which have been modelled using the electric circuit diagram for the specific rectifiers (Schaffner 2016). This due to lack of more sufficient data sources regarding GHG emissions of rectifiers of this model. One rectifier consists of two diodes and a casing of stainless steel. Assumptions and modelling of the filter can be found in appendix A9. One rectifier has an impact of 1.10 kg CO_2-eq.

3.4.2 Transports

As for the pick-up, climate impact from transport of constituent material for the OBC from vendors to Elonroad's production site has been estimated based on the total mass of the OBC. An average transport route is assumed to be Sofia in Bulgaria to Lund by truck. A large fraction of the total mass of the OBC is from a vendor having their production facility in Sofia, hence this assumed transport route. The calculation was performed with NTMcalc (NTM n.d.) with the same settings as for the rail and pick-up.

3.4.3 Manufacturing and installation

The OBC is assembled with all material described and thereby mounted onto a vehicle. The electricity usage of this process in not included since no large-scale production exists at present. Instead all electricity usage from Elonroad's production site has been allocated to the rail. Thus, no electricity usage is excluded, only attributed entirely to the rail.

3.4.4 Operation and maintenance

Maintenance needs for the OBC are at present not adequately investigated and GHG emissions emerging from such activities are therefore difficult to predict and excluded in the study. GHG emissions are expected during operation but these are related to the electricity required for supplying the vehicle with power. This will be investigated in the upcoming scenario analysis in section 4.6.8 and is therefore not included here.

3.5 Feed-in station

Additional required infrastructure for an implementation of ERS is a feed-in station, transferring power from the power grid to the rails. The station consists of a transformer and a rectifier where the transformer alters the AC voltage from grid level to an appropriate level in the ERS, whereas the rectifier converts the current from AC to DC. Typical values for the station is 10 kV input AC from the grid and 700 V output DC to the road. As of today the ERS is under development and no operating large-scale road has been built. Nevertheless it is expected that a 3 MW feed-in station will be required every 1 km of electric road. Furthermore, an electric cable between the feed-in station and the rail section is needed.

3.5.1 Manufacturing and installation

The feed-in station will most likely be ordered from and installed by another company, vendor 55. An EPD of a similar product as the one that will be used by Elonroad has been obtained from the vendor and used as a reference for the future product. The EPD is of a transformer thus lacking the rectifier part. It has been determined that using data from the actual vendor is still more actuate than using data from another company. Further the relevance of the obtained data has been compared to publicly available data. It is found that the emissions arising from transformer stations per MW are found in en interval between 7.8 and 41.5 tonne CO_2-eq/3 MW, as can be seen in table 4. The outlier is therefor the used data, obtained from vendor 55. Due to this source being significantly higher than emission data from other suppliers and since the actual feed-in station has not been produced is is assumed that the 153 tonne CO_2-eq/3 MW value used is an overestimate and that this might compensate for excluding the rectifier part. The data from vendor 55 will be used in the calculations moving forward.

Table 4: Literature findings on transformer stations.

	GWP manufacturing [kg CO_2-eq/kW]	**Scaled to 3 MW [t CO_2-eq/3 MW station]**	**Source**
Large distribution transformer 10 MVA (ONAN)	6.71	20.1	ABB (2003a)
Trasformatore trifase in olio minerale 25MVA	10.7	32.2	Tamini (2020)
Large distribution transformer 16/20 MVA	7.65	23.0	ABB (2003b)
Power transformers 40/50 MVA (ONAN/ONAF)	4.6	13.8	ABB (2003c)
Power transformer 250 MVA	2.6	7.8	ABB (2003d)
Power transformer	3.78	11.3	Hegedic et al. (2016)
Transformer 10 MVA	13.8	41.5	Santos Jorge et al. (2012)
Transformer 3 MW	-	153	Vendor 55

The electric cable connecting the feed-in station and the rail has been added separately to the feed-in station value obtained from the vendor. An approximately 40m long cable per feed-in station will be needed to supply the rails with electricity. The impact from the cable has been determined from the Ecoinvent data set "Cable production, three-conductor cable, GLO", details and result for this is found in appendix A10.

3.5.2 Operation and maintenance

The lifetime of the feed-in station is 40 years according to upstream vendor, which exceeds the lifetime of the other components considered in this system. Maintenance needs during its operating time has been excluded in the EPD upon which the GHG emissions are based. Therefore it is assumed that no maintenance that gives rise to GHG emissions is required during its operating lifetime. As for the rail and the OBC, electricity usage and losses are relevant parameters to consider when assessing the impact from operation. This will be investigated in the upcoming scenario section, section 4.6.8.

3.6 Results

Climate impact in terms of CO_2-equivalents for the different ERS components previously described are presented separately in this chapter.

3.6.1 Rail

Calculated GHG emissions from manufacturing of constituent material used in one rail unit are visualised in figure 8 and numerical values are found in appendix in table A4. The largest impact originates from the aluminium, a result that is reasonable given the large mass contribution of aluminium of 74%. The aluminium accounts for 1700 kg CO_2-equivalents, corresponding to 71% of the GWP for the life cycle stage manufacturing of constituent material. Stainless steel and EPDM are the second and third most abundant materials in the rail in terms of mass and it is therefore reasonable that they are top contributors to the total GWP. The PCBs, which only accounts for 0.46% of the mass, are however responsible for 16% of the material impact. This is due to the significantly higher emission factor assumed for the PCBs of around 300 kg CO_2-eq/kg compared to for example aluminium with around 7 kg CO_2-eq/kg. A high emission factor is also seen for many of the components found on a PCB, e.g. transistors, capacitors, integrated circuits and diodes.

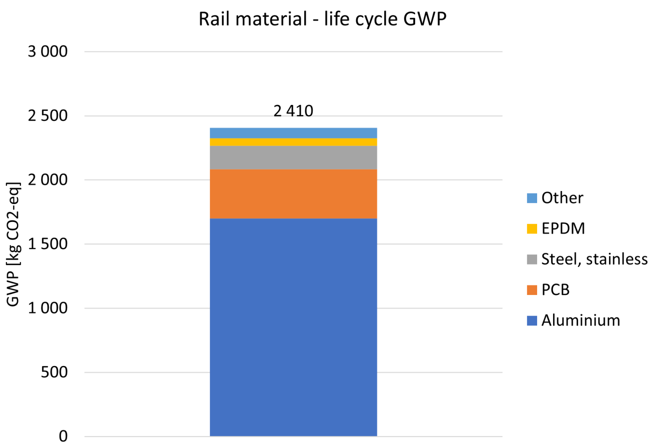


Figure 8: Contribution to GWP from constituent material per functional unit of one rail.

In figure 9 total GHG emissions divided between the different life cycle stages are specified. As seen, one rail has a total GWP of 2 590 CO_2-eq and the main contributor is manufacturing of constituent materials. Transport, manufacturing and installation together have a small impact on the total GWP and are all reflecting current conditions. It is however expected that the manufacturing process will be more efficient once the rails are produced at large-scale. As of now, the energy use of the entire production facility has been allocated entirely to the number of rails produced. This is a potential overestimation since other activities than rail production occur in the facility. Manufacturing of constituent material is thus found to be the hotspot in terms of climate impact, motivating further efforts to be focused on material choice and origin.

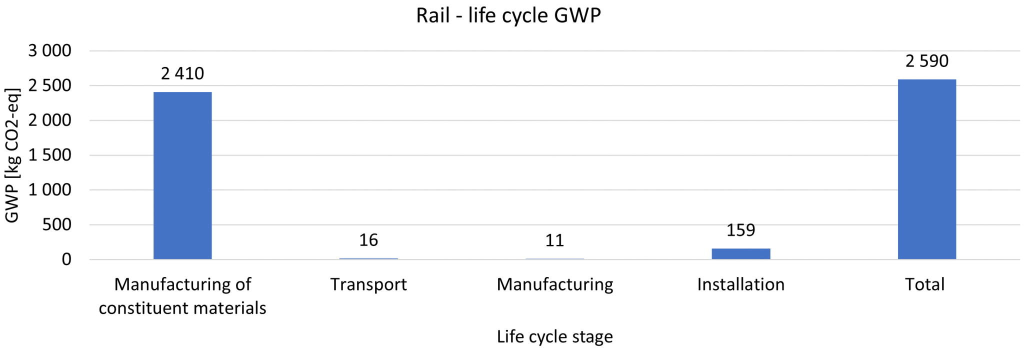


Figure 9: Contribution to GWP from the different life cycle stages per functional unit of one rail.

3.6.2 Pick-up

Emissions from manufacturing of constituent materials for the pick-up arises primarily from stainless steel and PCB production, as can be seen in figure 10. Out of the GWP of 197 kg CO_2-eq from constituent materials, 36% originates from stainless steel and 23% from the PCB. Numerical values for emissions per material can be found in appendix in table A6. PCB is found to have a relatively large impact despite its low mass as also discussed with regards to rail and OBC.

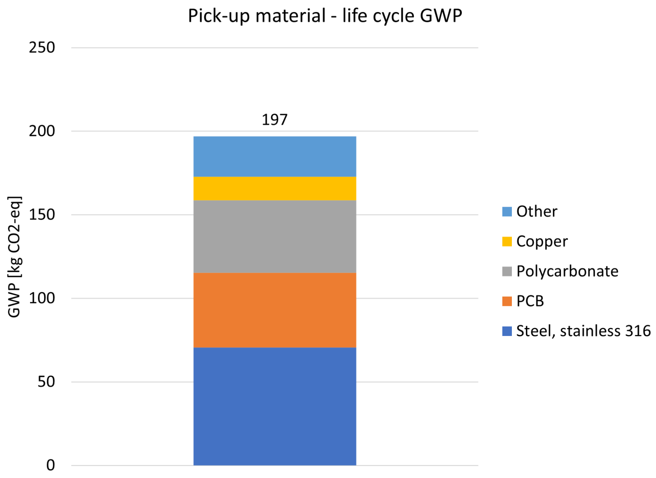


Figure 10: Contribution to GWP from constituent material per functional unit of one pick-up.

With an impact from transportation of 3 kg CO_2-eq the total life cycle impact from cradle to installation is 200 kg CO_2-eq for one pick-up, displayed in figure 11. As for the OBC, there is no contribution to GWP from manufacturing and installation, based on the assumption that all energy usage in the facility is allocated to the rail.

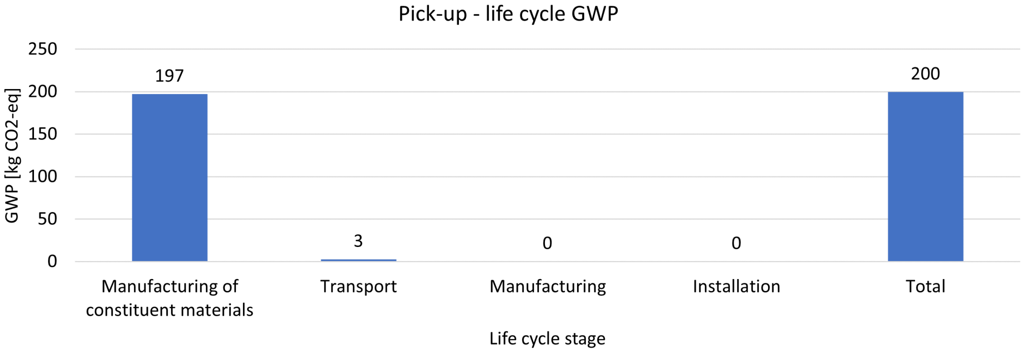


Figure 11: Contribution to GWP from the different life cycle stages per functional unit of one pick-up.

3.6.3 On-board charger

Calculated GWP from manufacturing of constituent materials for one OBC is 1 360 kg CO_2-eq and numerical values for all components and materials are found in table A7 in appendix. Figure 12 visualises the result, from where it can be seen that the majority of the impact emerges from the DC/DC converter even if it only constitutes around half of the total OBC mass. The converter gives rise to GHG emissions of 1 230 kg CO_2-eq per OBC. Climate calculations of this component is as earlier described based on a linear scaling of emissions by mass, an assumption that probably is an overestimation. The effect of assuming a lower impact form the converter will be evaluated in a sensitivity analysis in part II.

Besides the DC/DC converter, three other components with noticeable contribution are visualised in figure 12. Galvanised steel accounts for 42% of the OBC mass and with an emission factor of 2.56 kg CO_2-eq/kg it is reasonable that the impact is considerably lower than for the converter, having an emission factor of 43 kg CO_2-eq/kg. The PCB and the fan have a relatively low mass contribution but are both components with a high impact per mass unit. Despite this, their relative contribution is only around 1% of the total OBC GWP respectively.

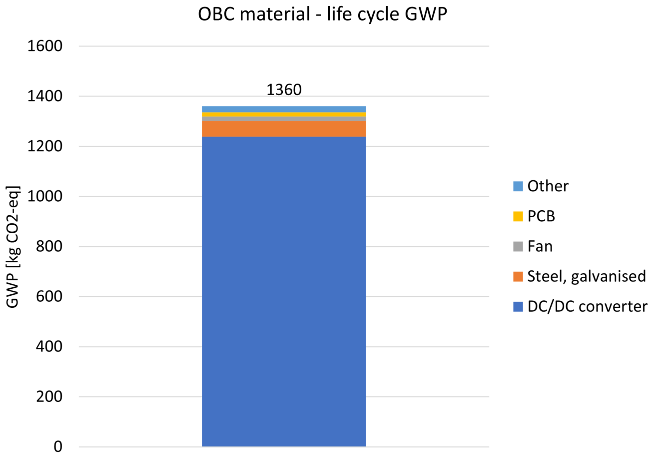


Figure 12: Contribution to GWP from constituent material per functional unit of one OBC.

Apart from upstream results from the materials, there are GHG emissions arising from transports. The total result from cradle to installation is 1370 kg CO_2-eq for one OBC and the contribution from each life cycle stage is seen in figure 13. As discussed, GWP from manufacturing and installation has been allocated to the rail since the OBC is assembled and installed mainly by hand. The transport part is based on a simplification where the entire OBC is assumed to be transported from the location where the DC/DC converter is produced. The relatively low impact from this life cycle stage does not motivate a more precise investigation.

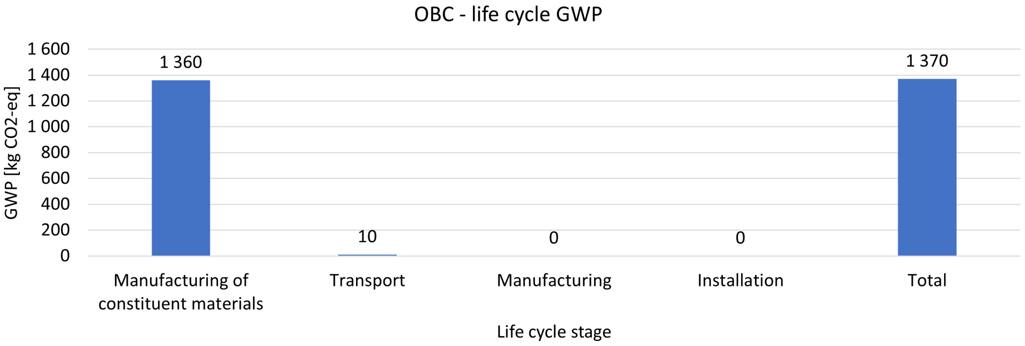


Figure 13: Contribution to GWP from the different life cycle stages per functional unit of one OBC.

3.6.4 Feed-in station

Climate impact from the feed-in station is not divided per material since this data are not reported from the vendor of the station. However, a distinction between material, transport and manufacturing is made by the vendor and a summary of this is shown in figure 14. As can be seen, total GWP of one station is 153 tonne CO_2-eq. In addition to data received from the vendor, electric cables are included and details on this are found in appendix table A10.

The result is a rough estimation since the actual feed-in station that will be used is not designed yet. The used data are based on a transformer station without a rectifier converting AC to DC and are significantly higher that what is reported from other producers of similar transformer stations as seen in table 4. Consequently, there are large uncertainties related to this ERS component.

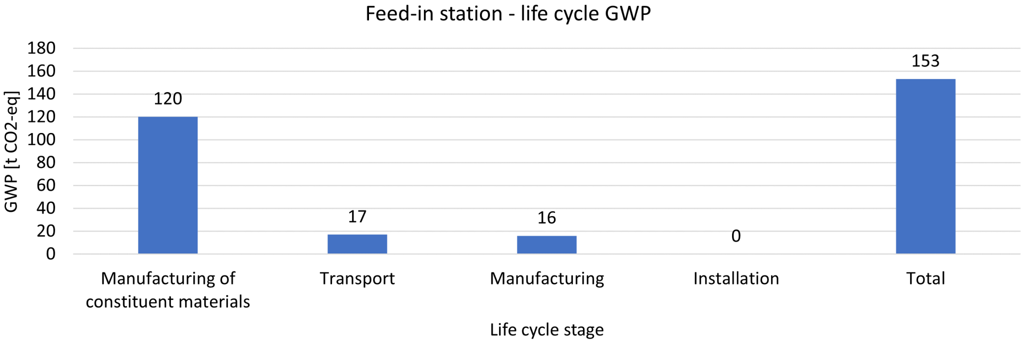


Figure 14: Contribution to GWP from the different life cycle stages per functional unit of one feed-in station in tonne CO_2-eq.

4 Part II - Scenario analysis

In this part of the study a comparison in terms of climate impact is made between different renewable transport solutions. The comparison includes heavy-duty vehicles and passenger cars respectively, both from a life cycle perspective comprising and combining results from part I with findings from literature. The propulsion systems considered in the comparison are the following:

- Fuel cell electric vehicles (FCEV) with hydrogen as fuel
- Internal combustion engine vehicles (ICEV) with biogas as fuel
- Battery electric vehicles (BEV) with electricity as fuel
- Battery electric vehicles using an electric road system (BEV-ERS), with electricity as fuel

4.1 Method

As declared in the aim of this study, the only considered impact category is climate change, expressed in terms of global warming potential with unit kg CO_2-equivalents. This applies also for this comparative part of the study. Vehicles are studied individually with an approach that enables comparison between the propulsion systems, both for passenger cars and heavy-duty trucks. In this method section the product system, general vehicle specifications, functional unit, system boundaries and data choices are described and motivated, valid for part II of the study. To keep the main report as concise as possible, detailed explanations, motivations, assumptions and calculations are found in appendix A.2.

4.1.1 Product system

In part II of the study the comparison is performed from a life cycle perspective, including the following life cycle stages: vehicle production, well-to-tank (WTT), infrastructure, tank-to-wheel (TTW) and maintenance. Since BEV-ERS includes the ERS components rail and feed-in station, corresponding infrastructure required for each vehicle type also needs to be considered in order to achieve a just comparison.

Another common approach when comparing GHG emissions from transports is to only consider a well-to-wheel (WTW) perspective, as done by for example Börjesson et al. (2016) examining biofuels. A WTW analysis is in turn often divided into two parts: well-to-tank and tank-to-wheel. The term WTT depicts the entire production chain of the fuel, from feedstock production to fuel production and downstream distribution, until the point where the fuel reaches the vehicle tank. TTW on the other hand refers to emissions arising from driving, mainly from tailpipe (Hill et al. 2020, p. v). Another alternative is to extend the WTW analysis to also include production of vehicle, maintenance and end-of-life treatment, meaning that the entire life cycle is considered. This is done by for example Hill et al. (2020) and as mentioned also in this study, with the exception if end-of-life. The WTW perspective is not sufficient for the systems that are compared in this study, why a life cycle perspective is chosen. The studied product system for part II is visualised in figure 15.

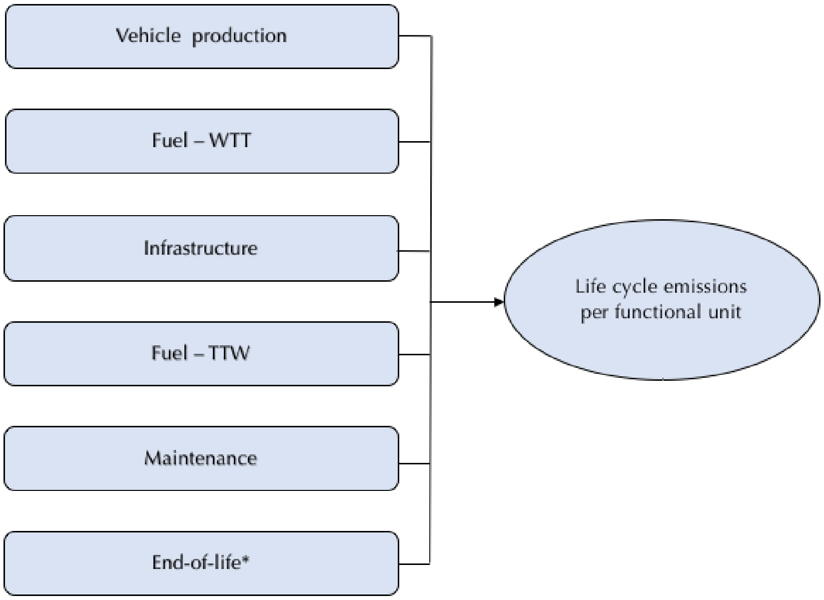
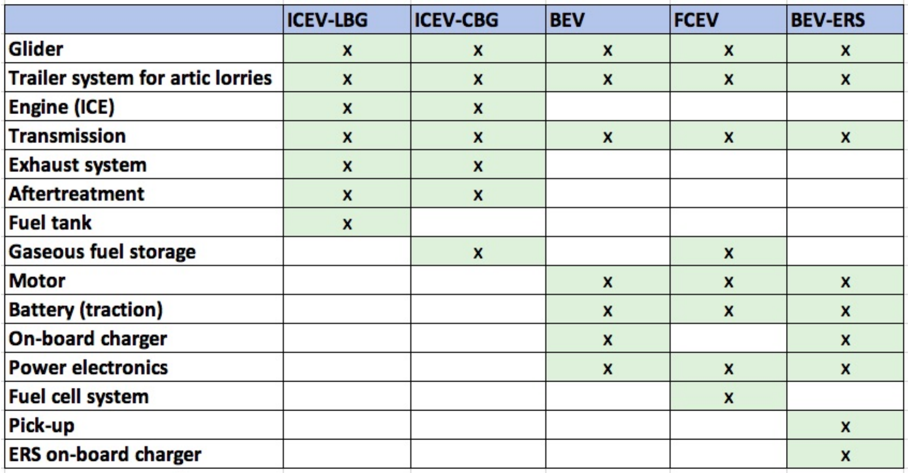


Figure 15: Life cycle stages for the studied propulsion systems.
*Excluded in the study

Vehicle production is a life cycle stage where the vehicle body without its powertrain often is assumed to be equal independent of propulsion system, commonly called vehicle glider. There are then additional specific components for each type that most often also are included in the production stage of a vehicle (Hill et al. 2020). A visualisation of what components that are included in the term vehicle production is shown in figure 16, divided between the vehicle types. For BEV and BEV-ERS, battery production is included in the vehicle production but is presented separately in the result section to clearly visualise the impact from this. In figure 16, ICEV-LBG refers to a heavy-duty vehicle using liquefied methane and ICEV-CBG to a passenger car using compressed methane, where ”B” denotes the origin being upgraded biogas. The table is derived from the report by Hill et al. (2020, p. 49), but have been altered to include only the types relevant for this study. In addition, a BEV-ERS column has been added including the two ERS components mounted on the vehicle, which thus is included in the life cycle stage vehicle production.



	ICEV-LBG	ICEV-CBG	BEV	FCEV	BEV-ERS
Glider	x	x	x	x	x
Trailer system for artic lorries	x	x	x	x	x
Engine (ICE)	x	x			
Transmission	x	x	x	x	x
Exhaust system	x	x			
Aftertreatment	x	x			
Fuel tank	x				
Gaseous fuel storage		x		x	
Motor			x	x	x
Battery (traction)			x	x	x
On-board charger			x		x
Power electronics			x	x	x
Fuel cell system				x	
Pick-up					x
ERS on-board charger					x

Figure 16: Components included in the term ”vehicle production” in this study, presented per propulsion system. The table is derived from Hill et al. (2020, p. 49) and supplemented with BEV-ERS and its additional components.

The life cycle stage well-to-tank does as already described involve the entire production chain of the fuel, i.e. either electricity, hydrogen or methane from upgraded biogas. This stage is onwards denoted ”fuel - WTT”. TTW on the other hand is only relevant for the ICEVs, since the other propulsion systems do not give rise to any tailpipe emissions affecting the climate. This life cycle stage is denoted ”fuel - TTW” onwards.

Infrastructure is a life cycle stage comprising refuelling equipment, which for the ICEV-BG and the FCEV is gas and filling stations, for the BEV stationary chargers and for BEV-ERS both dynamic and stationary chargers. Impact from infrastructure is a crucial factor in this study since the ERS technology, where electricity is used as fuel, involves manufacturing and implementation of rail and feed-in station. However, infrastructural impacts are in general not very well investigated in the literature. In the study from the European Commission conducted by Hill et al. (2020), a literature review of existing LCAs and environmental assessments for vehicles was performed. It was found that out of 347 reports included in the review only 4% included infrastructure for fuel supply.

Lastly, maintenance need for each vehicle type is included in the analysis and this generally involves measures such as service and exchange of parts as described by Hill et al. (2020).

4.1.1.1 General vehicle specifications

The considered heavy-duty vehicle is an articulated lorry with a gross vehicle weight of 40 tonnes, as investigated by Hill et al. (2020). This vehicle type is used for long-haul transports and has been chosen based on the described prospect made by the the Swedish Transport Administration where it is assumed that long-haul HDVs will be the the only vehicles using the ERS (Natanaelsson et al. 2021). The lorries differ in technical components depending on propulsion system as seen in figure 16, but are all used for transport of goods.

One important parameter is the load factor, which Hill et al. (2020) assume to be 40% for all types of lorries independent on propulsion system. This means that all lorries are assumed to be loaded to 40% of its total capacity. However, the mass of a lorry itself without load, called unladen mass, varies with propulsion system due to different technical components. One heavy component is the battery pack, clearly seen when comparing reported unladen mass for a BEV lorry with 940 kWh battery size and a ICEV-LBG lorry: 20.9 tonne against 14.8 tonne (Hill et al. 2020). This in turn implies a reduced load capacity in kg of goods, given the assumption that all lorries have a fixed load factor of 40%. Additionally, the unladen mass affects the fuel consumption, which is presented by Hill et al. (2020) for all propulsion systems including BEV-ERS. The effect of a varying unladen mass on the load capacity is however not obvious since it depends on whether the load is mass or volume constrained. If cargo with low density is transported and the unladen mass is assumed to not affect the volumetric load capacity of a truck, there would be no difference between the propulsion systems in terms of load capacity.

Concerning the passenger car, the type ”lower medium passenger car” has been chosen from the European Commission report, representing a segment C vehicle (Hill et al. 2020). Unladen mass is not given for passenger cars in the report since no transport of goods is evaluated. The parameter does still affect the fuel consumption, which also in this case is presented by Hill et al. (2020).

4.1.2 Functional unit

For this part of the study, the chosen functional unit is g CO_2-eq per tonne kilometre (tkm) for heavy-duty transports and g CO_2-eq per vehicle kilometre (vkm) for light-duty transports. One tonne kilometre equals the transport of one tonne cargo over a one kilometre distance, a common unit when comparing transport of goods. The total lifetime tkm for a truck equals the lifetime vkm multiplied by the load in tonne. Important to note is that the load is affected by the total load capacity, in turn determined by the unladen mass, together with the load factor. For passenger cars, a vehicle kilometre means travelling the distance of one km with the vehicle.

4.1.3 System boundary

Climate impact is assessed from a life cycle perspective with the above mentioned stages of vehicle production, well-to-tank, infrastructure, tank-to-wheel and maintenance. The study focuses on impact from transports in Sweden in the base case, which becomes especially relevant for the WTT stage. Concerning vehicle production and maintenance, data are taken from Hill et al. (2020), comprising existing literature on the subject and thus representing a wider geographical area. The baseline scenario in the report by Hill et al. (2020) reflects existing technology and conditions of 2020, but prospects and scenarios for 2030 and 2050 based on assumed progresses and future conditions are also included. Even if the ERS technology is not yet implemented and may not reach large-scale level before 2030 or 2035 at earliest according to Natanaelsson et al. (2020), the comparison is still based on current conditions and what is known today. This means that values for 2020 are taken from Hill et al. (2020) for all propulsion systems and that data from other sources as far as possible are chosen to reflect similar conditions. It is likely that the prerequisites in e.g. 2035 are altered due to technological advances and improved GHG performance in several areas, but that also applies to the ERS technology. The climate impact assessment of the ERS components in part I of the study is based on the conditions of today. To account for possible changed prerequisites, sensitivity analyses on the most important and uncertain parameters are instead performed.

Due to uncertainties regarding end-of-life treatment of both ERS components, vehicles and infrastructure, this is not included in the base case.

4.1.4 Types and sources of data

To reach an objective and fair comparison, vehicle characteristics and impact from production of the vehicles are all taken from the same report. The European Commission through Hill et al. (2020) have created an LCA compiling currently available LCA studies for a range of different vehicle and fuel types, named *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA*. The study includes 65 different powertrains and 60 fuel chains and is created to serve as basis for decision making for policy-makers within the transport sector. The functional unit in the report is either tonne or vehicle kilometre depending on vehicle type, similarly to this report. However, the WTT part have not entirely been taken from that report since the base case in this study primarily investigates fuel chains for Swedish conditions and Hill et al. (2020) generally consider average European conditions. The related dataset chosen for each vehicle type and propulsion system is described in detail under its respective section. Hill et al. (2020) do not include infrastructure explicitly, why other data on primarily Swedish conditions have been used. However, due to lack of data on this subject as previously mentioned, studies covering other European countries have also been used in the analysis.

4.2 Internal combustion engine vehicle - biogas

The first studied propulsion system is an internal combustion engine vehicle using liquefied methane in the articulated lorry and compressed methane in the lower medium car, both produced from biogas. Biogas is a gas consisting of methane (45-75%), carbon dioxide and other gases, where the exact composition varies with feedstock origin and production process (International Energy Agency [IEA] 2020). However, biogas cannot be used directly as a vehicle fuel. To be able to use it as a fuel in vehicles it needs to be upgraded, which is a process where water, carbon dioxide and other contaminants are removed in order to receive a methane content of 95-99% (Börjesson et al. 2016). After upgrading, the gas is often referred to as biomethane and it is chemically equal to natural gas of fossil origin, enabling it to for example be directly injected into the gas grid or used as a vehicle fuel (IEA 2020).

Methane as vehicle fuel is mainly used in ICEVs of spark-ignition (SI) type, i.e. the Otto motor. However, there is also another technology today called dual-fuelled compression-ignition engine with the ability of running on methane as main fuel (International Energy Agency - Advanced Motor Fuels [IEA-AMF] n.d.). For passenger cars the main option is the Otto engine fuelled with compressed methane and this is therefore chosen as vehicle type in this study, similar to what Börjesson et al. (2016) and Hill et al. (2020) have studied. There is however a limited storage capacity for fuels in gaseous form, which is more addressed for articulated lorries requiring a longer driving range. To manage this, the methane may be liquefied and then used in either an SI engine or a dual-fuelled diesel engine (Hill et al. 2020, p. 118). For the articulated lorry the latter is chosen, using a fuel blend of 95% methane and 5% diesel, which is investigated by both Hill et al. (2020) and Börjesson et al. (2016). The terms compressed natural gas (CNG) and liquefied natural gas (LNG) are sometimes used to denote methane as a vehicle fuel, independent of origin (Miljöfordon Sverige n.d.). For clarity, the terms compressed biogas (CBG) and liquefied biogas (LGB) are used onwards to stress the renewable origin, despite the fact that upgraded biogas is in the form of methane. This is also the notation used by Börjesson et al. (2016). If referring to biogas as fuel, not specifically liquefied or compressed, BG is used.

For both the articulated lorry and the lower medium car of ICEV type, details on assumptions and calculations are presented in appendix A.2.1 for each life cycle stage. The most relevant vehicle specifications regarding lifetime and TTW efficiency are found in table 5, whereas a summary of the contribution to GWP from the different life cycle stages is presented in table 6.

Table 5: Vehicle specifications for an ICEV-LBG articulated lorry and an ICEV-CBG lower medium car. Data adopted from Hill et al. (2020).

Articulated lorry		**Lower medium car**	
Lifetime [tkm]	8 026 000	Lifetime [vkm]	225 000
Lifetime [year]	10	Lifetime [year]	15
TTW efficiency [MJ/tkm]	1.33	TTW efficiency [MJ/vkm]	2.17

Table 6: GWP per life cycle stage for an ICEV-LBG articulated lorry and an ICEV-CBG lower medium car.

Articulated lorry	**[g CO_2-eq/tkm]**	**Lower medium car**	**[g CO_2-eq/vkm]**
Vehicle production	11.0	Vehicle production	39.0
Fuel - WTT	16.8	Fuel - WTT	22.5
Infrastructure	0.4	Infrastructure	5.2
Fuel - TTW	9.8	Fuel - TTW	3.8
Maintenance	4.0	Maintenance	6.0
Life cycle GWP	42.1	Life cycle GWP	76.5

GHG performance of the fuels LBG and CBG is taken from Börjesson et al. (2016), where specified data on different production pathways are presented. Both LBG and CBG are assumed to be produced via anaerobic digestion (AD) in this study and this is explained further in appendix A.2.1.2. As this data are a few years old, a comparison with the most recent figures reported by the Swedish Energy Agency (Energimyndigheten 2021a) for delivered biogas is made below. The reason for not using this data exclusively is because of a higher level of aggregation where no distinction between different production pathways is made.

The emission factor from Börjesson et al. (2016) for CBG used in a lower medium car is 10.4 g CO_2-eq/MJ for production, with additional 1.7 g CO_2-eq/MJ from methane leakage in the vehicle. The Swedish Energy Agency (Energimyndigheten 2021a) reports that during 2020 average emissions from CBG from a life cycle perspective were 12.6 g CO_2-eq/MJ. For the articulated lorry using LBG, values from Börjesson et al. (2016) are 12.3 g CO_2-eq/MJ for production and 7.9 g CO_2-eq/MJ from combustion due to the small fossil diesel content, summing up to 19.7 g CO_2-eq/MJ. This in relation to average emissions from LBG 2020 of 24.6 g CO_2-eq/MJ (Energimyndigheten 2021a). This deviation is reasonable since values from Börjesson et al. (2016) specifically cover upgraded biogas from anaerobic digestion and those from the Swedish Energy Agency cover an average where 2% have fossil origin.

4.3 Fuel cell electric vehicle

There are two types of vehicles fuelled with hydrogen gas: hydrogen internal combustion engine vehicles and fuel cell electric vehicles, where the latter is the most common and the one studied in this report. In a FCEV, H_2 is converted to mechanical energy via a proton exchange membrane (PEM) fuel cell. There are no tailpipe emissions from FCEVs besides water, but impact from production of hydrogen needs to be considered and is more or less CO_2-intensive depending on hydrogen production pathway (U.S department of energy n.d). Two different hydrogen production pathways are investigated for the FCEV: steam methane reforming (SMR) from natural gas and electrolysis. As of today, the majority of the H_2 in Sweden is produced via SMR, accounting for 67% of the total production. H_2 from electrolysis accounts for only 3% of the total annual production of 6 TWh hydrogen gas. The production pathway distribution is similar in Europe, with a majority of the production coming from SMR and residual streams and less than 5% from electrolysis. Hydrogen produced via electrolysis based on renewable electricity or an electricity mix with low CO_2-intensity is considered a renewable fuel whereas hydrogen produced via SMR is a non-renewable fuel (Fossilfritt Sverige 2021).

The market for FCEVs is as of today limited and the exact number of FCEVs in Sweden is not clear. Statistics Sweden states that there were 15 HDVs in 2021 with fuel type ”other”, including autogas, wood gas, hydrogen gas or unknown fuel, as well as 265 passenger cars in the same category (Trafikanalys 2021). FCEVs are however expected to increase in the coming years and 43 of the leading truck manufacturers in Europe have agreed to a common goal of pre-commercialising heavy-duty FCEVs by 2025, with 5 000-10 000 vehicles on the European market, reaching full commercialisation by 2030 with 95 000 vehicles (Malmberg & Falenius 2021).

The most important vehicle specifications in terms of lifetimes and TTW efficiencies are found in table 7. A summary of the GWP from the different life cycle stages are seen in table 8 for the SMR pathway and in table 9 for the electrolysis pathway. For the FCEV propulsion system including both the articulated lorry and the lower medium car, more details on vehicle specifications, calculations and other relevant parameters and assumptions are found in appendix A.2.2.

Table 7: Vehicle specifications for a FCEV articulated lorry and lower medium. Data adopted from Hill et al. (2020).

Articulated lorry		**Lower medium car**	
Lifetime [tkm]	7 674 000	Lifetime [vkm]	225 000
Lifetime [year]	10	Lifetime [year]	15
TTW efficiency [MJ/tkm]	1.08	TTW efficiency [MJ/vkm]	1.13

Table 8: GWP per life cycle stage for a FCEV articulated lorry and lower medium car, with hydrogen produced via SMR.

Articulated lorry [g CO_2-eq/tkm]		**Lower medium car** [g CO_2-eq/vkm]	
Vehicle production	17.4	Vehicle production	59.0
Fuel - WTT (SMR)	118	Fuel - WTT (SMR)	124
Infrastructure	0.32	Infrastructure	0.6
Maintenance	2.8	Maintenance	3.0
Life cycle GWP	139	Life cycle GWP	186

Table 9: GWP per life cycle stage for a FCEV articulated lorry and lower medium car, with hydrogen produced via electrolysis.

Articulated lorry [g CO_2-eq/tkm]		**Lower medium car** [g CO_2-eq/vkm]	
Vehicle production	17.4	Vehicle production	59.0
Fuel - WTT (electrolysis)	12.2	Fuel - WTT (electrolysis)	13.5
Infrastructure	0.3	Infrastructure	3.2
Maintenance	2.8	Maintenance	3.0
Life cycle GWP	32.7	Life cycle GWP	78.7

Calculations are primarily based on values from Hill et al. (2020) but with the addition of infrastructure and the use of a Swedish electricity mix for electrolysis. If comparing results from the WTT stage for electrolysis, a resulting emission factor of 11.3 g CO_2-eq/MJ is received in this report when using Swedish electricity mix and reported efficiency in the electrolysis process by Hill et al. (2020). The most comparable hydrogen pathway studied by Hill et al. (2020) is a prospect of future impact from hydrogen production with a combination of SMR and electrolysis using a European renewable electricity mix of 23 g CO_2-eq/kWh. This pathway would give rise to an emission factor of 17.2 g CO_2-eq/MJ (Hill et al. 2020), which thus is comparable to the results found in this study.

4.4 Battery electric vehicle

One large trend towards decarbonisation of the transport sector in Sweden has during the latest years been electrification. Today around 6% of the vehicles in Sweden are chargeable if including hybrids and around 2% if only including BEVs, with a total battery size of 8 100 MWh found in electric vehicles (Elbilsstatistik.se n.d.a).

The term "vehicle production" includes both vehicle glider and supplementing components as described earlier in figure 16, where also the battery is included. However, as the battery is an important factor in the comparison, GWP from this is presented individually for the BEV. A battery size of 940 kWh is assumed for the articulated lorry and 58 kWh for the lower medium car in the study by Hill et al. (2020), which is used in this study as well. The most common vehicle battery type is lithium-ion, with the dominating cathode type being nickel-manganese-cobalt (NMC). GWP of these batteries has been determined by Hill et al. (2020) based on current market share consisting of different types of lithium-ion batteries, with a CO_2-intensity of 89 kg CO_2-eq/kWh (Hill et al. 2020, p. 63).

Infrastructure for BEVs includes charging points used for recharging the batteries, which according to Hill et al. (2020, p. 6) is an area less investigated and often excluded in studies examining environmental impacts of BEVs. Since the comparison between propulsion systems includes the ERS technology, which serves as the infrastructure, it is thus necessary to also include the charging points for a just comparison. Climate impact from charging infrastructure is not evaluated in the study by Hill et al. (2020), but are studied in detail by Bekel and Pauliuk (2019). Bekel and Pauliuk (2019) have based their analysis on German conditions with 0.95 charging points per BEV and an assumption that a BEV is charged at three different power levels during its lifetime: 3.7, 22 and 50 kW. With respect to this, the authors have come up with a scenario for 2030 where 53% of all charging points are located at homes with a power level of 3.7 kW, 19% at companies with a level of 3.7 kW, 26% are public chargers with 22 kW and 1% public chargers with 50 kW power. Climate impact from charging infrastructure has been derived from the mentioned study and the results per functional unit is presented in table 11. Details on calculations and assumptions leading up to this result can be found in appendix A.2.3.3.

Similarly to the other studied propulsion systems further specifications regarding assumptions and data sources for this vehicle type are found in appendix A.2.3. The most important vehicle specifications are presented in table 10 and calculated GWP per life cycle stage is found in table 11.

Table 10: Vehicle specifications for a BEV articulated lorry and lower medium car. Data adopted from Hill et al. (2020).

Articulated lorry		**Lower medium car**	
Lifetime [tkm]	6 074 000	Lifetime [vkm]	225 000
Lifetime [year]	10	Lifetime [year]	15
Battery size [kWh]	940	Battery size [kWh]	58
TTW efficiency [MJ/tkm]	0.68	TTW efficiency [MJ/vkm]	0.57

Table 11: GWP per life cycle stage for a BEV articulated lorry and lower medium car.

Articulated lorry	**[g CO_2-eq/tkm]**	**Lower medium car**	**[g CO_2-eq/vkm]**
Vehicle production	12.2	Vehicle production	39.1
Battery production	13.8	Battery production	22.9
Fuel - WTT	5.5	Fuel - WTT	4.5
Infrastructure	2.9	Infrastructure	3.4
Maintenance	2.2	Maintenance	3.0
Life cycle GWP	36.6	Life cycle GWP	72.9

Life cycle GWP is found to be 72.9 g CO_2-eq/vkm for the lower medium car in this study, which could be compared with 60 g CO_2-eq/vkm reported by Hill et al. (2020) when using a renewable electricity mix. The higher value in this study is partly due to the inclusion of infrastructure and partly because the European renewable electricity mix assumed by Hill et al. (2020) has a lower emission factor than the Swedish electricity mix used in this report.

4.5 Battery electric vehicle with ERS

Whilst the other vehicle types are described and investigated thoroughly by Hill et al. (2020) and in addition are more or less are commercialised, the ERS technology is related to more assumptions. Nevertheless, a BEV-ERS is included in the study by Hill et al. (2020), but all ERS infrastructure components are excluded, which further motivates the purpose of this study. For all other propulsion systems, climate impact per FU is mainly related to characteristics of vehicle and fuel. What is unique for the ERS is the correlation between infrastructure, vehicle characteristics and usage, together determining the life cycle emissions. To assess climate impact it is therefore necessary to set up a scenario for the ERS where it is assumed how vehicles are using it.

The potential for downsizing the battery in a vehicle using the ERS has as mentioned been pointed out as the main emission reducer compared to a BEV. The extent to which the battery size can be reduced depends on what driving range that is required for the vehicle outside the ERS. The more roads that are electrified, the larger is the possible battery size reduction. The driving range is in turn dependent on what type of transport and vehicle that is considered. For example, heavy-duty transports and vehicles driving a fixed route on the largest roads most of the time, a battery size only managing the driving distance between the ERS and the terminal might be sufficient.

Another important parameter affecting the GHG performance is the electrification rate of the ERS, since it determines how many rails are required on a certain distance. This is described in section 1.4.1 and is further treated in the chapter regarding infrastructure, 4.5.3.

An additional parameter affecting the life cycle GHG emissions of a vehicle is how many vehicles that share the infrastructure. Depending on where the ERS is implemented and how many vehicles are driving and utilising the system there, each vehicle will be assigned a different share of the total infrastructure impact. This relates to the concept AADT, investigated by Natanaelsson et al. (2021) and described in section 1.4.1. The AADT may be seen as a utilisation rate, where the AADT of vehicles using the ERS determines how many vehicles that share the impact. This study does not intend to answer future utilisation rate of the ERS, but rather to investigate during what conditions an ERS might perform better or worse than other vehicle types, why different AADT values are used in the base case comparison. The influence of AADT on the results and possible intersections with other vehicle types depending on AADT are further examined in a sensitivity analysis.

For the BEV-ERS, it is possible to compare an arbitrary driving distance of 1 km given that the above mentioned parameters are determined. If a system with a fixed ERS distance is evaluated, as made by Natanalesson et al. (2021), the share of total travelled km by a vehicle that occurs on versus outside the ERS network may be determined. This is an important parameter, since it determines how much of the infrastructure that should be assigned to a specific vehicle.

4.5.1 Vehicle production

As of today, there are no electric roads with vehicles using it on a commercial scale. For a vehicle to be able to use Elonroad's electric road, it must be a BEV with two additional components added enabling electricity to be transferred from road to vehicle: OBC and pick-up. For both articulated lorry and lower medium car it is assumed that the vehicle body characteristics of a BEV-ERS are the same as the BEV investigated in the previous section. Although with the exception that the mentioned ERS components are added and that the battery size can be reduced. Impact from vehicle production is therefore based on the values presented for the BEV in the European Commission report by Hill et al. (2020). Regarding OBC and pick-up, values from part I of the study are used, but scaled to match the size of the vehicle. This is described in appendix A.2.4.

The capacity of the downsized battery is determined with basis in the prospect by the Swedish Transport Administration described in section 1.4.1. The report states that a battery reduction to 30% of the size for a BEV is possible for vehicles using ERS (Natanaelsson et al. 2021). The reduced battery size also implies a decrease in vehicle unladen mass, thus giving an increased lifetime in tonne kilometre compared to a BEV. Details on this mass alteration are further presented in appendix A25. The decrease only influences the comparison in terms of the functional unit comparison in tkm. The total lifetime emissions are based on the assumption that a HDV operates for 10 years and that during its lifetime it will have travelled 800 000 vehicle kilometres, which is the basis for the total lifetime emission calculation.

One uncertain parameter for both the BEV-ERS articulated lorry and the lower medium car is the TTW efficiency. Along with a downsized battery and consequently a lower unladen mass of the vehicle, it is likely that the TTW efficiency is increased. Despite this, the BEV-ERS lorry is assumed to have a similar efficiency in MJ/vkm as the BEV lorry when driving with energy from the battery in the report by Hill et al. (2020). No consideration is made with respect to this for neither lorry nor car, other than the mentioned effect of an altered total lifetime tkm for the lorry. Another factor counteracting a lower fuel consumption for the BEV-ERS is a potential additional drag due to friction between rail and pick-up. The magnitude of this is however not investigated and is therefore disregarded in this report as well as by Hill et al. (2020). The most important vehicle specifications for the BEV-ERS are summarised in table 12.

Table 12: Vehicle specifications for a BEV-ERS articulated lorry and lower medium car. Data adopted from Hill et al. (2020) and Natanaelsson et al. (2021).

Articulated lorry		**Lower medium car**	
Lifetime [tkm]	7 771 891	Lifetime [vkm]	225 000
Lifetime [year]	10	Lifetime [year]	15
Battery size compared to BEV [%]	30	Battery size compared to BEV [%]	30
Battery size [kWh]	282	Battery size [kWh]	17.4
TTW efficiency [MJ/tkm]	0.53	TTW efficiency [MJ/vkm]	0.56

In table 12 battery capacities and TTW efficiencies are presented, from where driving-ranges can be determined. A battery size of 282 kWh combined with a TTW efficiency of 0.53 MJ/tkm result in a driving range of around 196 km for the HDV. The BEV-ERS lorry investigated by Hill et al. (2020) is modelled with an electric range of 250 km, without explicitly presenting what battery size that is assumed. This means a less downsized battery compared to the base case in this study. For the lower medium car, a battery size of 17.4 kWh together with corresponding TTW efficiency give a driving range of around 111 km.

In a report by Domingues-Olavarría (2018) examining optimisation possibilities of electromobility, the author concludes that a battery giving 60 km driving range is sufficient for both long-haul trucks and passenger cars to cover trips within cities and on roads without ERS. However, the potential battery reduction is directly related to what system the vehicle operates in. Nevertheless are the ranges of 196 km respectively 111 km an indication of the 30% assumption not being an underestimate compared to what Domingues-Olavarría (2018) have concluded. In another study Márquez-Fernández et al. (2022) suggest a reduced battery size in passenger cars from 60 to 25 kWh, which also is relatively close to what is assumed in this study. For HDVs, Márquez-Fernández et al. (2022) examines a truck with an BEV battery size of 500 kWh, which is suggested to be downsized to 75 kWh given a transition to ERS. For the truck this means a larger reduction than to 30% of the BEV size, but for the car the reduction is smaller. It can however be concluded that the assumption of 30% is a reasonable value for the base case.

4.5.2 Fuel - WTT

Similarly to a BEV, the fuel used in a BEV-ERS is in the form of electricity. As also described in the BEV section, charging efficiency needs to be considered when evaluating the WTT life cycle stage, in addition to electricity mix and TTW efficiency. For a BEV-ERS there are two different charging efficiencies to account for, one for the stationary part and one for the dynamic part. The stationary charging efficiency is assumed to be 90% and the ERS charging efficiency 93%, which are explained and motivated further in appendix A.2.5.

Since the two charging efficiencies are not equal, a division between how much electricity that is supplied via each type during the entire lifetime of the vehicle is required. This is made with starting point in the Swedish Transport Administration scenario by Natanaelsson et al (2021) described earlier, where it is predicted that 40% of the total travelled distance for a HDV using the ERS will occur outside the ERS and 60% on the ERS during its lifetime. Therefore, the assumption is made that the energy required for propulsion is supplied 60/40 from ERS versus stationary chargers. Since the scenario only includes HDVs, an assumption regarding lower medium cars is needed. A driving pattern of 50% on ERS and 50% outside ERS is assumed, based on a probable higher level of irregular travels than for a HDV.

4.5.3 Infrastructure

Infrastructure for a BEV-ERS consists of the dynamic charging ERS components rail and feed-in station, and the stationary charging infrastructure. As previously described, implementation of an ERS does not imply that all electricity needed for propulsion of a vehicle is supplied via the ERS. A portion of the total energy will also be supplied via stationary chargers. Calculated GWP from infrastructure is explained in the upcoming section, divided between dynamic and stationary infrastructure.

4.5.3.1 Dynamic charging infrastructure

The dynamic charging infrastructure involves rails and feed-in stations and the environmental burden from the entire life cycle of these components needs to be shared between all vehicles using them during each component's lifetime. As no ERS exist on commercial or large-scale level today, several assumptions are needed in order to assess climate impact. Instead of basing the calculations on a specific scenario with a total ERS length as described by Natanaelsson et al. (2021), this study examines one arbitrary kilometre of electric road, in line with the functional unit. However, input data on certain parameters regarding usage and design are made with respect to the results presented by Natanaelsson et al. (2021), which in turn have based their calculations on a system with 3 000 km ERS.

In the base case, an electrification rate of 60% is assumed according to what is reported by Natanaelsson et al. (2021) for Elonroad's technology. This means that 66 rails are required per km ERS. Furthermore, a rail lifetime of 15 years is assumed as a base case after consultation with Elonroad engineers. One feed-in station is estimated per km ERS, with a lifetime of 40 years according to upstream vendor. This is then scaled with respect to 60% electrification rate and to the functional unit only concerning a one-way electric road. Impact from the stated infrastructure is then determined based on the utilisation rate, i.e. the previously described AADT. In order to visualise the AADT influence on the final result, several AADT values from table 1 are used in the base case for articulated lorries. These are the low case prediction for 2030 of 172 vehicles/day, the high case predictions for 2035 and 2040 of 896 and 1 088 vehicles/day respectively, and the total predicted AADT for 2040 of 4 400 vehicles/day. The latter is chosen in order to account for a scenario where also other vehicle types are using the ERS, e.g. passenger cars. For the lower medium car, calculations are made for AADT values of 300, 1 000 and 5 000 vehicles/day in the base case. Natanaelsson et al. (2021) do not include cars in their analysis, but Elvägsutredningen (2021) takes this into account. They investigate total costs for an AADT between zero and 12 000 vehicles/day, in addition presenting maps with which roads that have an passenger car AADT exceeding 2 000 and 5 000 vehicles/day respectively.

The allocation of impact between dynamic and stationary charging infrastructure is made with respect to driving patterns and accordingly usage. Along with what is investigated by Natanaelsson et al. (2021) and described earlier, 60% of the total electricity is assumed to be supplied from the ERS and 40% from stationary charging for HDVs. In a base case, the relationship 50/50 is assumed for passenger cars. The assumptions described above are further described in appendix A.2.4 together with calculations in A.2.6. The influence of the mentioned parameters are evaluated in a sensitivity analysis.

4.5.3.2 Stationary charging infrastructure

The stationary charging infrastructure is assumed to provide 40% and 50% of the total electricity consumed by the articulated lorry and the lower medium car respectively. For the car, the stationary charging infrastructure is assumed to be equal to that of a BEV, described in appendix A.2.3.3. This means that the same pattern of charging at three different voltage levels (3.7, 22 and 50 kW) with data from Bekel & Pauliuk (2019) is assumed also with ERS.

Stationary charging of BEV-ERS articulated lorries are on the other hand not assumed to be exactly equal to that of a BEV lorry. Natanaelsson et al. (2021) make the assumption that HDVs using ERS only will use depot charging at power levels of 22-50 kW. Therefore, stationary charging of BEV-ERS lorries is assumed to be performed entirely with 50 kW chargers. Data for this charger is taken from Bekel & Pauliuk (2019) similarly to the BEV and specific values on this are presented in appendix A.2.6.5. Relevant to note is that Natanaelsson et al. (2021) base their cost estimations on having one depot charger per battery vehicle, whilst Bekel & Pauliuk (2019) have calculated with 0.95 chargers per vehicle in total.

4.5.3.3 Summary infrastructure

Since GWP of the infrastructure is varying with AADT per functional unit, a summary of this life cycle stage is presented for some specific values of AADT in table 13.

Table 13: Summary of impact from infrastructure for BEV-ERS articulated lorry and lower medium car at different AADT values.

Articulated lorry

AADT [vehicles/day]	Rail and feed-in station [g CO_2-eq/tkm]	Stationary charging infrastructure [g CO_2-eq/tkm]	Total [g CO_2-eq/tkm]
172	26.2	0.2	26.4
896	5.0	0.2	5.3
1 088	4.1	0.2	4.4
4 400	1.0	0.2	1.3

Lower medium car

AADT [vehicles/day]	Rail and feed-in station [g CO_2-eq/vkm]	Stationary charging infrastructure [g CO_2-eq/vkm]	Total [g CO_2-eq/tkm]
300	54.4	1.7	56.1
1 000	16.3	1.7	18.0
5 000	3.3	1.7	5.0

4.5.4 Maintenance

Maintenance are needed for both vehicle and ERS components during their respective lifetime. The vehicle maintenance impact are taken from Hill et al. (2020) as for the other propulsion systems. The durability and lifetime of the four ERS components and which parts that may need more maintenance measures during its lifetime is not thoroughly investigated at present. However, it is currently being studied by Elonroad and the knowledge in this area will probably increase continuously while testing and fine-tuning the products. What is assumed today is that the copper braid on the pick-up, i.e. the material in contact with the rail, probably will need to be exchanged. A rough estimation is that the braid needs to be replaced once a year during its lifetime according to Elonroad engineers. Due to lack of other data, additional impact from maintenance measures are excluded in this study. The resulting values from maintenance are presented in appendix table A30.

4.5.5 Summary of impact from life cycle stages

Calculated GWP of the life cycle stages described above are summarised in table 14 for different AADT values.

Table 14: GWP per life cycle stage for a BEV-ERS articulated lorry and lower medium car. AADT has the unit vehicles/day.

Articulated lorry [g CO2-eq/tkm]		**Lower medium car [g CO2-eq/vkm]**	
Vehicle production	9.6	Vehicle production	39.1
Battery production	3.2	Battery production	6.9
OBC and pick-up	1.0	OBC and pick-up	7.0
Fuel - WTT	4.2	Fuel - WTT	4.5
Infrastructure - rail and feed-in station AADT 172	26.2	Infrastructure - rail and feed-in station AADT 300	122
Infrastructure - rail and feed-in station AADT 896	5.0	Infrastructure - rail and feed-in station AADT 1 000	36.5
Infrastructure - rail and feed-in station AADT 1 088	4.1	Infrastructure - rail and feed-in station AADT 5 000	7.3
Infrastructure - rail and feed-in station AADT 4 400	0.5		
Infrastructure - stationary	0.2	Infrastructure - stationary	1.7
Maintenance	4.0	Maintenance	6.3
Life cycle GWP AADT 172	48.4	Life cycle GWP AADT 300	187
Life cycle GWP AADT 896	27.2	Life cycle GWP AADT 1 000	102
Life cycle GWP AADT 1 088	26.4	Life cycle GWP AADT 5 000	72.6
Life cycle GWP AADT 4 400	22.7		

4.6 Results

Results on GWP per functional unit for the base case of articulated lorry and passenger car are presented in this section, followed by sensitivity analyses. A summary of abbreviations and important parameters are presented in table 15.

Table 15: Explanation of propulsion systems, abbreviations and life cycle stages seen in the results.

Abbreviation	Explanation
FCEV-SMR	Fuel cell electric vehicle fuelled with H_2 produced via steam methane reforming from natural gas
FCEV-electrolysis	Fuel cell electric vehicle fuelled with H_2 produced via electrolysis
ICEV-LBG	Internal combustion engine vehicle fuelled with liquefied methane from upgraded biogas
ICEV-CBG	Internal combustion engine vehicle fuelled with compressed methane from upgraded biogas
BEV	Battery electric vehicle using stationary charging
BEV-ERS	Battery electric vehicle using ERS and stationary chargers
AADT	Annual average daily traffic in vehicles/day, describing utilisation rate of the ERS
Vehicle production	Cradle-to-gate emissions from vehicle, for BEV-ERS this includes pick-up and OBC
Fuel - WTT	Emissions from production and distribution of fuel (well-to-tank)
Infrastructure	Emissions from refuelling stations and chargers, for BEV-ERS this includes rail and feed-in station
Fuel - TTW	Emissions from driving (tank-to-wheel)
Maintenance	Emissions from maintenance of vehicles and infrastructure

4.6.1 Articulated lorry - base case

Base case results on GHG performance for the articulated lorries are presented per propulsion system in figure 17. As seen in the graph the different life cycle stages contribute differently depending on propulsion system. The outlier is the FCEV-SMR, having significantly higher GWP per tkm than the other. Producing hydrogen via SMR means a non-renewable fuel since the methane used is of fossil origin but is included as this is the most common hydrogen production pathway of today. A great reduction is reached if hydrogen instead is produced via electrolysis with a Swedish electricity mix as in the base case. This pathways is however not widespread yet. The ICEV-LBG includes tailpipe emissions unlike the rest of the vehicles, emerging from a fuel mixture of 5% fossil diesel. A relatively large share of a BEVs impact originates from the battery production, causing this to perform worse than the FCEV-electrolysis but still better than the ICEV-LBG. As seen with BEV-ERS, the infrastructure is a crucial parameter placing this type either at the top or the bottom amongst the renewables depending on AADT.

Both BEV and BEV-ERS are assumed to have the same requirement of energy for propulsion per vehicle kilometre. However, the BEV with its significantly larger battery is heavier, thus requiring a higher energy input for propulsion per tonne kilometre since it transports less goods. This combined with a lower assumed charging efficiency for stationary compared to dynamic charging give rise to a difference in WTT as can be seen in the figure. Specific values for each life cycle stage are found in respective section presented earlier and also in the appendix. For the WTT stage, GWP per tkm is 5.5 and 4.2 g CO_2-eq/tkm respectively for BEV and BEV-ERS.

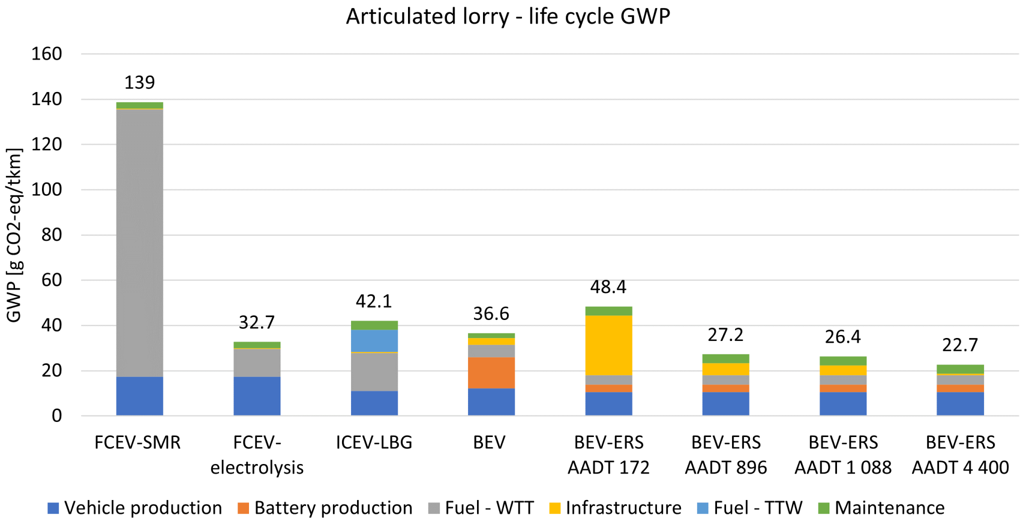


Figure 17: Life cycle GWP per propulsion system and life cycle stage for articulated lorry. AADT has the unit vehicles/day.

The main parameter affecting the performance of BEV-ERS is the infrastructure in the form of rail and feed-in station. In figure 18 GWP per tkm for BEV-ERS is plotted as a function of AADT together with the other propulsion systems except from FCEV-SMR. The other types are not affected by a change in AADT and the intersection between the BEV-ERS line and the other lines represents the point were BEV-ERS performs better than or equal to the other propulsion systems. Out of the studied renewable systems, ICEV-LBG has the highest impact with 42.1 g CO_2-eq/tkm, intersecting BEV-ERS at an AADT of 226 vehicles/day. Break-even between BEV-ERS and BEV occurs at an AADT of 313 vehicles/day, where the impact for both types is 36.6 g CO_2-eq/tkm. FCEV-electrolysis has the lowest impact of all types, 32.7 g CO_2-eq/tkm, considering an AADT below the break-even of 428 vehicles/day.

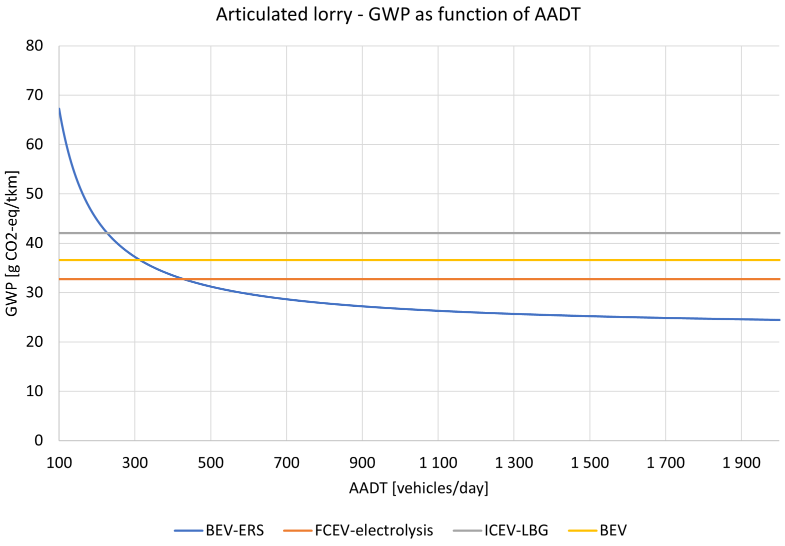


Figure 18: Life cycle GWP per propulsion system and life cycle stage for an articulated lorry as function of AADT.

To clearly see the impact from the specific ERS components, a more detailed graph only including the BEV-ERS cases are found in figure 19. It can be seen that OBC and pick-up are unaffected by AADT with a constant value of 1 g CO_2-eq/tkm. GWP of rail and feed-in station vary between 26.2 and 0.5 g CO_2-eq/tkm for the studied AADT values. The stationary charging infrastructure is independent of AADT with a value of 0.2 g CO_2-eq/tkm, thereby constituting a small portion of the infrastructure impact at low AADT values.

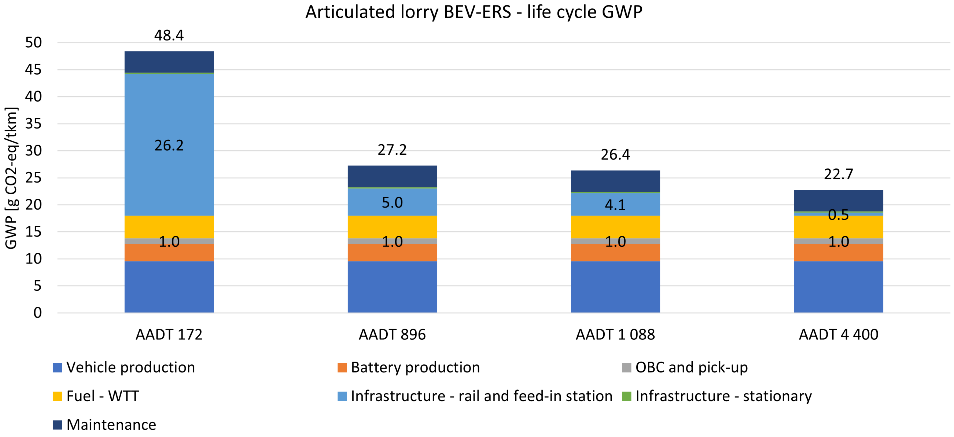


Figure 19: Life cycle GWP of BEV-ERS specified with respect to the ERS components. AADT has the unit vehicles/day.

As earlier described, all lorries have an assumed total lifetime mileage of 800 000 km. The lifetime tkm is however affected by unladen mass and thus the load capacity of each lorry, giving different lifetime tkm for the different propulsion systems. A lighter vehicle will be able to transport more goods over its lifetime, which is an adopted property from the European commission report (Hill et al. 2021). With the assumption that the lorries are limited by mass and not by volume, a lighter vehicle will be able to carry more load, thus increasing the lifetime tkm. The effect of this is reflected in the total life cycle GHG emissions for the propulsion systems seen in figure 20. The BEV-ERS lorry is lighter than the BEV due to a smaller battery, resulting in an increased lifetime tkm. Even though the BEV-ERS still shows a lower overall impact from AADT 896 vehicles/day and above, the difference in total lifetime emissions is smaller than the emissions per tkm if evaluated in percentage. This is a result of the difference in total lifetime tkm, amplifying the effect per tkm differently depending on vehicle type.

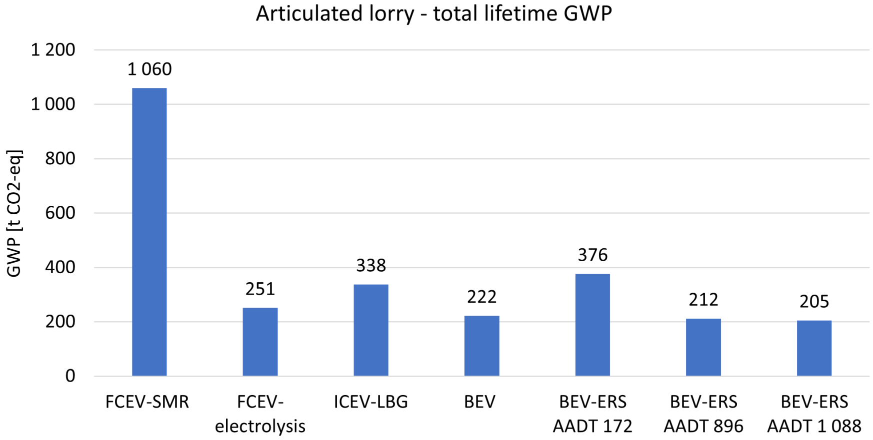


Figure 20: Total lifetime GWP in tonne CO_2-eq per propulsion system for articulated lorry. AADT has the unit vehicles/day.

4.6.2 Lower medium car - base case

The considered functional unit for lower medium car is vehicle kilometre and GWP for all propulsion systems per life cycle stage is presented in figure 21. Highest GHG emissions per vkm is found for FCEV-SMR with 186 g CO_2-eq/vkm, which is due to a great impact from fossil fuels in the SMR process combined with a high vehicle production impact. The FCEV with H_2 from electrolysis then follows, with an impact of 78.7 g CO_2-eq/vkm. Relatively comparable is ICEV-CBG with 76.5 g CO_2-eq/vkm and also BEV with 72.9 g CO_2-eq/vkm. The comparison with BEV-ERS is less straight forward as it is strongly influenced by AADT via the infrastructure. As seen in the graph, a relatively high value of AADT is required for BEV-ERS to perform better than the other propulsion systems for cars.

Impact from BEV-ERS vehicle production consists of production of both vehicle and the ERS components OBC and pick-up. This together with battery production and WTT constitutes the life cycle stages unaffected by AADT. BEV has a significantly higher impact from battery production, a comparable impact from WTT but a slightly lower impact from vehicle production. The latter is because the BEV does not require the additional components OBC and pick-up. The net result is that BEV has a higher impact than BEV-ERS only considering the parts not affected by the AADT.

For passenger cars the vehicle mass only affects the GHG performance via its TTW efficiency in MJ/vkm. The vehicle with lowest TTW efficiency is the ICEV-CBG, with 2.2 MJ/vkm as seen in table A11. The second lowest is the FCEV with 1.1 MJ/vkm. Even though the ICEV-CBG has the highest energy consumption, the vehicle production stage has a lower impact than the FCEV. BEV and BEV-ERS are the most efficient vehicles in terms of energy consumption, both with a TTW efficiency of 0.56 MJ/vkm. Assuming an equal efficiency for BEV-ERS as BEV might however be an overestimation given a lighter vehicle for BEV-ERS due to a reduced battery size. This is further evaluated in a sensitivity analysis.

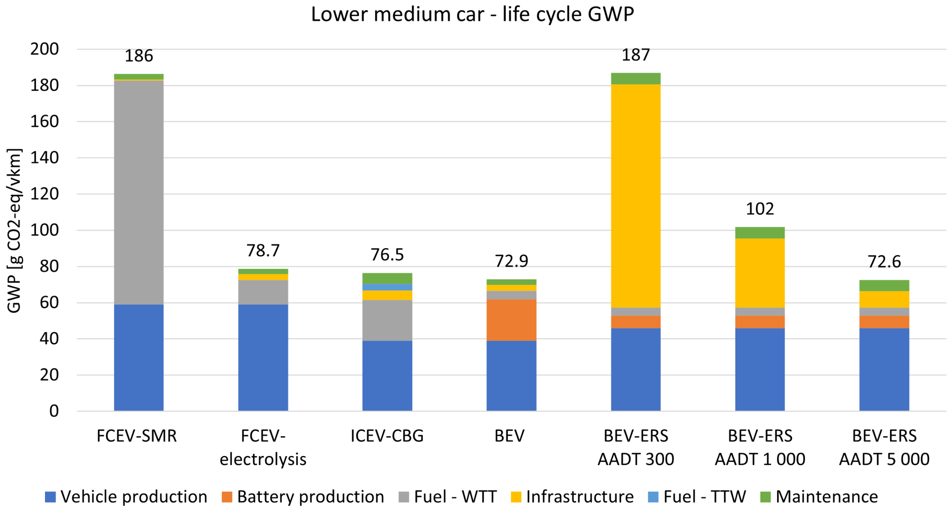


Figure 21: Life cycle GWP per propulsion system and life cycle stage for lower medium car. AADT has the unit vehicles/day.

As previously stated, this report does not intend to answer the question of what ERS scenario is most likely, but rather to investigate how this system performs under certain conditions compared to other renewable transport solutions. At low AADTs the BEV-ERS reaches high life cycle emissions and specific break-evens between BEV-ERS and the other propulsion systems are investigated in figure 22.

Higher AADT values are evaluated than for the articulated lorry in line with reported total AADT values by Elvägsutredningen (2021) concerning the 3 000 km ERS network. An interval from 500 to 10 000 vehicles/day in AADT is presented in figure 22. The intersection between BEV-ERS and FCEV-electrolysis occurs at an AADT of 2 720 vehicles/day. For the ICEV-CBG, break-even is found at an AADT of 3 250 vehicles/day and for BEV at 4 780 vehicles/day. Thus, below 4 780 vehicles/day the BEV performs better under the assumed conditions in the base case. As a reference, E6 between Malmö and Gothenburg has a total AADT exceeding 20 000 vehicles/day on the entire road length in both directions, of which HDV AADT exceeds 4 500 vehicles/day (Trafikverket 2022). The relevant AADT to consider is the total AADT from both HDVs and LDVs using the ERS. Even if the comparison with other propulsion systems is made separately for lorry and passenger car, the AADT using the ERS may consist of either of them or a combination.

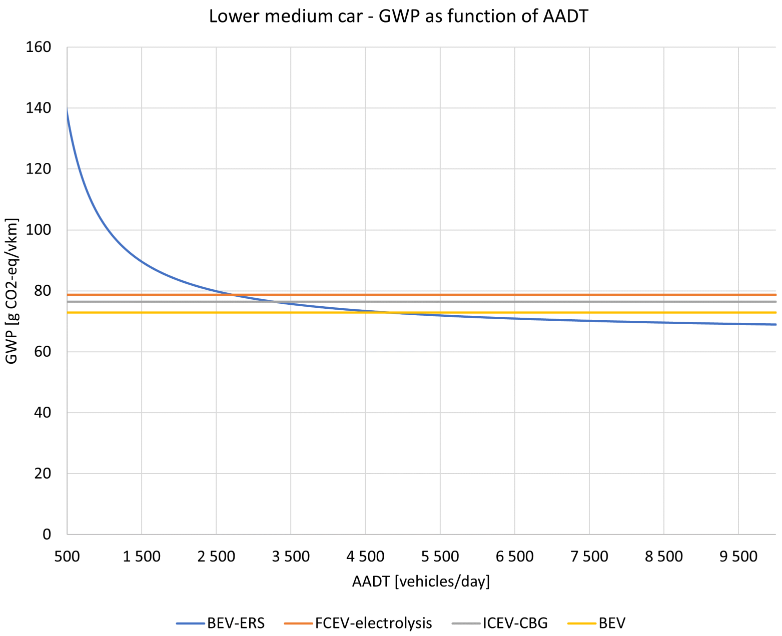


Figure 22: Life cycle GWP per propulsion system and life cycle stage for lower medium car as function of AADT.

To clearly see the impact from the specific ERS components, a more detailed graph only including the BEV-ERS cases are found in figure 23. As for the articulated lorry, impact from OBC and pick-up is constant whereas infrastructure GWP decreases with increasing AADT. The value of GWP from OBC and pick-up is 7.0 g CO_2-eq/vkm, which is a higher numerical value than for the articulated lorry since this is expressed in a different functional unit. One vkm is a longer distance than one tkm, thus giving a higher numerical value. It is from the figure also clear that the stationary charging infrastructure has a small contribution.

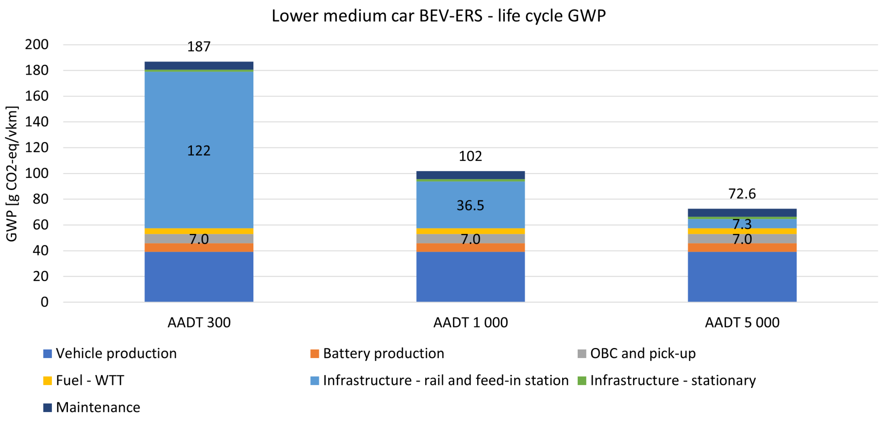


Figure 23: Life cycle GWP of BEV-ERS specified with respect to the ERS components. AADT has the unit vehicles/day.

Since all passenger cars are modelled with the same lifetime vkm, total lifetime emissions will be equally scaled with a factor of 225 000 for all propulsion systems. Therefore total lifetime GWP is not presented, unlike for the articulated lorry.

4.6.3 Sensitivity analysis - European electricity mix for articulated lorry

This report examines climate impact from BEV-ERS compared to other renewable transport solutions with Sweden as a base case scenario. The Swedish electricity mix mainly consists of electricity produced from low carbon sources and renewable sources (Energimyndigheten 2021b). A prerequisite for reaching the high level of AADT predicted by 2040 in the report by Natanaelsson et al. (2021) is that a fraction of the HDVs contributing to the AADT using the system is foreigner vehicles. Indirectly this implies that the ERS technology exists in other parts of Europe as well. Since Swedish conditions are not representative for most countries in terms of carbon intensity in electricity generation, it is relevant to study the potential for BEV-ERS in comparison to the other propulsion systems for an average European electricity mix. The chosen value for the European electricity mix is from Hill et al. (2020), with an emission factor of 439 g CO_2-eq/kWh. This is to be compared with the base case of 26 g CO_2-eq/kWh in Sweden. Impact from this change in electricity mix has been studied in a sensitivity analysis and the results are presented in figure 24.

The SMR pathway is in the base case assumed to use a Swedish electricity mix for transport and distribution, included in the WTT emissions, even though emissions from production represent a European average. Therefore, a change to a European electricity mix causes a slight change in the performance compared to the base case, 144 g CO_2-eq/tkm compared to 139 g CO_2-eq/tkm. This increase is however relatively small compared to what is seen for FCEV using hydrogen produced from electrolysis. The altered emission factor gives rise to emissions of 231 g CO_2-eq/tkm compared to the base case of 33 g CO_2-eq/tkm. The BEV-ERS and BEV are also affected by this alteration, where the BEV-ERS in this case performs better than the BEV for all considered AADT values.

The only vehicle type assumed to be unaffected by a change in electricity mix is the ICEV-LBG. This is however an uncertain result. It is likely that electricity is used in production of the biogas from AD and that a altered electricity mix would impact the GHG performance. A report examining the influence of carbon intensity in electricity generation for different vehicle fuels concluded that a more carbon intense electricity mix increases the net GHG emissions from production of biogas from AD (Gustafsson et al. 2021). Since a separate value of electricity usage in the biogas production is not presented by Börjesson et al. (2016), a dependence on electricity mix is not modelled in this sensitivity analysis. In addition, if a performance of European conditions not only considering electricity mix is investigated, it is possible that other parameters are altered in the biogas production since data used in this report reflect existing Swedish conditions. This reasoning applies to both the passenger car and the articulated lorry.

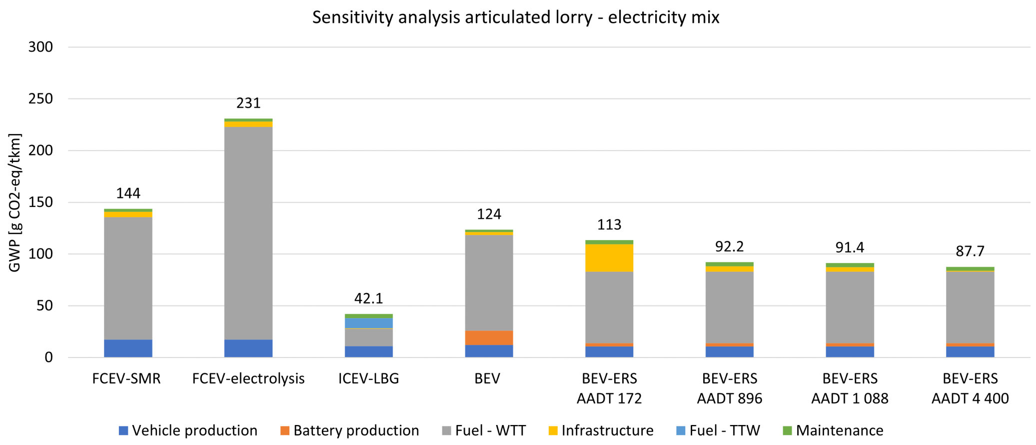


Figure 24: Sensitivity analysis with European electricity mix instead of Swedish. Life cycle GWP per propulsion system and life cycle stage for articulated lorry. AADT has the unit vehicles/day.

The effect on GHG performance from using a European electricity mix instead of Swedish can be seen in figure 25. All systems differ in total electricity need for propulsion. The hydrogen production pathway via electrolysis requires a high electricity input per tkm due to a relatively low efficiency in the hydrogen conversion processes. With a carbon intense electricity mix, this low efficiency is amplified, causing FCEV-electrolysis to perform worst instead of one of the best. A similar reasoning applies to the BEV against the BEV-ERS, where the first has a lower charging efficiency and a lower TTW efficiency per tkm than the latter. This effect on the GWP is less pronounced with a Swedish electricity mix, but amplified when using a European.

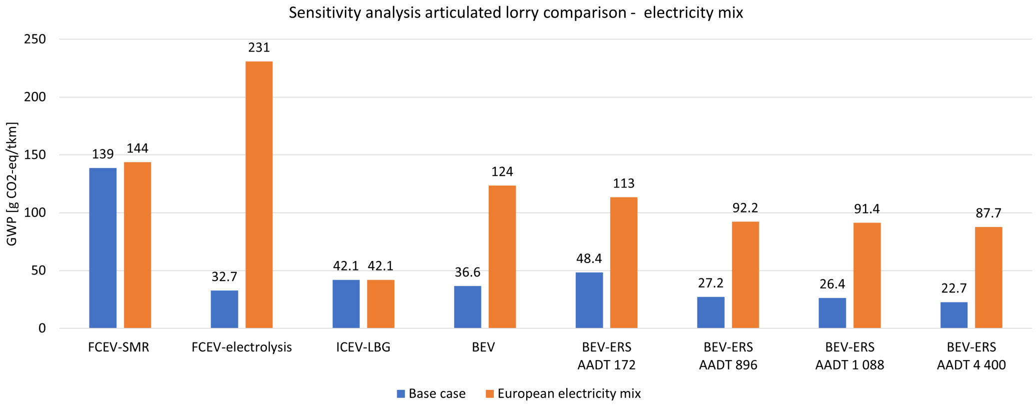


Figure 25: Comparison between base case with Swedish electricity mix and sensitivity analysis with European electricity mix for life cycle GWP per tkm for an articulated lorry. AADT has the unit vehicles/day.

4.6.4 Sensitivity analysis - European electricity mix for lower medium car

The effect on the performance of a lower medium car when changing to a European electricity mix is seen in figure 26. In this scenario, the FCEV with hydrogen from electrolysis performs worst, as was also seen for HDVs. The same reasoning concerning the effect from different efficiencies and electricity need described for the lorries is valid for the cars as well. The ICEV-CBG result is uncertain with the same reasoning as for the HDV since it is assumed to be unaffected by an altered emission factor from electricity.

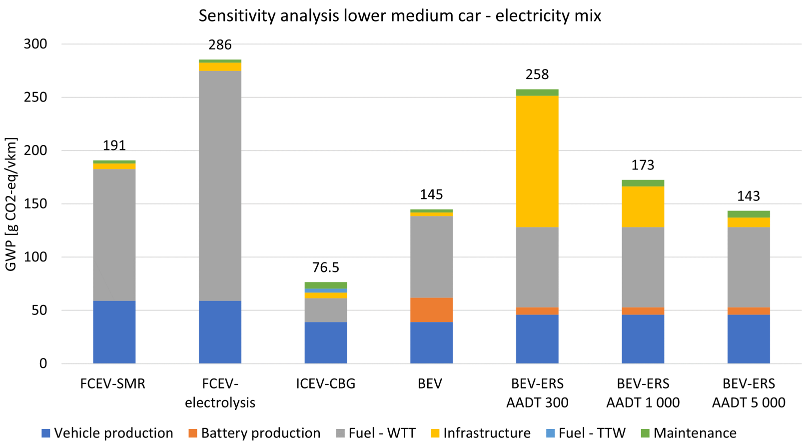


Figure 26: Sensitivity analysis with European electricity mix instead of Swedish. Life cycle GWP per propulsion system and life cycle stage for lower medium car. AADT has the unit vehicles/day.

Life cycle GWP per vkm for a European electricity mix compared to the base case is seen in figure 27. The outlier is the FCEV with hydrogen from electrolysis, as already discussed. Since BEV-ERS has a higher charging efficiency than BEV, the effect of a changed electricity mix have a larger impact on the BEV. Noteworthy is the FCEV-SMR performance, which in the base case is clearly the worst together with BEV-ERS at low AADTs. In this case it is instead comparable to some of the other alternatives and significantly better than the FCEV using hydrogen from electrolysis.

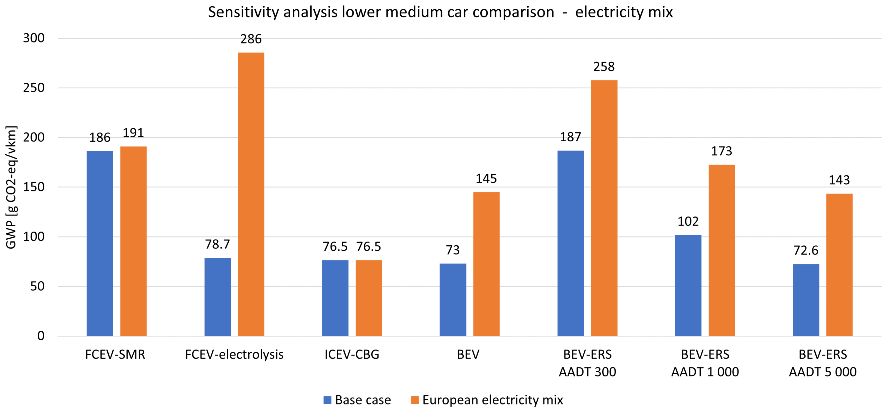


Figure 27: Comparison between base case with Swedish electricity mix and sensitivity analysis with European electricity mix for life cycle GWP per vkm for lower medium car. AADT has the unit vehicles/day.

4.6.5 Sensitivity analysis - battery production and size for articulated lorry

With an increasing share of BEVs in the vehicle fleet, more focus is directed towards production of the batteries. In the base case comparison, a European average value for production of lithium-ion batteries of 89 kg CO_2-eq/kWh is used. However, emissions from battery production varies depending on production pathway. A report from IVL examining emissions from production of lithium-ion batteries concluded that the use of a renewable electricity mix in the production combined with a more energy efficient process are key factors leading to a low GWP of battery production (Emilsson & Dahllöf 2019). The report found that today production of lithium-ion batteries gives rise to emissions between 61 och 106 kg CO_2-eq/kWh, depending on production pathway. The lower value depicts battery manufacturing with a renewable electricity mix, something that is not yet common but is predicted to be in the coming years. A sensitivity analysis examining the effect of a varying carbon intensity in battery production on total GWP per tkm is therefore performed. The low case is set to 61 kg CO_2-eq/kWh and the high case to 106 kg CO_2-eq/kWh. The result in g CO_2-eq/tkm for a BEV articulated lorry is presented in figure 28.

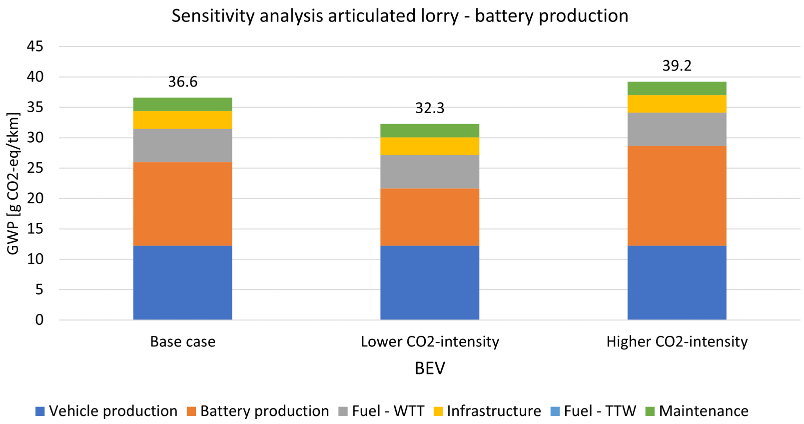


Figure 28: Sensitivity analysis of CO_2-intensity in battery production for BEV articulated lorry. Base case is 89 kg CO_2-eq/kWh, lower 61 kg CO_2-eq/kWh and higher 106 kg CO_2-eq/kWh.

A lower GWP of battery production yields lower GHG emissions per tkm and vice versa. However, what is interesting to compare is the influence in relation to the BEV-ERS. BEV-ERS has a smaller battery and will thus be less affected by an altered carbon intensity in the battery production. The BEV-ERS battery size is also an important factor to study in this context. Therefore, the sensitivity analysis on the BEV-ERS includes a high and low case on production emissions together with a case where the size of the battery is altered. The latter is with the base case emission factor for the battery. It is assumed in the base case that a battery size of 30% of the original size is required for the battery, which for an articulated lorry means a battery of 282 kWh, corresponding to a range of around 196 km. In the report by Domingues-Olavarría (2018) previously mentioned, a battery range of 60 km for both HDVs and cars is determined to be a sufficient range. This would with the BEV-ERS TTW efficiency in this study correspond to a battery of 86 kWh, which is evaluated in the sensitivity analysis. The result are presented in figure 29. The figure only presents the result for an AADT of 896 vehicles/day since the effect on the battery production part is constant for all AADT scenarios.

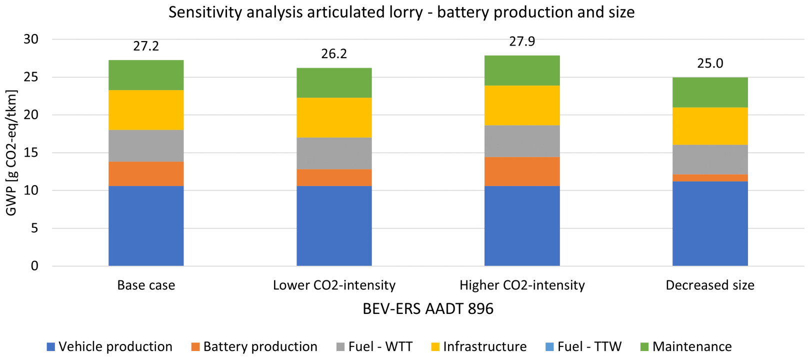


Figure 29: Sensitivity analysis of CO_2-intensity in battery production and battery size for BEV-ERS articulated lorry with AADT of 896 vehicles/day. Base case is 89 kg CO_2-eq/kWh with size of 282 kWh, lower 61 kg CO_2-eq/kWh, higher 106 kg CO_2-eq/kWh and decreased size 86 kWh.

The results from all sensitivity analyses on batteries together with the base case are found in figure 30.

As can be seen, a lower CO_2-intensity in battery production reduces GHG emissions for BEV more than for BEV-ERS due to its larger battery size. With a more optimised battery production in terms of GHG performance as predicted in future, a vehicle with a larger battery has more to gain on the reduction than a vehicle with a smaller. For the BEV-ERS, the reduction with a decreased CO_2-intensity is lower than with a decreased size, compared to the base case. In the comparison it is further seen that a BEV with a battery produced with lower emissions reaches lower GWP per tkm than a FCEV-electrolysis. Producing hydrogen from electrolysis with renewable electricity is as previously discussed not commercialised.

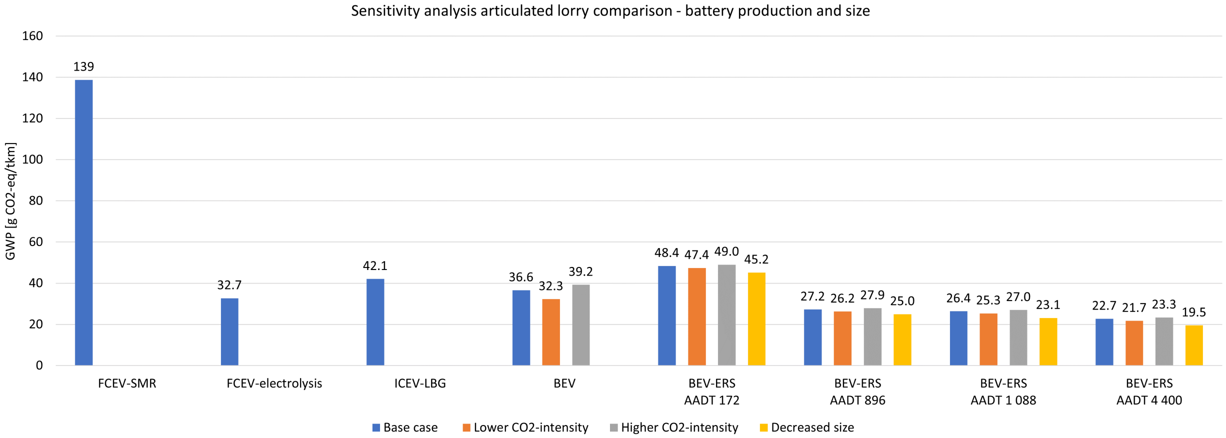


Figure 30: Comparison between base case and sensitivity analysis of CO_2-intensity in battery production and battery size for articulated lorry. Base case is 89 kg CO_2-eq/kWh, lower 61 kg CO_2-eq/kWh, higher 106 kg CO_2-eq/kWh and decreased size 86 kWh for BEV-ERS. AADT has the unit vehicles/day.

4.6.6 Sensitivity analysis - battery production and size for lower medium car

A similar sensitivity analysis to that of the lorry regarding CO_2-intensity in battery production and battery size is applied also to the lower medium car. The results for a BEV are presented in figure 31, where only CO_2-intensity is altered.

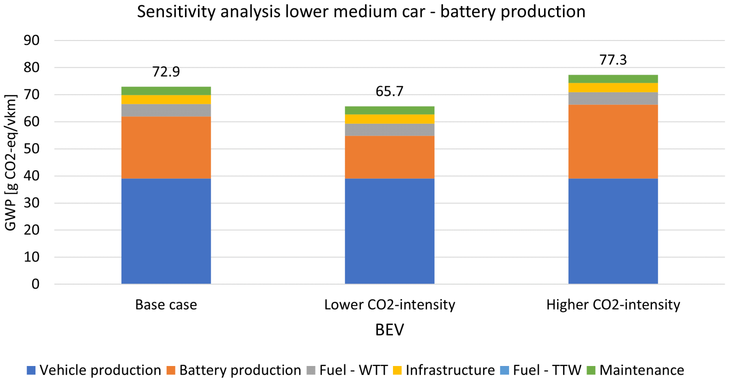


Figure 31: Sensitivity analysis of CO_2-intensity in battery production for BEV lower medium car. Base case is 89 kg CO_2-eq/kWh, lower 61 kg CO_2-eq/kWh and higher 106 kg CO_2-eq/kWh.

The resulting GWP per vkm from the sensitivity analysis on a BEV-ERS is presented in figure 32. The BEV-ERS is in the base case assumed to have a battery size of 17.4 kWh, corresponding to a driving range of 111 km. With a decreased range to 60 km the battery is downsized to 9.4 kWh given a TTW efficiency of 0.56 MJ/vkm.

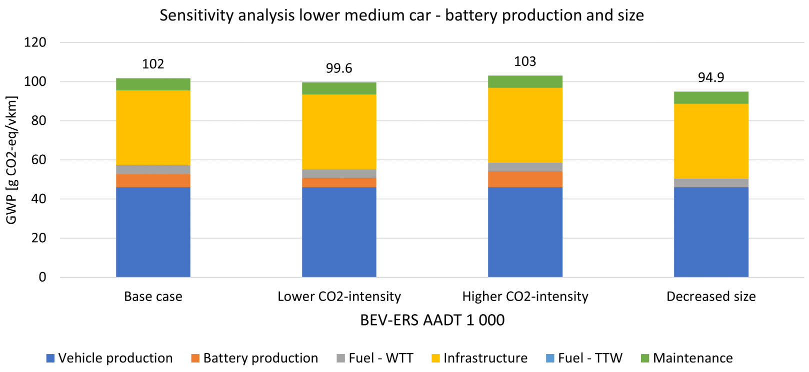


Figure 32: Sensitivity analysis of CO_2-intensity in battery production and battery size for BEV-ERS lower medium car with AADT of 1 000 vehicles/day. Base case is 89 kg CO_2-eq/kWh with size of 282 kWh, lower 61 kg CO_2-eq/kWh, higher 106 kg CO_2-eq/kWh and decreased size 9 kWh.

To further evaluate the impact of an altered battery production and size on the life cycle GWP per vkm a comparison with the other propulsion systems is shown in figure 33. The results are in accordance with what is observed for the articulated lorry, with a greater reduction seen for the BEV with the lower CO_2-intensity than for the BEV-ERS. This is due to the larger share of impact originating from battery production for a BEV because of its greater size in kWh.

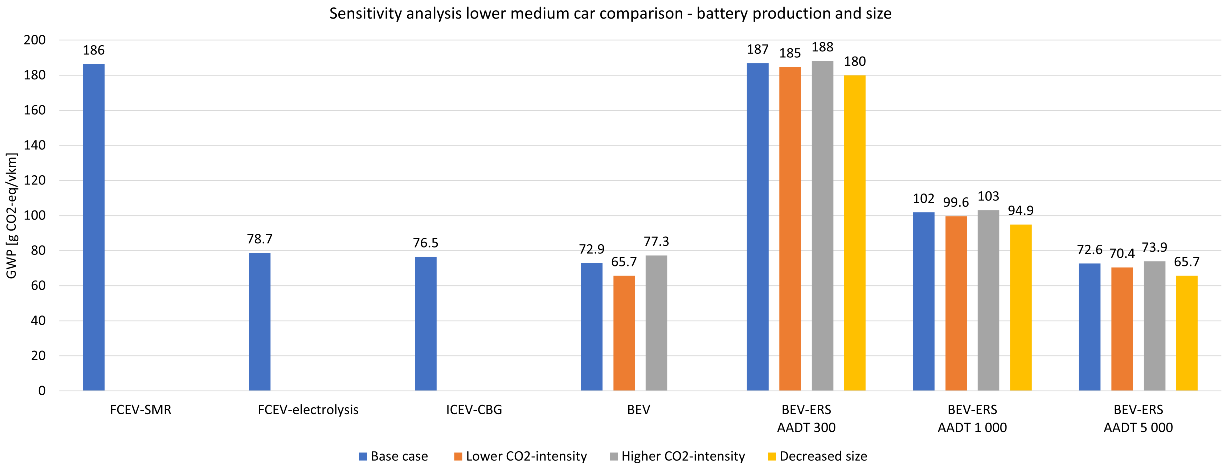


Figure 33: Comparison between base case and sensitivity analysis of CO_2-intensity in battery production and battery size for lower medium car. Base case is 89 kg CO_2-eq/kWh, lower 61 kg CO_2-eq/kWh, higher 106 kg CO_2-eq/kWh and decreased size 9 kWh for BEV-ERS.

4.6.7 Sensitivity analysis - material impact from ERS components

In part I impact from all ERS components is examined. For the rail the largest contribution is from the aluminium, accounting for 74% of the rail in terms of mass and 71% in terms of GWP. For the OBC the majority of the emissions originates from the DC/DC converter. The relative contribution from both aluminium and converter to GWP per FU is highly related to AADT, even though AADT only affects the absolute contribution from aluminium. At low AADT values the rails and feed-in stations account for a large share of the impact, whereas at higher AADT values impact from OBC and pick-up is more pronounced. This motivates a further analysis on both DC/DC converter and aluminium.

The aluminium from vendor 21 used in the rail is related to emissions of 6.7 kg CO_2-eq/kg according to the vendor. The same vendor also offer an aluminium type with a higher share of recycled aluminium, instead having an emission factor of 2.3 kg CO_2-eq/kg. The influence of a change to this aluminium type on life cycle GWP per FU is studied in a sensitivity analysis. The results for only the BEV-ERS articulated lorry specified per life cycle stage are visualised in figure 34, whereas the total values together with the other propulsion systems are seen in figure 35. The effect of an altered aluminium type on the total GWP per rail compared to the base case can be further seen in appendix figure A1. A reduction in total life cycle GWP per rail from 2 590 to 1 480 kg CO_2-eq is reached with this measure. Only considering the aluminium, its relative contribution to GWP from constituent materials is decreased from 71% to 45% with this change.

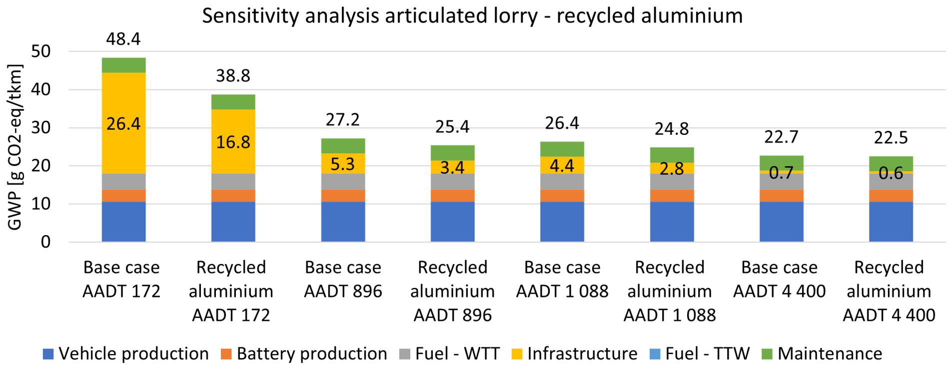


Figure 34: Comparison between base case and sensitivity analysis of recycled aluminium in rails for BEV-ERS articulated lorry. AADT has the unit vehicles/day.

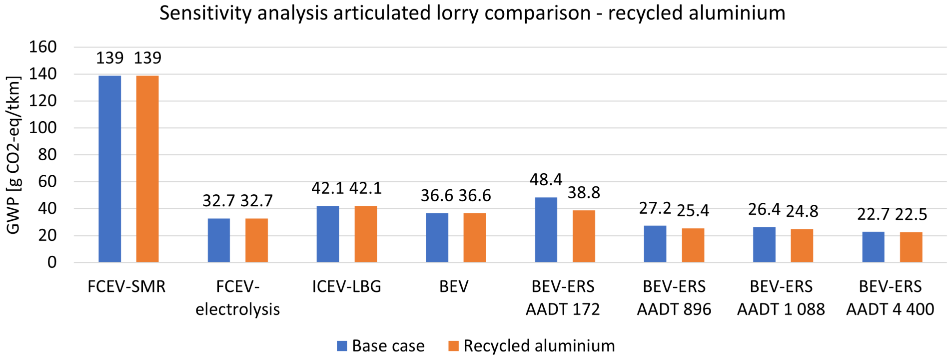


Figure 35: Comparison between base case and sensitivity analysis of recycled aluminium in rails for articulated lorry with all propulsion systems. AADT has the unit vehicles/day.

A similar sensitivity analysis on recycled aluminium for the lower medium car is presented in figure 36 and 37.

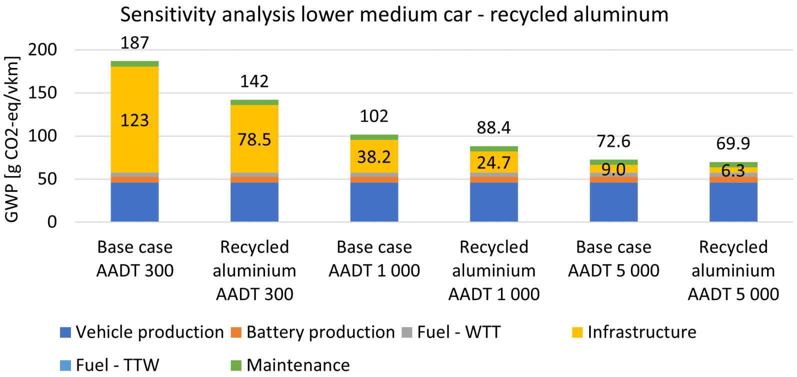


Figure 36: Comparison between base case and sensitivity analysis of recycled aluminium in rails for BEV-ERS lower medium car. AADT has the unit vehicles/day.

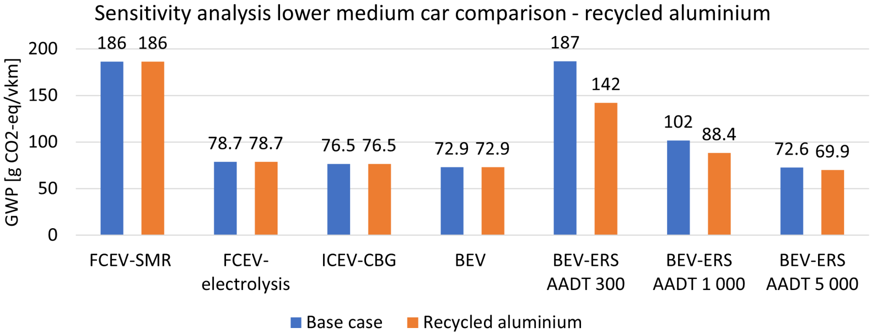


Figure 37: Comparison between base case and sensitivity analysis of recycled aluminium in rails for lower medium car with all propulsion systems. AADT has the unit vehicles/day.

As can be seen in the figures above, a greater reduction in absolute values is seen at low AADT values with an increased share of recycled aluminium. This is a result of infrastructure having a larger relative impact on the total GWP per FU due to a lower utilisation rate. Break-even between BEV-ERS and the FCEV-electrolysis for an articulated lorry occurs at an AADT of 271 compared to 428 vehicles/day in the base case. The BEV-ERS lower medium car break-even with BEV is found at an AADT of 2 020 compared with at 4 780 vehicles/day in the base case.

For the DC/DC converter used in the OBC the impact is included in the life cycle stage vehicle production, which is independent of AADT. The converter accounts for 90% of the total GWP per OBC but this is as previously discussed related to uncertainties and might be a potential overestimate. The chosen emission factor is from Ecoinvent, covering a 4.8 kg converter unit. This is then scaled to a size corresponding to the converter used by Elonroad. An alternative value have been studied in a sensitivity analysis, based on a converter modelled by Kabus et al. (2020). Following their methodology a 50 kW converter would give rise to 104 kg CO_2-eq, to be compared with 1 230 kg CO_2-eq of the 40 kW converter used as base case in this report. More details on how their converter is modelled are found in appendix A31. Applying 104 instead of 1 230 kg CO_2-eq for the DC/DC converter GWP probably means covering the extremes, but may therefore indicate in what interval the converter most likely is within.

The effect of assuming this decreased value on life cycle GWP per tkm for a BEV-ERS articulated lorry is presented in figure 38 for AADT 896 vehicles/day. The result is a decrease from 1 g CO_2-eq/tkm to 0.1 g CO_2-eq/tkm from OBC and pick-up together. With this altered value, break-even in AADT between BEV-ERS and ICEV-LBG occurs at 226 vehicles/day, which still is the same as for the base case. Towards

BEV, break-even is found at an AADT of 295 compared to the base case of 312 vehicles/day. For the FCEV, break-even is reached at 395 instead of 428 vehicles/day.

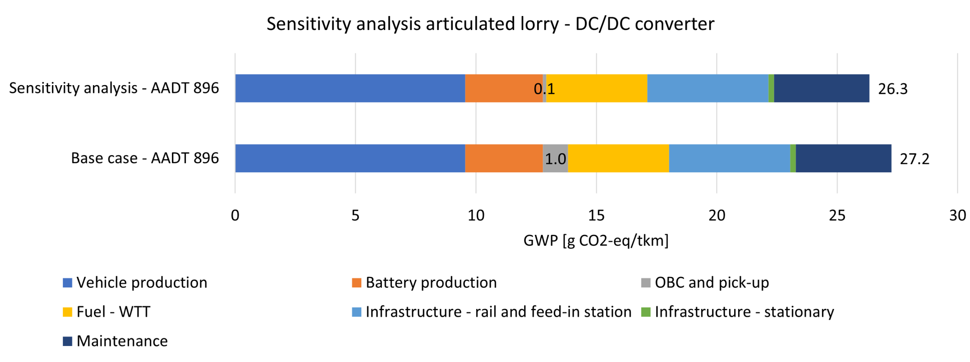


Figure 38: Comparison in GWP between base case and sensitivity analysis on DC/DC converter in OBC per tkm for articulated lorry. Result per life cycle stage for BEV-ERS with an AADT of 896 vehicles/day.

In the case of the passenger car, OBC and pick-up account for 7 g CO_2-eq/vkm in the base case, decreased to 1.9 g CO_2-eq/vkm in the sensitivity analysis. This causes break-even for AADT to shift from 4 780 vehicles/day between BEV-ERS and BEV to 2 890 vehicles/day with the lower value of converter GWP. For ICEV-CBG the AADT break-even is decreased to 2 250 from 3 250 vehicles/day, whereas for the FCEV it occurs at 1 980 compared to 2 720 vehicles/day in the base case.

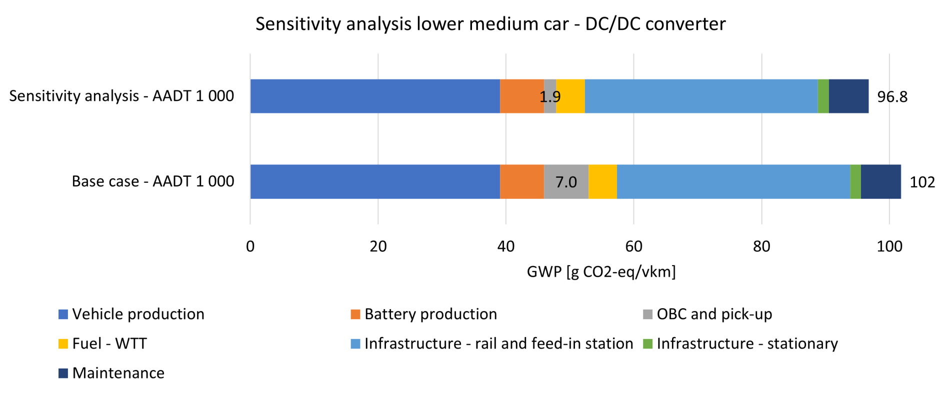


Figure 39: Comparison in GWP between base case and sensitivity analysis on DC/DC converter in OBC per vkm for lower medium car. Result per life cycle stage for BEV-ERS with an AADT of 1 000 vehicles/day.

4.6.8 Additional sensitivity analysis

Besides above presented sensitivity analyses, influence on the final results for the BEV-ERS from varying other parameters are presented in table 16 for articulated lorry and table 17 for lower medium car. More details on calculations are presented in appendix table A32 and A33.

In the first case additional infrastructure in the form of a medium-voltage transmission network required to provide electricity to the feed-in stations is added. There are a number of uncertainties regarding this since it is not clear whether this network will be built only due to the ERS or if it can be used for other applications as well. It may also be that current transmission network at some places could be sufficient to provide enough electricity. Due to the novelty of the technology and the uncertainties related to this, the network is not included in the base case but evaluated in a sensitivity analysis. The Ecoinvent dataset "transmission network construction, electricity, medium voltage, CH", based on Swiss data for a medium voltage transmission network, is used as data source. GWP per FU is determined similarly to GWP of rail and feed-in station, described in equation 6-8.

In a second sensitivity analysis effects of an altered TTW efficiency are investigated. The TTW efficiencies are derived from the European commission report by Hill et al. (2020), in which it is assumed that both BEV and BEV-ERS have the same efficiency per vehicle kilometre. However, for the articulated lorry there is a difference in MJ/tkm due to differences in unladen mass and load capacity, resulting in a higher efficiency for the BEV-ERS than for the BEV in terms of MJ/tkm. Nevertheless, it is likely that the BEV-ERS will have a higher TTW efficiency also in terms of MJ/vkm due to its reduced mass. What real-world TTW efficiency that is to expect for a BEV-ERS is therefore uncertain, why a sensitivity analysis is performed. This is done with both an increased and a decreased value, seen in table 16 and 17.

The third case evaluates a change in number of rails installed per kilometre, termed electrification rate. In the base case 60% of a certain ERS distance is assumed to be covered with rails and 40% without. Other reports such as Domingues-Olavarría (2018) point towards an optimal electrification rate of 50%. Therefore, this value is investigated.

The fourth case considers a changed lifetime of rails and feed-in stations. In the base case a lifetime of 15 years is assumed for the rail and 40 years for the feed-in station, but it is not fully investigated whether this is to expect or not. The effect of an increased or decreased lifetime is therefore evaluated in a sensitivity analysis. If the lifetime is increased, more vehicles will be using the components, leading to a decrease in GWP per FU. The opposite is observed for a decrease.

Lastly, the fifth case investigates influence of the term fraction of total driving distance on ERS. In the base case a relationship of 60/40 towards on ERS against outside ERS is assumed for the articulated lorry and 50/50 for the lower medium car. In this sensitivity analysis impact from altering the fraction with ±20 percentage points is examined for both the HDV and the car. An increased fraction of total driving distance on ERS increases impact from the life cycle stage infrastructure. This is an effect of the chosen functional unit, since the unit considered is focused on the vehicle and not on rails and feed-in stations. An increased fraction of driving on ERS means that the vehicle drives a larger share of its total distance on the ERS during its lifetime, allocating more of the total infrastructure impact to that specific vehicle. In practical, this is question of both driving pattern and how much ERS that is implemented. However, the environmental burden of driving on one rail is only determined by the number of vehicles driving on it, i.e. the AADT, which is assumed to be constant.

Table 16: Change in GWP compared to base case from additional sensitivity analyses on BEV-ERS articulated lorry. Base case values are 48.4, 27.2, 26.4 and 22.7 g CO_2-eq/tkm for AADT values of 172, 896, 1 088 and 4 400 vehicles/day respectively.

Articulated lorry				
	AADT 172	**AADT 896**	**AADT 1 088**	**AADT 4 400**
Transmission network added	+4.6%	+1.6%	+1.3%	+0.4%
Changed TTW efficiency ±10%	±0.9%	±1.5%	±1.6%	±1.8%
Changed electrification rate to 50%	-7.7%	-2.6%	-2.2%	-0.3%
Changed lifetime rails and feed-in stations to 10 and 35 years	+24.3%	+8.3%	+7.0%	+1.0%
Changed lifetime rails and feed-in stations to 20 and 45 years	-12.4%	-4.2%	-3.6%	-0.5%
Changed fraction of total driving distance on ERS ±20 percentage points	±17.7%	±5.6%	±4.7%	±0.1%

Table 17: Change in GWP compared to base case from additional sensitivity analyses on BEV-ERS lower medium car. Base case values are 187, 102 and 72.6 g CO_2-eq/vkm for AADT values of 300, 1 000 and 5 000 vehicles/day respectively.

Lower medium car			
	AADT 300	**AADT 1 000**	**AADT 5 000**
Transmission network added	+6.6%	+3.7%	+1.0%
Changed TTW efficiency ±10%	±0.2%	±0.4%	±0.6%
Changed electrification rate to 50%	-9.3%	-5.1%	-1.4%
Changed lifetime rails and feed-in stations to 10 and 35 years	+29.2%	+16.1%	+4.5%
Changed lifetime rails and feed-in stations to 20 and 45 years	-15.0%	-8.2%	-2.3%
Changed fraction of total driving distance on ERS ±20 percentage points	±25.6%	±13.6%	±3.0%

This report investigates climate impact of an ERS implementatiom in comparison to other renewable transport solutions. Since previous studies on the subject primarily investigate the impact in comparison to a fossil alternative, results from Hill et al. (2020) for an ICEV lower medium car fuelled with gasoline and an ICEV articulated lorry fuelled with diesel is included as a reference. The GWP for the lower medium car is in that study found to be 269 g CO_2-eq/vkm and for the articulated lorry 188 g CO_2-eq/tkm. A reduction of 31-73% depending on AADT is seen for the lower medium car BEV-ERS compared to the fossil reference. In the case of the articulated lorry, the corresponding reduction is 74-88% with BEV-ERS.

5 Part III - Case study Stockholm bus line 4

In this part of the study climate impact from the ERS technology is evaluated in relation to a specific scenario in the form of a case study. The case study concerns implementation of ERS on bus line 4 in Stockholm, with conditions and prerequisites already investigated in a previous master thesis by Jakobsson and Lindström (2021), although from an economical point of view. Thus, results from part I and II are combined with findings on important parameters from recently mentioned work in order to compare GHG performance between current system of biogas and biodiesel buses with a system of stationary charged battery electric buses and a system of battery electric buses together with Elonroad's ERS technology. A new parameter involved indirectly in this part is transport efficiency. The longer refuelling time of stationary charged BEVs compared to ICEVs fuelled with gaseous or liquid fuels will have an effect on the transport efficiency. This also applies to the comparison between ERS and stationary charging, where ERS as already mentioned is beneficial from that perspective. The parameter specifically affected here is the total number of buses needed to operate the bus line, differing depending on refuelling or recharging time. This is included by Jakobsson and Lindström (2021) and the values are adopted from their study.

5.1 Method

The case study is as already mentioned based on a previous work by Jakobsson and Lindström (2021), why their results and assumptions have been adopted and used as input data in this study. This concerns parameters as e.g. traffic density, electrification rate and type of buses. Moreover, a similar approach as in part II is used, with GWP determined from the life cycle stages vehicle production, well-to-tank (WTT), infrastructure, tank-to-wheel (TTW) and maintenance, visualised previously in figure 15. The bus line is situated in Sweden, why data on fuels are taken from sources depicting Swedish conditions as in part II. Several data derived in part II is useful and relevant also in this part, but expressed in another functional unit. For example, data on vehicle production and maintenance are as in part II taken from Hill et al. (2020). The three systems will be described in separate sections with data presented per bus type, which then is used to evaluate impact from an entire bus fleet of line 4 per year. GHG emissions per year are calculated with the respective lifetime of each component. A qualitative discussion is lastly included regarding the overhead catenary ERS solution used in trolley buses compared to Elonroad's conductive rail solution.

5.1.1 Functional unit

The functional unit considered for part III is total life cycle emissions in tonne CO_2-eq per year, reflecting emissions from an entire bus fleet operating bus line 4 in Stockholm. The reason for expressing the results in GWP per year is to account for different lifetimes of vehicles, components and infrastructure.

5.2 Existing system

Bus line 4 in Stockholm is the public transport line with highest traffic density of all lines in Sweden with over 60 000 passengers daily (Region Stockholm 2021). The route extends from Radiohuset to Gullmarsplan and is currently operated by 33 buses. The total line distance with both directions included is 24 km and the total distance driven by all buses during a year is 1.5 million km. The entire bus fleet of Region Stockholm is made up of an equal share of biogas and biodiesel buses, which is assumed to be representative for the buses operating line 4 (Jakobsson & Lindström 2021). However, the exact share today are according to SL (n.d.) 15% biogas buses, 4.5% ethanol buses and 80% biodiesel buses (RME and HVO). Despite this, the 50/50 relationship is assumed as base case in this scenario, with an alteration investigated in the sensitivity analysis. All buses today are preheated before operation and this is done with biodiesel. This consumption together with other relevant parameters from Jakobsson and Lindström (2021) are presented in table 18.

Table 18: Parameters used in this study based on existing conditions at bus line 4 in Stockholm according to Jakobsson and Lindström (2021).

Bus line 4 Stockholm	
Number of buses [pcs]	33
Total annual distance driven by all buses [km/year]	1 500 000
Annual distance driven per bus [km/year]	45 455
Share of biogas buses of entire fleet [%]	50
Share of biodiesel buses of entire fleet [%]	50
Total line distance including both two directions [km]	24
Heating of buses with biodiesel [l/km]	0.1

The route is visualised in figure 40.

Figure 40: Route for bus line 4 in Stockholm (Moovit 2022).

5.3 Biodiesel bus

Buses fuelled with biodiesel are almost identical to buses fuelled with conventional diesel, although some modifications are needed if 100% biodiesel is used (f3 2017). Since the difference is relatively small and no specific biodiesel bus is presented by Hill et al. (2020), data on vehicle production and maintenance are taken for a conventional diesel bus.

Biodiesel commonly refers to fatty acid methyl ester (FAME), but there is also another widespread type of renewable diesel called hydrogenated vegetable oil (HVO) (Energimyndigheten 2021a). Since Jakobsson and Lindström (2021) have not specified which fuel type that is intended and SL (n.d.) reports that both are used, biodiesel is onwards referring to both FAME and HVO. These fuels are both blended in conventional diesel in order for fuel suppliers to fulfil the obligation of continuously reducing the life cycle GHG emissions from fuels, according to the Swedish greenhouse gas reduction mandate (Energimyndigheten 2021c). Both fuels also exist as pure biogenic fuels, called HVO100 and FAME100. HVO100 constituted 3.2% of the total delivered fuel quantity in Sweden 2020 and was mainly produced from slaughterhouse waste (72%) and tall oil (12 %), whereas the palm fatty acid distillate has decreased and made up 6% of the feedstock 2020. FAME100 was responsible for 1.6% of the total amount delivered fuel 2020 and the feedstock was dominated by rapeseed (90%). FAME produced from rapeseed oil via esterification is commonly called rapeseed methyl ester (RME) (Energimyndigheten 2021a). Life cycle emission data are taken from Energimyndigheten (2021a), depicting fuels delivered in Sweden at 2020.

Data and parameters for one biodiesel bus are presented in table 19. TTW efficiency is recalculated from the value given by Jakobsson and Lindström (2021) with lower heating value. More details on this together with other data and relevant parameters used in calculations are found in appendix A.3.1. The authors did not specify which type of biodiesel that is used and due to lack of other data a share of 50/50 is assumed in the base case, with variations investigated in a sensitivity analysis. The GHG emissions originating from production of the fuel is calculated with TTW efficiency and annual driving distance per bus, found in table 18.

Due to lack of other data, impact from biodiesel infrastructure, i.e. distribution and filling stations, is assumed to be similar to that of compressed biogas as given by Börjesson et al. (2016). Since all biodiesel has a biogenic origin, no contribution to climate change is expected from the TTW stage despite there are tailpipe emissions from the vehicle.

Table 19: GWP per year from different life cycle stages for one biodiesel bus together wits its data source.

Biodiesel bus		**Source**
Lifetime [year]	13	Jakobsson & Lindström (2021)
TTW efficiency [MJ/km]	21.1	Adopted from Jakobsson & Lindström (2021)
Vehicle production [t CO_2-eq/year]	7.9	Adopted from Hill et al. (2020)
Fuel - WTT [t CO_2-eq/year]	29.6	Adopted from Energimyndigheten (2021a)
Infrastructure [t CO_2-eq]	2.3	Adopted from Börjesson et al. (2016)
Fuel - TTW [t CO_2-eq/year]	0	
Maintenance [t CO_2-eq/year]	2.7	Adopted from Hill et al. (2020)

5.4 Biogas bus

As described in part II, biogas vehicles are fuelled with methane of biogenic origin, either from upgraded biogas or from thermal gasification of biomass. Data on vehicle production and maintenance for a biogas bus are taken from Hill et al. (2020), recalculated from g CO_2-eq per vkm to a value in tonne CO_2-eq per year with assumed total lifetime vkm in the same study and assumed lifetime in years by Jakobsson and Lindström (2021). There are two types of methane fuelled buses investigated by Hill et al. (2020), one conventional SI engine using compressed natural gas (CNG) and one lean-burn SI engine using CNG, both 12 m single deck. The conventional one is chosen in this study.

Impact from infrastructure is taken from Börjesson et al. (2016) as in part II. It is assumed that impact originating from distribution and filling station for passenger cars is comparable to that of public transport busses, why the value has been used and adapted to existing conditions. According to Jakobsson and Lindström (2021), biodiesel is assumed to be used in preheating even for biogas buses (0.1 l/km).

All values for a biogas bus is found in table 20. Emissions from production of fuel is taken from Energimyndigheten (2021a) instead of Börjesson et al. (2016) as in part II. This is because no specific type of biogas, e.g. liquefied from anaerobic digestion, is studied. It is also used in order to calculate with the actual conditions with most recent values for delivered biogas today. The translation of tank-to-wheel efficiency from kg biomass per km into MJ per km is found in appendix A.3.2. As described in part II, there is a small methane leakage from biogas fuelled vehicles causing the TTW part to be nonzero, despite the biogenic origin of the fuel. Due to lack of other data, this leakage from a bus is assumed to be the same as for a light-duty vehicle, which values are presented by Börjesson et al. (2016).

Table 20: GWP per year from different life cycle stages for one biogas bus together with its data source.

Biogas bus		**Source**
Lifetime [year]	13	Jakobsson & Lindström (2021)
TTW efficiency [MJ/km]	39.3	Adopted from Jakobsson & Lindström (2021)
Vehicle production [t CO_2-eq/year]	8.1	Adopted from Hill et al. (2020)
Fuel - WTT [t CO_2-eq/year]	26.6	Adopted from Energimyndigheten (2021a)
Infrastructure [t CO_2-eq/year]	4.1	Adopted from Börjesson et al. (2016)
Fuel - TTW [t CO_2-eq/year]	6.4	Adopted from Börjesson et al. (2016)
Maintenance [t CO_2-eq/year]	2.1	Adopted from Hill et al. (2020)

5.5 Battery electric bus

Battery electric vehicles with stationary charging have been described in part II and most of the assumptions and values are utilised also in this part. Impact from vehicle production and maintenance are taken from Hill et al. (2020) for a 12m single deck urban bus. These values are then recalculated as for the other vehicle types earlier described. What is a new parameter affecting the total results is the transport efficiency, represented by the total number of buses needed on the bus line. If only stationary charged BEV buses were to be used, Jakobsson and Lindström (2021) argue that 46 buses instead of today's 33 buses are needed. This does not influence the values presented in this section where only values for one bus is given, but will be reflected in the total impact seen in the results.

All relevant parameters and values can be seen in table 21. The lifetime of the BEV is set to 10 years whereas the battery lifetime is assumed to be seven years, according to the findings of Jakobsson and Lindström (2021). This implies that a battery replacement will be needed, in contrast to what is assumed in part II. This is accounted for by in the result section were the impact is expressed as impact per year. The TTW efficiency adopted from the same report does include heating of the buses, which in this case is performed with electricity instead of biodiesel (Jakobsson and Lindström 2021).

No values are given by Jakobsson and Lindström (2021) on BEV battery size. Given 46 buses and a total annual driving distance of 1.5 million km all buses together, each BEV would drive around 90 km as a daily average. One relationship between battery size for BEV vs BEV-ERS is the cost, which is assumed to be one third for a BEV-ERS compared to a BEV (Jakobsson & Lindström 2021). This reduction is applied also to battery size in kWh and calculated from the assumed BEV-ERS size presented in section 5.6. With this assumption a BEV battery size of 200 kWh is received, resulting in a driving range of 133 km. This might be an overestimation, but a smaller battery is evaluated in a sensitivity analysis. More details on the derived values on battery production and vehicle production are found in appendix A.3.3.

Data on GHG emissions from infrastructure, i.e. chargers, are gathered from Bekel and Pauliuk (2019) as in part II. The summarised value in table 21 reflects all chargers for an entire BEV bus fleet. 40 chargers in total will be needed according to Jakobsson and Lindström (2021). However, the power level of these chargers is not specified and therefore an assumptions has been made that all are 50 kW chargers, which is charger with highest power level that Bekel and Pauliuk (2019) have investigated.

The vehicle maintenance value is recalculated from the value given by Hill et al. (2020). In that study one battery replacement is predicted during the assumed lifetime of the vehicle (15 years), which is included in the maintenance part. Since this is already accounted for in this study by the lifetime of the battery (seven years), this additional impact is subtracted from the total maintenance given by Hill et al. (2020). For further details see appendix A.3.3.

Table 21: GWP per year from different life cycle stages for one stationary charged BEV bus, together with its data source. Infrastructure includes all 40 chargers.

BEV bus		**Source**
Lifetime [year]	10	Jakobsson & Lindström (2021)
Battery lifetime [year]	7	Jakobsson & Lindström (2021)
TTW efficiency [MJ/km]	5.4	Jakobsson & Lindström (2021)
Battery size [kWh]	200	
Vehicle production (without battery) [t CO_2-eq/year]	10.1	Adopted from Hill et al. (2020)
Battery production [t CO_2-eq/year]	2.5	Adopted from Hill et al. (2020)
Fuel - WTT [t CO_2-eq/year]	2.0	Adopted from Energimyndigheten (2021b)
Infrastructure [t CO_2-eq/year]	18.9	Adopted from Bekel & Pauliuk (2019)
Fuel - TTW [t CO_2-eq/year]	0	
Maintenance [t CO_2-eq/year]	2	Adopted from Hill et al. (2020)

5.6 Battery electric bus with ERS

Given an ERS implementation, buses of BEV type with installed pick-up and on-board charger will be used. However, the battery can be significantly downsized compared to a pure BEV case. The prerequisites for an ERS implementation are altered when studying a bus driving in a city compared to a car or a truck driving on a highway. Since the buses stop regularly at bus stations during its route and have a low average velocity, more energy could potentially be transferred. Thus, placement of the rails is an important factor to maximise energy transfer and also minimise the number of rails needed. This has been optimised by Elonroad and is presented by Jakobsson and Lindström (2021). Due to buses being charged dynamically, a bus fleet consisting of only BEV-ERS will require 33 buses, i.e. as many as the current biogas system according to Jakobsson and Lindström (2021).

A summary of impact from the different life cycle stages is found in table 22, whereas details on the ERS part are presented in table 23. Impact from rails and feed-in stations are included in ”infrastructure” and that from pick-up and OBC in ”vehicle production”. As can be seen in table 22, the vehicle lifetime is 20 years instead of 10 years as for BEVs. This assumptions is evaluated in a sensitivity analysis.

A BEV-ERS urban bus is included in the study by Hill et al. (2020), however with few details on what assumptions that has been made. Therefore, data on vehicle production and maintenance are taken for a BEV, similarly as in part II, but recalculated with a downsized battery. Details on how this calculations have been performed are found in appendix A.3.4. No maintenance is included for the stationary charging infrastructure and for the ERS maintenance of the pick-up unit is the only included measure.

No battery size is explicitly presented by Jakobsson and Lindström (2021) for a BEV-ERS. Theoretically the batteries may be small due to the dynamical charging, but a safety margin is likely to be needed in case of unexpected events. According to Jakobsson and Lindström (2021) the buses charge stationary in the terminal at 6 kW during 10 hours per 24 hours, thus charging 60 kWh. It is therefor assumed that the battery size is 60 kWh, resulting in a driving range of 32 km with a TTW efficiency of 6.8 MJ/km. This is enough for driving the entire line distance once and some additional kilometres.

Table 22: GWP per year from different life cycle stages for one BEV-ERS bus together with its data source. Infrastructure impact depicts the entire bus fleet and not only for one single bus.

BEV-ERS bus		**Source**
Lifetime [year]	20	Jakobsson & Lindström (2021)
Battery lifetime [year]	7	Jakobsson & Lindström (2021)
TTW efficiency [MJ/km]	6.8	Jakobsson & Lindström (2021)
Battery size [kWh]	60	
Vehicle production without battery [t CO_2-eq/year]	5.3	Adopted from Hill et al. (2020)
Battery production [t CO_2-eq/year]	0.8	Adopted from Hill et al. (2020)
Fuel - WTT [t CO_2-eq/year]	2.4	Adopted from Energimyndigheten (2021b)
Infrastructure [t CO_2-eq/year]	161	
Fuel - TTW [t CO_2-eq/year]	0	
Maintenance [t CO_2-eq/year]	1.2	

Further details on the ERS components and its respective GWP are presented in table 23 together with some important parameters. An ERS distance of 5.7 km has been calculated internally by Elonroad given the conditions at bus line 4 to the study by Jakobsson and Lindström (2021). However, a safety margin is added, leading to a total distance of 7.3 km with both directions covered with rails according to the mentioned study. This equals an electrification rate of 30%, reflecting a lower average velocity and more stops compared to a truck or a car driving on a highway with ERS. The ERS components have an assumed lifetime of 15 years according to Jakobsson and Lindström (2021), but with possibility to restore to original conditions for 25% of its purchase price to last an additional period of 15 years. This restoration is not included in calculations of climate impact, since it is not clear which components that can be restored or not. GHG performance of the different ERS components are taken from part I in this study.

Table 23: GWP and data on the ERS and its components for implementation on bus line 4.

ERS specifications		**Source**
Total ERS distance both directions [km]	7.3	Jakobsson & Lindström (2021)
Electrification rate [%]	30	Adopted from Jakobsson & Lindström (2021)
ERS charging power [kW]	100	Jakobsson & Lindström (2021)
Lifetime ERS components [year]	15	Jakobsson & Lindström (2021)
Lifetime feed-in station [year]	40	Vendor 55
Number of rails [pcs]	795	
GWP all rails [t CO_2-eq/year]	137	
Number of feed-in stations [pcs]	6	Jakobsson & Lindström (2021)
GWP all feed-in stations [t CO_2-eq/year]	23	
GWP one pick-up [t CO_2-eq/year]	0.02	
OBC capacity [kW]	100	Jakobsson & Lindström (2021)
GWP one OBC (100 kW) [t CO_2-eq/year]	0.2	

5.7 Results

The results from part III are visualised in figure 41. Note that this depicts the entire bus fleet, either with a 50/50 share of 33 biogas and biodiesel buses, or with 46 BEV buses, or with 33 BEV-ERS buses. Numerical values are found in appendix A.3.

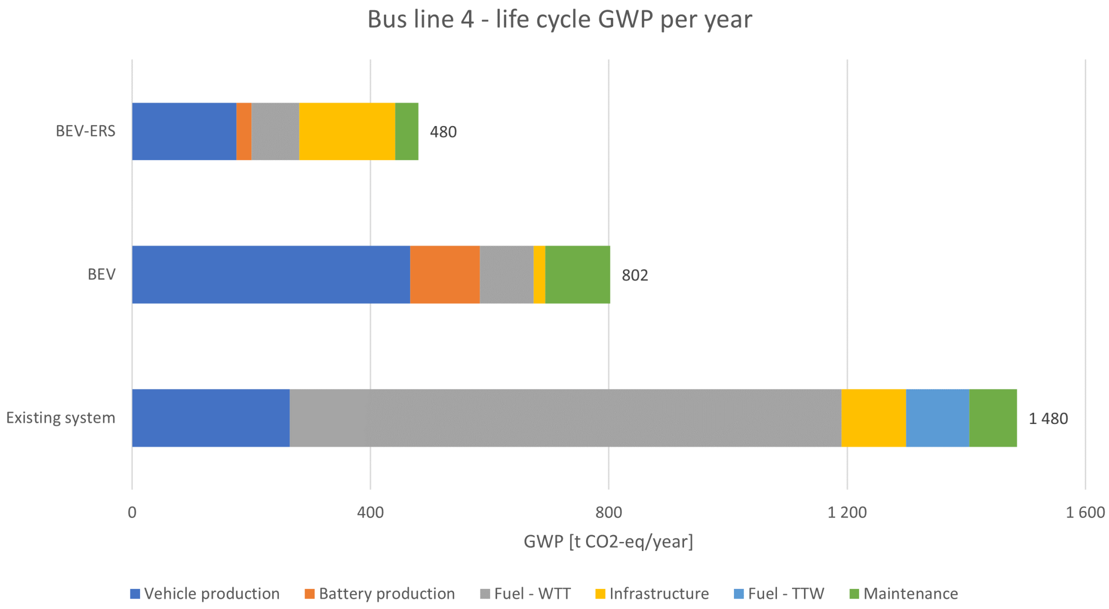


Figure 41: Climate impact of bus line 4 in Stockholm per year, where existing system is a bus fleet with 50/50 share of biogas and biodiesel buses. Existing system includes 33 buses, BEV 46 and BEV-ERS 33.

As visualised in figure 41, BEV-ERS reaches significantly lower GWP compared to the other two alternatives. A reduction from around 1 480 to 480 tonne CO_2-eq per year is seen with a BEV-ERS system compared to existing conditions, which equals a decrease of 68% from today's level. The result further shows that transitioning to a fleet consisting of only BEV busses compared to today's system would would also lower the emissions, instead with 46% to around 800 tonne CO_2-eq per year. A lower decreased than for the BEV-ERS case but still substantial.

5.8 Sensitivity analysis

The sensitivity analysis investigates the influence on key parameters and how these affect the total results if altered. This is presented in table 24.

The first case investigated is a system where all vehicles have a lifetime of 15 years, unlike the base case where the two ICEVs have 13 years, the BEV 10 years and the BEV-ERS 20 years. As seen in table 24 the difference between BEV and BEV-ERS is diminished, but both options perform significantly better than the existing biogas system.

Secondly, the existing system is modelled with 20% biogas buses and 80% biodiesel buses, compared to a 50/50 share in the base case. This due to what is reported by SL (n.d.) on how their bus fleet is made up today, with 15% biogas buses, 4.5% ethanol buses and 80% biodiesel buses. However, the ethanol contribution is not considered. The result show that the effect of the biogas case is small, decreasing the impact of the base case with 3.3% but does not change the relation between the studied vehicle types noticeably, The BEV and BEV-ERS still performers better.

As no specification was made by Jakobsson and Lindström (2021) on which biodiesel that is used, the initial assumption of a 50/50 share between HVO and FAME is evaluated by altering to either 100% HVO or 100% FAME. As can be seen in table 24, lower emissions are reached with a higher share of HVO.

In part II, no battery replacement were assumed during the lifetime of either the articulated lorry (10 years) or the passenger car (15 years) according to Hill et al. (2020). Although a replacement is needed for the urban bus investigated in the report by Hill et al. (2020), an increased lifetime from seven to 15 years is investigated in a sensitivity analysis. This affect the BEV bus the most, with a decrease of almost 8% from the base case. An expected result due to the larger battery size compared to the BEV-ERS case.

Due to a large variation in climate impact from battery production, which also is seen in literature as earlier described, the baseline assumption adopted from Hill et al. (2020) of 89 kg CO_2-eq/kWh is altered to 61 respectively 106 kg CO_2-eq/kWh similarly as in part II of the study. This change is influencing BEV more than BEV-ERS because of its larger battery size, and alters the results with a few percentage points.

As done i the sensitivity analysis in part II, a case is also included with an increased share of recycled aluminium in the rails. This is based on vendor data where impact can be reduced from 6.7 to 2.3 kg CO_2-eq/kg. This alteration affects the final BEV-ERS performance clearly, with a decrease of 12% from base case value.

One sensitivity analysis involves a reduced battery size for the BEV, from 200 kWh with 133 km driving range to 100 kWh with 67 km range. No battery size is presented by Jakobsson and Lindström (2021), why this is investigated. A decreased GWP with 7% is found with this downsize.

The last analysis is made with respect to the number of BEV buses needed to operate the bus line. The base case value is set to 46 according to Jakobsson and Lindström (2021). This is lowered to 33, which is the same value that the other two systems have. This results in a decrease of around 28%, but still with a higher GWP than the base case BEV-ERS.

Table 24: Sensitivity analysis on key parameters for the case study on Stockholm bus line 4. The columns with difference show the percentage change from base case of the same vehicle type.

	Existing system [t CO_2-eq/year]		**BEV [t CO_2-eq/year]**		**BEV-ERS [t CO_2-eq/year]**	
Base case	1 480		802		480	
	New value	Difference [%]	New value	Difference [%]	New value	Difference [%]
Lifetime 15 years all buses	1 440	-3.1	610	-23.9	549	+14.3
20% biogas buses, 80% biodiesel buses	1 440	-3.3	802	0	480	0
Fuel 100% HVO	1 390	-6.6	802	0	480	0
Fuel 100% FAME	1 560	+5.4	802	0	480	0
Lifetime battery 15 years	1 480	0	740	-7.8	467	-2.8
Lower CO_2-intensity battery production	1 480	0	766	-4.6	473	-1.6
Higher CO_2-intensity battery production	1 480	0	825	+2.8	485	+1.0
Recycled aluminium in rails	1 480	0	802	0	421	-12.3
Reduced battery size BEV (100 kWh)	1 480	0	744	-7.3	480	0
Reduced number of BEV buses (33)	1 480	0	581	-27.6	480	0

5.8.1 Conductive rail vs conductive catenary

Of the four ERS technologies currently being tested in Sweden, one of them is the conductive overhead catenary solution with a pantograph on the vehicle, similar to a trolley bus system. Implementation of a catenary solution on Stockholm bus line 4 is included by Jakobsson and Lindström (2021), but excluded in their final cost calculation as both investment and maintenance cost are estimated to be higher compared to Elonroad's. In addition, the authors state that the overhead solution will have a large impact on the cityscape and require more space.

As described in section 1.4.1, there are some studies comparing environmental impact between the different ERS technologies, however with rough estimations. Both Balieu, Chen and Kringos (2019) and Nàdasi (2017) conclude that overhead catenary seem to perform worse than the conductive rail due to the extensive use of copper cables. A similar study to this instead focusing on the conductive catenary technology is however recommended before making a final comparison. Lastly, there is also a difference in which vehicles that are able to use the ERS, where overhead catenary is limited to vehicles with a certain height.

6 Discussion

The discussion is divided between the three different parts of the study as follows.

6.1 Part I

Part I of the study investigates climate impact of Elonroad's electric road system and its complementing technology. The identified hotspot for the rail is found to be aluminium, accounting for 66% of the total life cycle impact. In a sensitivity analysis a different aluminium type with increased share of recycled aluminium is tested, which is found to decrease the total GWP of the rail with 43%. The components contributing the second most to the total GWP of the rail are the PCBs. There are several uncertainties related to this since it was not possible to obtain data reflecting the exact composition of the PCBs used in the rails. It is however reasonable that the these account for a large share of the impact since such components are known to be amongst the top contributors to GWP per kg material. Due to the relatively high impact from these components on the total GWP, it is recommended to analyse this further and to evaluate possible alternative designs or materials with lower impact.

The majority of the climate impact from the OBC originates from the DC/DC converter, found to be 90%. As both discussed and investigated in the sensitivity analysis, there are uncertainties in the determination of the converter GWP. Scaling emissions linearly with mass likely gives rise to an overestimation of GWP, but due to unavailability of other more appropriate data this conservative approach was applied in the base case. The pick-up is mostly constructed from raw materials with low complexity and with emission data corresponding to the actual materials, why the results are related to a lower level of uncertainty. In comparison with the OBC also mounted to the car, GWP of the pick-up accounts for 14% of their total GWP together.

Regarding the feed-in station, an exact determination is difficult to make since the final design is not determined. Impact was estimated with help of upstream vendor, but based on a transformer station not including a rectifier. Comparing the obtained data to similar constructions shows that the used data are higher that what has been reported in literature and from other manufacturers. What additional impact the rectifier will have is subject for future studies, together with a more accurate analysis on the final design of the entire feed-in station.

This study excludes end-of-life treatment since an end-of-life strategy for the components has not yet been determined. To aid the transition towards a circular economy, waste prevention, re-use and recycling are desirable end-of-life strategies compared to recovery and disposal (European commission n.d). The choice of end-of-life treatment will affect the performance of the entire ERS from a climate perspective since it allows emissions to be shared between more products via allocation to e.g. reused material. End-of-life and recylability are heavily dependent on type of material, where aluminium can be recycled an infinitely number of times and plastics encounter several challenges in recyclability (Government of Canada 2022; European Parliament 2021). Based on this, it is recommended to determine an end-of-life strategy already in the development phase.

6.2 Part II

In part II of the study it is found that climate impact from BEV-ERS is strongly dependent on AADT, since it determines how many users that share the environmental burden from infrastructure. The literature findings reveal that for an articulated lorry, an AADT of 172 vehicles/day for BEV-ERS has the highest GWP per tkm amongst the renewable types, followed by ICEV-LBG, BEV and FCEV-electrolysis in descending order. The remaining studied AADT values for BEV-ERS, 896, 1 088 and 4 400 vehicles/day, are found to all have a lower GWP, with the highest AADT giving the lowest impact. FCEV using hydrogen from SMR is the outlier from a climate perspective, an expected result since this is the only fuel with fossil origin. In the case of a lower medium car, FCEV-electrolysis, ICEV-CBG and BEV show a relatively comparable performance in GWP per vkm. For BEV-ERS to perform better than these, higher AADT values than observed for the articulated lorry is required. A similar result for FCEV-SMR is seen for the car with significantly higher impact.

It is found that break-even for ICEV-LBG is at an AADT of 226 vehicles/day, for BEV at 313 vehicles/day and for FCEV-electrolysis at 428 vehicles/day. Reaching these AADT values may be expected between year 2030 and year 2035 depending on whether the high or low prospect is considered in the report by Natanaelsson et al. (2021). For the lower medium car the required AADT values for break-even are higher, with an intersection between BEV-ERS and FCEV-electrolysis occurring at 2 720, at 3 250 for ICEV-CBG and at 4 780 vehicles/day for BEV. This is significantly higher, but if assuming that AADT could constitute of both heavy-duty vehicles and cars, this higher AADT is not unrealistic. For example, an AADT of 2 720 vehicles/day can be reached with a combination 1 088 HDVs/day and the remaining being cars. At what year it could be expected to see such values is however not possible to say, since no previous study has examined the prospects for cars using ERS.

This study does not intend to answer the question of which AADT scenario is most likely. However, a possible hindrance for reaching the discussed AADT values where BEV-ERS is advantageous is the plan for reducing traffic work as a measure to reach the climate targets. Since comparably lower AADT values are needed for HDVs, steering towards decreased traffic work is more likely to affect the climate benefit for BEV-ERS cars. The conflict between on one hand reduced traffic work and on the other hand a desired high traffic work in favour of BEV-ERS is an important issue to consider in future. In this context it is also interesting to investigate the opposite, i.e. what effect an ERS implementation would have on the traffic work. It is possible that an ERS gives incitement of travelling a longer distance in order to cover roads equipped with rails, as discussed in the introduction regarding energy consumption.

The functional unit considered in this study is tonne kilometre for heavy-duty vehicles and vehicle kilometre for passenger cars. The HDV comparison between the propulsion systems in terms of tkm is influenced by the unladen mass of the vehicle, in turn affecting the load capacity. This causes ICEV-LBG and FCEV to be favoured in the comparison, followed by BEV-ERS and least BEV with its heavy battery pack. A lighter truck can carry more load, thus affecting the performance per functional unit, where a lower unladen mass gives a longer lifetime in tkm and a lower impact per tkm. How unladen mass actually affects goods transport and what impact future progresses in for example battery densities will have are important parameters to take into account.

It is important to note that the studied propulsion systems differ in maturity and technical readiness level. For example, the FCEV is a vehicles type that is not yet commercialised. This novelty implies several uncertainties regarding impact from a future implementation. An aspect of the ERS that has been excluded from this study is the cloud services needed when implementing the ERS. This implies an increased impact during operation, but to what extent require further investigations. With regards to maintenance, it is possible that some parts or components in the rails will need to be exchanged during the assumed lifetime of 15 years, which in turn will increase the GWP for both the ERS component and the vehicles per FU. The same applies to the OBC and pick-up, even though a maintenance measure for the pick-up is included.

Previous studies investigating climate performance of an ERS implementation generally considers it in comparison to fossil alternatives. Taljegard et al. (2020) stated that implementing ERS in Sweden had the potential to reduce GHG emissions from the HDV fleet by around 55% and by 36% for the passenger cars. The finding of this report shows a reduction per FU compared to fossil alternatives in an interval between 31% and 73% for the lower medium car of BEV-ERS type. For the articulated lorry, the reduction is between 74% and 88%. Previous studies all indicate that BEV-ERS are advantageous compared to fossil alternatives when considering a renewable electricity mix. The novelty in this study is however the comparison between other renewable solutions with infrastructure included.

The ability of reducing the battery size is the main reducer of GHG emissions from the vehicle production for BEV-ERS compared to BEV. However, there are other important aspects that need to be considered if a large-scale electrification of the vehicle fleet is to be implemented. Other relevant impact categories for battery production are acidification, eutrophication and resource depletion (Temporelli, Carvalho & Girardi 2020). A BEV is found to have a higher acidification potential compared to both ICEVs using gasoline and diesel (Hill et al. 2020). Resource depletion is an impact category often disregarded in this context, despite its importance for the battery industry and the predicted increased demand for batteries in the future (Temporelli, Carvalho & Girardi 2020). Compared to an ICEV fuelled with gasoline, a BEV shows a

40% larger impact on resource depletion (Hill et al. 2020). In addition, most vehicle batteries contain the rare earth minerals lithium and cobalt, which along with increased battery production volume will meet an increased demand (Hill et al. 2019). If the lithium demand continues to increase according to current trend, it is expected that the lithium demand will exceed today's possible production volumes already at 2035. Therefore, a need for alternative battery chemistries and introduction of recycling pathways are needed. This issue could in part be managed with a vehicle fleet requiring smaller batteries and thus less material. Another aspect to consider in future studies is particle emissions. Even though electric vehicles, both BEV and BEV-ERS, reduce particle emissions from combustion compared to ICEVs, emissions from for tyres, brakes and road surface remain. In addition, it is not clear if additional particle emissions are to expect from wear of the sliding contacts between pick-up and rails for the BEV-ERS.

An ERS implementation of Elonroad's technology would however increase the need for aluminium, where an implementation of 3 000 km ERS would require around 100 000 tonnes of aluminium according to the assumptions made in part II of this study. This could be related to the consumption of refined primary aluminium in Sweden 2020 of 80 000 tonne (Statista 2022a) and a secondary production in 2019 of 68 000 tonne (Statista 2022b). Aluminium does not pose a scarcity risk as of today and the annual primary aluminium production amounted to 65.3 million tonne in 2020 (Government of Canada 2022). This combined with bauxite ore reserves of 29.7 billion tonnes and the fact that aluminium can be recycled an infinite number of times indicates that the increased aluminium demand will be more easily met.

The sensitivity analysis shows that a changed electricity mix significantly alters the result for all propulsion system except ICEV-BG. The parameters with largest impact on the BEV-ERS are the emission factor of the aluminium in the rails, lifetime of the ERS components and fraction of total driving distance on ERS. The latter relates to assumptions regarding design and utilisation of an ERS, more relevant on a system level than on a manufacturing level. For Elonroad, this further motivates that aluminium and lifetime are two important hotspots, since effects are seen on GWP per FU on a system level.

Despite a probable overestimation of OBC impact, the influence from this is not significant for the articulated lorry on a system level in GWP per FU. However, for the lower medium car it is seen that altering the OBC value to a lower, as done in a sensitivity analysis, causes the AADT break-even between BEV-ERS and the other propulsion systems to occur at significantly lower AADT values. In absolute values and for accurate communication towards Elonroad it is therefore important that the estimation reflects the actual conditions of their component, why this is something that would be of interest to investigate more thoroughly in future studies.

6.3 Part III

From the case study on bus line 4 in Stockholm it is clear that implementation of ERS would reduce climate impact significantly, both from today's system with biogas and biodiesel buses but most likely also from a system with BEV buses. This large difference is not seen in part II and is partly a consequence of the input data taken from a previous master thesis on the subject. The sensitivity analysis shows that lifetime and number of buses are key parameters, with possibility to alter the results in favour for BEV over BEV-ERS. However, the results are still clear regarding that a large reduction in GHG emissions from the bus line is reached with a transition to electrified buses from today's system with combustion engines.

It is thus of importance to further analyse prerequisites and key parameters such as lifetime and number of buses in order to receive a trustworthy estimation in terms of GWP. The literature findings does also motivate a thoroughly performed optimisation of the ERS if it is to be implemented. By smart placing of the rails on sites where buses stop or drive slower, more electricity could be transferred per rail. This will reduce the required ERS length and in turn have effects on both cost, climate and battery size.

The study did only consider utilisation of the ERS by the buses operating line 4, but it is theoretically possible even for other vehicles travelling along the line to utilise it. If so, the infrastructure part for the BEV-ERS, accounting for around 30% of its total impact, could be further reduced due to a higher utilisation rate. If this is practically possible under existing circumstances is not investigated here.

Another interesting finding from part III, not evaluated in part II, is the effect of transport efficiency.

Stationary charged BEVs require a relatively long recharging time compared to BEV-ERS or vehicles with gaseous or liquid fuels. For a passenger car this may be considered as a comfort aspect only implying some extra travel time. For a bus fleet on the contrary, the effect is likely that more buses are needed for accomplishing the same transport work. How large impact this effect has on the total performance is case specific but also dependent on for example power level and thus recharging time of the stationary charging system.

As already mentioned, one specific target set for decreasing emissions in the transport sector is to increase the transport efficiency. In this study it has been clear that this not only concerns aspects such as increasing the number of persons travelling in a vehicle, which for example could be attained by an increased utilisation of public transports. It is also about how effectively a vehicle is able to be used, where the ERS enters as an interesting technology. On a system level this is a factor to evaluate further also for HDVs transporting goods and not only in the case of a bus line. Part II of this study examined the impact from one truck with different propulsion systems, but there might be additional effects only seen when studying the entire truck fleet, similarly to what is seen in part III. If trucks need to stop several hours per day to charge, the amount of travelled tkm per day will decrease, unless the number of trucks are increased. Having in mind that the vehicle production stage has an impact that is not negligible, the difference in absolute terms between a BEV and a BEV-ERS truck fleet is of interest to investigate in future studies. From this perspective biofuels and hydrogen have a similar effect as BEV-ERS.

With basis in the results from part III, it can be concluded that ERS should not be limited to being an alternative for long-haul transports on the roads with highest traffic density. The technology may also be able support GHG reductions in other contexts, for example on bus lines. What other systems and conditions where ERS is beneficial from a climate perspective are yet to be evaluated.

In the sensitivity analysis in part III it is clearly seen how large impact the aluminium has on the total results. An increased share of recycled aluminium in the rails, lowering upstream emissions from the material from 6.7 to 2.3 kg CO_2-eq/kg decrease the annual GWP with 12%. It is therefore strongly recommended to take a circular approach in the development of ERS, not only on aluminium but on the entire technology and its components. This will except from minimising waste and reducing the need for virgin material also have a positive impact on the climate performance.

7 Conclusion

By conducting a life cycle assessment, climate impact from the four different ERS components of Elonroad's technology is determined in part I. It is found that one rail contribute to a GWP of 2 590 kg CO_2-eq from cradle to installation. Corresponding value for one pick-up is 200 kg CO_2-eq, one OBC 1 370 kg CO_2-eq and one feed-in station 153 000 kg CO_2-eq. For all four components, the life cycle stage accounting for almost the entire impact is manufacturing of constituent materials, i.e. upstream processing of used material in the components. Identified hotspots are aluminium and PCBs for the rail and DC/DC converter for the OBC. By changing aluminium type to one with an increased share of recycled, total GHG emissions of one rail can be reduced with 43%. Impact from the DC/DC converter is related to uncertainties, why it is suggested to investigate this further.

In part II of the study a comparison between the four propulsion systems FCEV, ICEV-BG, BEV and BEV-ERS is made for both an articulated lorry and a lower medium passenger car, based on results from part I and a literature review. One advantage with BEV-ERS over BEV is the ability to downsize the battery. This is seen in the study, where impact from the life cycle stage vehicle production is significantly lower for BEV-ERS than BEV. It is further concluded that BEV-ERS is strongly dependent on annual average daily traffic (AADT), used to express utilisation rate, where an increased AADT leads to a reduced impact from the infrastructure in g CO_2-eq per tkm and vkm respectively. In the base case for the articulated lorry, the FCEV-SMR is found to have a GWP of 139 g CO_2/tkm, the FCEV-electrolysis 32.7 g CO_2/tkm, the ICEV-LBG 42.1 g CO_2/tkm and the BEV 36.6 g CO_2/tkm. With an AADT exceeding 428 vehicles/day, BEV-ERS is the best performing lorry among the studied types. In the case lower medium car, corresponding value for FCEV-SMR is 186 CO_2/vkm, FCEV-electrolysis 78.7 CO_2/vkm, ICEV-CBG 76.5 CO_2/vkm and BEV 72.9 CO_2/vkm. Here break-even instead occurs at an AADT of 4 780 vehicles/day and above this value the BEV-ERS has a lower GWP per vkm than the other types.

In the sensitivity analysis it is concluded that electricity mix, aluminium type, lifetime of ERS components and fraction of total driving distance on ERS are the parameters with largest impact on the result, in addition to AADT. The electricity mix alters the prerequisites for all propulsion systems except ICEV-BG, with the potential to favour this type under the assumption that biogas is unaffected by this parameter. Remaining mentioned parameters relate to the ERS, where lifetime and aluminium type are factors in the manufacturing process that Elonroad may influence, whereas fraction of driving distance on ERS relates to how the system is implemented on a large scale.

An implementation of ERS on Stockholm bus line 4 by exchanging the current system of biogas and biodiesel buses to BEV-ERS buses and required infrastructure is investigated in part III. It is found that BEV-ERS has the potential to reduce climate impact from today's 1 480 tonne CO_2-eq/year to 480 tonne CO_2-eq/year for the entire bus fleet. If instead transitioning to BEV buses, a decrease to 802 tonne CO_2-eq/year is seen, a smaller reduction than with BEV-ERS. The results show the importance of considering transport efficiency on a system level, in this case meaning that more BEV buses are required to perform the same transport work as BEV-ERS or ICEV buses since these will spend more time recharging.

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A Appendix

A similar structure to that in the main report is adopted also in the appendix, divided between the three parts of the study.

A.1 Part I

In appendix for part I additional data on the ERS components rail, pick-up, OBC and feed-in station are presented.

A.1.1 Rail

A.1.1.1 Material

Table A1: Material used in one rail unit of 9.18 m. Primary data from Elonroad via vendors, measurements, assumptions and CAD models.

Material	**Mass [kg]**
Acetal	0.094
Aluminium	254.38
Brass	0.13
Brass, nickel-plated	0.004
Cable	1.10
Colour primer	0.24
Colour UVR	2.13
Copper	8.12
Copper alloy, nickel-plated	0.009
Copper, silver-plated	0.20
Copper, tin-plated	0.12
EPDM	17.19
Epoxy	0.16
Mylar	0.087
Network cable	0.90
PCB	1.59
Polyamide	0.096
Polyamide 6	0.001
Polyamide 6-GF30	0.52
Polycarbonate	0.080
Polyolefin	2.05
Ribbon cable	0.050
Silicone	0.96
Steel	0.004
Steel, galvanised	0.35
Steel, stainless	54.21
Total	**344.8**

Table A2: Material used in one rail unit of 9.18 m divided between vendors together with corresponding emission factor for each material.

Material	**Vendor**	**Mass [kg]**	**Emission factor [kg CO_2-eq/kg material]**	**Source**
Acetal	2	0.094	3.14	Hoppe, Thonemann & Bringezu (2017)
Aluminium	21	248.93	6.716	Vendor 21
Aluminium	2	5.45	5.043	Gesamtverband der Aluminiumindustrie e.V. (2020)
Brass	54	0.13	6.6949	Ecoinvent 3.8, dataset: ”brass production, CH”
Brass, nickel-plated	51	0.004	6.6949	Ecoinvent 3.8, dataset: ”brass production, CH”
Cable	11	0.002	6.8895	Ecoinvent 3.8, dataset: ”cable production, unspecified, GLO”
Cable	12	1.10	6.8895	Ecoinvent 3.8, dataset: ”cable production, unspecified, GLO”
Colour primer	42	0.24	5.21	Jotun A/S (2021)
Colour UVR	42	2.13	0.357	Jotun A/S (2017)
Copper	2	6.12	4.1	International Copper Institute (2018)
Copper	27	2.00	4.1	International Copper Institute (2018)
Copper alloy, nickel-plated	13	0.009	4.1	International Copper Institute (2018)
Copper, silver-plated	8	0.004	4.1	International Copper Institute (2018)
Copper, silver-plated	2	0.19	4.1	International Copper Institute (2018)
Copper, tin-plated	27	0.12	4.1	International Copper Institute (2018)
EPDM	24	0.053	3.37	Adopted from Inèdit Innovació SL (2018) with reported 1.23 kg/m^2
EPDM	47	17.14	3.37	Adopted from Inèdit Innovació SL (2018) with reported 1.23 kg/m^2
Epoxy	31	0.16	8.1	DACOMAT (2018)
Mylar	24	0.087	3.364	DuPont Teijin Films (2021)
Network cable	5	0.90	15.7	Adopted from Ecoinvent 3.8, dataset: ”cable production, network cable, category 5, without plugs, GLO” with reported 0.036 kg/m
PCB type 1	25	1.44	235.5	See appendix table A3
PCB type 2	25	0.15	307.63	See appendix table A3
Polyamide	3	0.030	5.77	Radici Novacips SpA (2020)
Polyamide	39	0.060	5.77	Radici Novacips SpA (2020)
Polyamide	40	0.001	5.77	Radici Novacips SpA (2020)
Polyamide	15	0.005	5.77	Radici Novacips SpA (2020)
Polyamide 6	4	0.001	5.77	Radici Novacips SpA (2020)
Polyamide 6-GF30	36	0.52	5.54	Radici Novacips SpA (2020)
Polycarbonate	36	0.080	7.6	Ecoinvent 3.8, dataset: ”polycarbonate production, RER”
Polyolefin	9	2.05	3.67	Mannheim & Simenfalvi (2020)
Ribbon cable	5	0.048	10.46	Ecoinvent 3.8, dataset: ”cable production, ribbon cable, 20-pin, with plugs, GLO”
Ribbon cable	30	0.002	10.46	Ecoinvent 3.8, dataset: ”cable production, ribbon cable, 20-pin, with plugs, GLO”
Silicone	35	0.28	6.58	Brandt et al. (n.d)
Silicone	24	0.18	6.58	Brandt et al. (n.d)
Silicone	29	0.50	7.08	FEICA - Association of the European Adhesive and Sealant Industry (2016)
Steel	51	0.004	3.38	Karlsson (2021)
Steel, galvanised	51	0.13	2.56	ArcelorMittal Europe (2019)
Steel, galvanised	38	0.090	2.56	ArcelorMittal Europe (2019)
Steel, galvanised	4	0.13	2.56	ArcelorMittal Europe (2019)
Steel, stainless	2	53.13	3.38	Karlsson (2021)
Steel, stainless	50	0.64	3.38	Karlsson (2021)
Steel, stainless	51	0.24	3.38	Karlsson (2021)
Steel, stainless	4	0.20	3.38	Karlsson (2021)
Total		**344.8**		

Table A3: PCB data and assumptions in calculations of GWP. Type 1 comprises one type of PCB whereas type 2 comprises five different types of PCBs.

PCB type	**Material**	**Mass per unit [kg]**	**Number of units**	**Total mass [kg]**	**Emission factor [kg CO_2-eq/kg material]**	**Source**
Type 1	PCB	0.165	4	0.66	307.63	Ecoinvent 3.8, dataset: ”printed wiring board production, surface mounted, unspecified, Pb free, GLO”
	Transistor	0.007	112	0.78	174.73	Ecoinvent 3.8, dataset: ”transistor production, wired, big size, through-hole mounting, GLO”
Subtotal				**1.44**	**235.5**	
Type 2	PCB	-	28	0.145	307.63	Ecoinvent 3.8, dataset: ”printed wiring board production, surface mounted, unspecified, Pb free, GLO”
Total				**1.59**		

Table A4: Calculated GWP from constituent material used in one rail unit with length of 9.18 m, presented per material.

Material	**GWP [kg CO_2-eq/rail]**	**Percentage of rail material GWP [%]**
Acetal	0.30	0.01
Aluminium	1699.3	70.6
Brass	0.88	0.04
Brass, nickel-plated	0.03	0.001
Cable	7.61	0.32
Colour primer	1.25	0.05
Colour UVR	0.76	0.03
Copper	33.3	1.4
Copper alloy, nickel-plated	0.04	0.002
Copper, silver-plated	0.81	0.03
Copper, tin-plated	0.47	0.02
EPDM	57.9	2.4
Epoxy	1.30	0.05
Mylar	0.29	0.01
Network cable	14.1	0.59
PCB	384.6	16.0
Polyamide	0.55	0.02
Polyamide 6	0.008	0.000 03
Polyamide 6-GF30	2.88	0.12
Polycarbonate	0.61	0.03
Polyolefin	7.51	0.31
Ribbon cable	0.52	0.02
Silicone	6.54	0.27
Steel	0.02	0.001
Steel, galvanised	0.89	0.04
Steel, stainless	183.2	7.6
Total	**2405.7**	**100**

A.1.1.2 Transport

Table A5: GWP from transport of constituent material to Elonroad for one rail, divided between material and vendor.
*Primary data from vendor
**Secondary data based on vendor information on production facility
***Assumed transport route based on vendor production facility

Material	**Vendor**	**Mass [kg]**	**Transport route**	**Travelled distance [km]**	**[CO_2-eq/kg]**	**[kg CO_2-eq]**
Acetal	2	0.094	Baden-Württemberg (DEU)-Lund **	1 209		0.008
Aluminium	21	248.9	Confidential*		0.03	7.47
Aluminium	2	5.45	Baden-Württemberg (DEU)-Lund **	1 459		0.47
Brass	54	0.13	Pori (FIN)-Lund***	2 248		0.021
Brass, nickel-plated	51	0.004	Baden-Württemberg (DEU)-Lund**	1 209		0.0003
Cable	11	0.002	Lund-Lund***	0		0
Cable	12	1.10	Baden-Württemberg (DEU)-Lund **	1 209		0.095
Colour primer	42	0.24	Uppsala (SWE)-Lund ***	669		0.012
Colour UVR	42	2.13	Uppsala (SWE)-Lund ***	669		0.10
Copper	2	6.1226	Baden-Württemberg (DEU)-Lund **	1 209		0.53
Copper	27	2.00	Baden-Württemberg (DEU)-Lund ***	1 176		0.17
Copper alloy, nickel-plated	13	0.009	USA-Lund ***	8 677		0.001
Copper, silver-plated	8	0.004	Amsterdam (NLD)-Lund ***	974		0.0003
Copper, silver-plated	2	0.19	Baden-Württemberg (DEU)-Lund **	1 209		0.017
Copper, tin-plated	27	0.12	Baden-Württemberg (DEU)-Lund ***	1 176		0.0010
EPDM	24	0.053	Gothenburg (SWE)-Lund ***	262		0.0003
EPDM	47	17.1	Ljubljana (SVN)-Lund **	1 777		2.18
Epoxy	31	0.16	Ytterby (SWE)-Lund ***	634		0.007
Mylar	24	0.087	Gothenburg (SWE)-Lund ***	262		0.002
Network cable	5	0.90	Champagne (FRA)-Lund ***	1 341		0.086
PCB	25	1.59	China-Lund ***	17 662		0.29
Polyamide	3	0.030	Canada-Lund ***	7 280		0.002
Polyamide	39	0.060	Baden-Württemberg (DEU)-Lund ***	1 209		0.005
Polyamide	40	0.001	Baden-Württemberg (DEU)-Lund ***	1 209		0.0001
Polyamide	15	0.005	Baden-Württemberg (DEU)-Lund ***	1 209		0.0004
Polyamide 6	4	0.001	Hallsberg (SWE)-Lund ***	468		0.000 05
Polyamide 6-GF30	36	0.52	Jönköping (SWE)-Lund ***	283		0.01
Polycarbonate	36	0.080	Jönköping (SWE)-Lund ***	283		0.002
Polyolefin	9	2.05	Cheltenham (GBR)-Lund ***	1 609		0.24
Ribbon cable	5	0.048	Champagne (FRA)-Lund ***	1 341		0.005
Ribbon cable	30	0.002	Baden-Württemberg (DEU)-Lund ***	1 209		0.0002
Silicone	35	0.28	Bjursås (SWE)-Lund ***	691		0.014
Silicone	24	0.18	Gothenburg (SWE)-Lund ***	262		0.003
Silicone	29	0.50	Geneve (CH)-Lund ***	1 583		0.057
Steel	51	0.004	Baden-Württemberg (DEU)-Lund ***	1 209		0.0004
Steel, galvanised	51	0.13	Baden-Württemberg (DEU)-Lund ***	1 209		0.011
Steel, galvanised	38	0.090	Lissabon (PT)-Lund ***	3 143		0.020
Steel, galvanised	4	0.13	Hallsberg (SWE)-Lund ***	468		0.004
Steel, stainless	2	53.13	Baden-Württemberg (DEU)-Lund **	1 459		4.60
Steel, stainless	50	0.64	Hisings Backa (SWE)-Lund ***	266		0.012
Steel, stainless	51	0.24	Baden-Württemberg (DEU)-Lund ***	1 209		0.020
Steel, stainless	4	0.20	Hallsberg (SWE)-Lund ***	468		0.007
Total		**344.8**		**71 608**		**16.5**

A.1.1.3 Installation

Emission factor for top sealant is taken from an EPD for polymer modified bitumen with value of 0.28 kg CO_2 per kg (Peab Asfalt AB 2021). The elastic top layer is assumed to correspond to a polymer-enhanced bituminous thick coating with a GWP of 1.1 kg CO_2-eq per kg according to an EPD by Deutsche Bauchemie e.V. (2020).

In addition, installation of the rail will also result in emissions from the process of milling and laying the two bitumen materials. Climate impact from milling is approximated with help of a report studying asphalt paving, giving 0.0048 kg CO_2 per kg of milled asphalt (Lundberg n.d.). The report has not clarified whether other GHGs are included in the calculation, but it is assumed that the deviation is small when expressing in CO_2-equivalents. The density is taken from a report by the Swedish Transport Administration (Trafikverket 2005).

Emissions from laying the bottom sealant layer of bitumen is assumed to correspond to the reported values of laying asphalt by Lundberg (n.d.), 0.0057 kg CO_2 per kg. GHG emissions from laying the top sealant material is included in the previous mentioned EPD for this material, with a value of 0.278 kg CO_2 per kg (Deutsche Bauchemie e.V 2020).

A.1.2 Pick-up

A.1.2.1 Material

Table A6: Material used in one pick-up unit together with chosen emission factor and calculated GWP per material. Primary data from Elonroad via vendors, measurements, assumptions and CAD models.

Material	**Mass** [kg]	**Emission factor** [kg CO_2-eq/kg material]	**GWP** [kg CO_2-eq]	**Source**
Acetal	1.42	3.14	4.45	Hoppe, Thonemann & Bringezu (2017)
Aluminium	0.05	5.043	0.23	Gesamtverband der Aluminiumindustrie e.V. (2020)
Cable	0.45	6.8895	3.09	Ecoinvent 3.8, dataset: ”cable production, unspecified, GLO”
DC/DC converter	0.13	43.01	5.59	Ecoinvent 3.8, dataset: ”DC/DC converter production, for electric passenger car, GLO”
Copper	3.46	4.1	14.2	International Copper Institute (2018)
Polycarbonate	5.71	7.6	43.4	Ecoinvent 3.8, dataset: ”polycarbonate production, RER”
Polylactic acid	0.37	1.7	0.63	Rezvani Ghomi et al. (2021)
PCB	0.15	307.63	44.6	Ecoinvent 3.8, dataset: ”printed wiring board production, surface mounted, unspecified, Pb free, GLO”
PVC	0.29	4.739	1.38	Saray (2021)
Steel, stainless	2.60	3.38	8.79	Karlsson (2021)
Steel, stainless 316	15.0	4.72	70.6	Øglænd System AS (2018)
Total	**29.6**		**197.0**	

A.1.3 On-board charger

Table A7: Material used in one on-board charger together with chosen emission factor and calculated GWP per material. Primary data from Elonroad via vendors, measurements and assumptions.

Material	**Mass** [kg]	**Emission factor** [kg CO_2-eq/kg material]	**GWP** [kg CO_2-eq]	**Source**
Aluminium	0.20	5.043	1.01	Gesamtverband der Aluminiumindustrie e.V. (2020)
Brass, nickel-plated	0.24	6.6949	1.61	Ecoinvent 3.8, dataset: ”brass production, CH”
Cable	0.16	6.8895	1.11	Ecoinvent 3.8, dataset: ”cable production, unspecified, GLO”
Ceramic	0.02	1.8298	0.04	Ecoinvent 3.8, dataset: ”sanitary ceramics production, RoW”
Circuit breaker	0.12	4.61	0.56	Schneider Electric (2009)
Contact block	0.011	7.9	0.09	Adopted from Schneider Electric (2018)
Copper	0.086	4.1	0.35	International Copper Institute (2018)
DC/DC converter	28.8	43.01	1238.3	Ecoinvent 3.8, dataset: ”converter production, for electric passenger car, GLO”
Diode	0.002	252.89	0.45	Ecoinvent 3.8, dataset: ”diode production, glass-, for through-hole mounting, GLO”
EMC filter	0.90	6.74	6.07	See appendix table A8
EPDM	0.01	3.37	0.03	Inèdit Innovació SL (2018)
Epoxy	0.38	8.1	3.08	DACOMAT (2018)
Fan	1.20	14.574	17.5	Ecoinvent 3.8, dataset: ”fan production, for power supply unit, desktop computer, GLO”
Ferrite	0.38	2.0659	0.79	Ecoinvent 3.8, dataset: ”ferrite production, GLO”
LED indicator	0.048	7.9	0.38	Adopted from Schneider Electric (2018)
Melamine	0.028	4.2878	0.12	Ecoinvent 3.8, dataset: ”melamine production, RER”
Mylar	0.01	3.364	0.03	DuPont Teijin Films (2021)
PCB	0.055	307.63	16.9	Ecoinvent 3.8, dataset: ”printed wiring board production, surface mounted, unspecified, Pb free, GLO”
Polyamide	0.25	5.77	1.44	Radici Novacips SpA (2020)
Polycarbonate	0.05	7.6	0.38	Ecoinvent 3.8, dataset: ”polycarbonate production, RER”
Polyester	0.01	5.5678	0.06	Ecoinvent 3.8, dataset: ”polyester resin production, unsaturated, RER”
PVC	0.10	4.739	0.47	Saray aluminium (2021)
Rectifier	0.24	4.63	1.10	See appendix table A9
Relay	0.12	11.9	1.38	Adopted from Schneider Electric (2019)
Resistor	0.008	29.779	0.24	Ecoinvent 3.8, dataset: ”resistor production, wirewound, through-hole mounting, GLO”
Steel, galvanised	24.9	2.56	63.6	ArcelorMittal Europe (2019)
Steel, stainless	0.06	3.38	0.20	Karlsson (2021)
Stop button	0.06	9.6	0.57	Adopted from Schneider Electric (2017)
Wemid	0.31	5.77	1.79	Radici Novacips SpA (2020)
Total	**58.7**		**1359.6**	

A.1.3.1 EMC filter

Together with Elonroad engineers and studied LCI data of filters for charging equipment by Kabus et al. (2020), an assumed composition of the EMC filter has been modelled, found in table A8. The printed wiring board (PWB) is an unmounted printed circuit board and the area of this unit has been assumed based on the filter size. The PWB is modelled with the Ecoinvent dataset ”printed wiring board production, for surface mounting, Pb free surface, GLO”. The mass of the PWB is calculated from the reported value of 3.26 kg/m^2 in Ecoinvent. Emission data for capacitors and resistors are also taken from Ecoinvent datasets. For stainless steel the same EPD data are utilised as for the rail (Karlsson 2021).

Table A8: GWP of assumed EMC filter composition based on known total weight and casing of stainless steel, together with emission factor and corresponding data source.

Material	**Number of units**	**Total mass [g]**	**Emission factor [kg CO_2-eq/kg material]**	**GWP [kg CO_2-eq]**	**Source**
Capacitor	2	50	63.045	3.1	Ecoinvent 3.8, dataset: ”capacitor production, electrolyte type, <2cm height, GLO”
PWB	1	0.13	33.2	0.004	Adopted from Ecoinvent 3.8, dataset: ”printed wiring board production, for surface mounting, Pb free surface, GLO”
Resistor	2	0.96	29.779	0.04	Ecoinvent 3.8, dataset: ”resistor production, wirewound, through-hole mounting, GLO”
Steel, stainless	1	849	3.38	2.87	Karlsson (2021)
Total		**900**	**6.74**	**6.1**	

A.1.3.2 Rectifier

The total mass of the rectifier is known but the mass of each individual material is unknown. The diode mass is assumed to be the same as given in the utilised Ecoinvent dataset ”diode production, glass-, for surface-mounting, GLO”. The rest is then assumed to be stainless steel, with climate impact data from Karlsson (2021). The assumed rectifier model can be seen in table A9.

Table A9: GWP of assumed rectifier composition based on known total mass and the electric circuit diagram for the rectifier.

Material	**Number of units**	**Total mass [g]**	**Emission factor [kg CO_2-eq/kg material]**	**GWP [kg CO_2-eq]**	**Source**
Diode	2	1.2	252.89	0.30	Ecoinvent 3.8, dataset: ”diode production, glass-, for through-hole mounting, GLO”
Steel, stainless	1	236	3.38	0.80	Karlsson (2021)
Total		**238**	**4.63**	**1.1**	

A.1.4 Feed-in station

Table A10: GWP of one feed-in station per life cycle stage together with its data source.

Life cycle stage	**GWP [kg CO_2-eq]**	**Source**
Manufacturing of constituent materials		
- Feed-in station	120 000	Vendor 55
- Cable, three-conductor (1 kV) 40m	238	Ecoinvent 3.8, dataset: ”cable production, three-conductor cable, GLO”
Transport	17 000	Vendor 55
Manufacturing	16 000	Vendor 55
Installation		Vendor 55
Total	**153 238**	

A.2 Part II

In this section the different propulsion systems compared in part II are described in detail regarding assumptions, calculations and data sources for both articulated lorry and lower medium car. The descriptions are divided between the studied life cycle stages.

A.2.1 Internal combustion engine vehicle - biogas

A.2.1.1 Vehicle production

Vehicle data are taken from Hill et al. (2020) and are presented in table A11. Note that TTW efficiency for the articulated lorry is recalculated to MJ/tkm from MJ/km with lifetime tkm and vkm of the vehicle, both given by Hill et al. (2020). This calculation is shown in equation 1. The load capacity is found by dividing lifetime tkm with lifetime vkm.

$$\text{TTW efficiency} = 13.3 * \frac{800000}{8206000} = 1.33 \text{ MJ/tkm} \tag{1}$$

Table A11: Vehicle specifications for ICEV-LBG articulated lorry and ICEV-CBG lower medium car. Data adopted from Hill et al. (2020).

Articulated lorry	
Lifetime [vkm]	800 000
Lifetime [year]	10
Lifetime [tkm]	8 026 000
Unladen mass [kg]	14 842
Load capacity [tonne]	10.0
TTW efficiency [MJ/km]	13.3
TTW efficiency [MJ/tkm]	1.33
Vehicle production [g CO_2-eq/tkm]	11.0

Lower medium car	
Lifetime [vkm]	225 000
Lifetime [year]	15
TTW efficiency [MJ/vkm]	2.17
Vehicle production [g CO_2-eq/vkm]	39.0

A.2.1.2 Fuel - WTT

Biogas before being upgraded is a gas with renewable origin produced via anaerobic digestion (AD) of organic matter by microbes in an environment with absence of oxygen. It can be produced from e.g. sewage sludge, organic waste or manure, or in landfills (IEA 2020). Most of the data regarding WTT impact form fuel production are taken from a study conducted by Börjesson et al. (2016), covering climate impact of methane as a vehicle fuel from a well-to-wheel perspective for Swedish conditions.

Another possibility of producing biomethane is via thermal gasification, a process where solid biomass is used as feedstock to produce the methane directly (IEA 2020). This pathway is also included in the study by Börjesson et al. (2016), but is not chosen over the anaerobic digestion pathway since there is a great competition between many sectors for future access to biomass (Hjort 2019). For anaerobic digestion it is instead possible to use waste and residues as feedstock and there is also an untapped potential here according to several studies, with a possible production volume of around 6 TWh/year in Sweden (Hjort 2019) compared to the production volume today of 2 TWh (Energimyndigheten 2020). On a global scale the potential is even larger (Jain et al. 2019).

There are several different techniques for upgrading biogas to biomethane and the ones studied by Börjesson et al. (2016) are water scrubber and amine scrubber. Furthermore, two different calculation procedures are applied by Börjesson et al. (2016) in the evaluation of biomethane production, following the ISO and the

Renewable Energy Directive (RED) methodology respectively. The latter is chosen for this study, which is based on an energy allocation. This means that no system expansion is made where for example effects from substitution of mineral fertiliser with digestate from the AD process are included (Börjesson et al. 2016).

The GHG performance for the WTT stage is presented in table A12. Values for production of upgraded biogas are from Börjesson et al. (2016), including an average of the AD biogas production pathway for the two studied scales of 30 and 100 GWh, an average of the upgrading processes water and amine scrubber, and also compression/liquefaction of the gas. However, distribution and filling stations are excluded and treated under infrastructure. Impact per tkm and vkm are calculated respectively with the TTW efficiencies found in table A11.

Table A12: Well-to-tank GWP for upgraded biogas used in ICEV-LBG articulated lorry and ICEV-CBG lower medium car, calculated per tkm and vkm respectively with TTW efficiencies found in table A11.

Articulated lorry		**Source**
Production of LBG [g CO_2-eq/MJ]	12.3	Börjesson et al. (2016)
Fraction of diesel in fuel [%]	5	Börjesson et al. (2016); Hill et al. (2020)
Production of diesel [g CO_2-eq/MJ]	18.9	Prussi et al. (2020)
Fuel - WTT [g CO_2-eq/tkm]	16.8	

Lower medium car		**Source**
Production of CBG [g CO_2-eq/MJ]	10.4	Börjesson et al. (2016)
Fuel - WTT [g CO_2-eq/vkm]	22.5	

A.2.1.3 Infrastructure

Climate impact from infrastructure is determined by Börjesson et al. (2016) for Swedish conditions and includes both distribution and filling stations. The authors assume distribution of LBG with trucks and CBG mainly with trucks and to a smaller extent in existing gas grids. The values from mentioned report are used and presented in table A13.

Table A13: GWP of infrastructure for ICEV-LBG articulated lorry and ICEV-CBG lower medium car, calculated per tkm and vkm respectively with TTW efficiencies found in table A11. Data from Börjesson et al. (2016).

Articulated lorry	
Distribution and filling stations LBG [g CO_2-eq/MJ]	0.3
Infrastructure [g CO_2-eq/tkm]	0.4

Lower medium car	
Distribution and filling stations CBG [g CO_2-eq/MJ]	2.4
Infrastructure [g CO_2-eq/vkm]	5.2

A.2.1.4 Fuel - TTW

Vehicles using methane as fuel are the only one of the studied propulsion systems included in the comparison that uses a traditional internal combustion engine. As a consequence, driving a vehicle of this type implies tailpipe emissions unlike the other ones. Since biogas produced via anaerobic digestion from e.g. manure is examined, the carbon is part of a fast biogenic cycle (approximately one year), why the combustion emissions may be seen as zero. However, the articulated lorry included in this study utilises a 5% blend of diesel, which is not assumed to have renewable origin and therefore needs to be accounted for as tailpipe emissions. Total emissions in g CO_2-eq/MJ are given by Börjesson et al. (2016). Passenger cars with an SI engine have a small methane leakage causing a net escape of the gas, which gives rise to an small TTW impact despite the 100% biogenic origin of the fuel and the leaked methane. The values are presented in table A14.

Table A14: Tank-to-wheel GWP for ICEV-LBG articulated lorry and ICEV-CBG lower medium car, where the lorry uses a fuel blend of 95% methane and 5% diesel. Data from Börjesson et al. (2016), calculated to tkm and vkm respectively with TTW efficiencies found in table A11.

Articulated lorry	
GHG emissions per energy content [g CO_2-eq/MJ]	7.4
Fuel - TTW [g CO_2-eq/tkm]	9.8

Lower medium car	
GHG emissions per energy content [g CO_2-eq/MJ]	1.7
Fuel - TTW [g CO_2-eq/vkm]	3.8

A.2.1.5 Maintenance

Impact from maintenance measures are taken from Hill et al. (2020) and presented in table A15.

Table A15: GWP of maintenance for ICEV-LBG articulated lorry and ICEV-CBG lower medium car. Data from Hill et al. (2020).

Articulated lorry	
Maintenance [g CO_2-eq/tkm]	4.0

Lower medium car	
Maintenance [g CO_2-eq/vkm]	6.0

A.2.2 Fuel cell electric vehicle

A.2.2.1 Vehicle production

Data on vehicle production and vehicle characteristics have been taken from the previous mentioned European commission report (Hill et al. 2020) and are presented in table A16. TTW efficiency in MJ/tkm and load capacity for the articulated lorry are both calculated similarly to what is described for ICEV-LBG in section A.2.1.

Table A16: Vehicle specifications for FCEV articulated lorry and lower medium car. Data adopted from Hill et al. (2020).

Articulated lorry	
Lifetime [vkm]	800 000
Lifetime [year]	10
Lifetime tkm [tkm]	7 674 000
Unladen mass [kg]	15 944
Load capacity [tonne]	9.59
TTW efficiency [MJ/km]	10.4
TTW efficiency [MJ/tkm]	1.08
Vehicle production [g CO_2-eq/tkm]	17.4

Lower medium car	
Lifetime [vkm]	225 000
Lifetime [year]	15
TTW efficiency [MJ/vkm]	1.13
Vehicle production [g CO_2-eq/vkm]	59.0

A.2.2.2 Fuel - WTT

SMR is a process where hydrogen is produced via a methane source, commonly natural gas. The methane reacts with water vapour under high pressure and high temperature, forming hydrogen gas and carbon monoxide. Most common is a methane source of fossil origin, but using methane from a biochemical process is possible and would result in lower GHG emissions compared to its fossil equivalent (U.S department of energy 2022a). The considered hydrogen gas produced via SMR for the FCEV is a European average value, where the natural gas is an average value of natural gas production in Europe (Hill et al. 2020).

Table A17: Well-to-tank GWP for H_2 produced via SMR used in FCEV articulated lorry and lower medium car, calculated per tkm and vkm respectively with TTW efficiencies found in table A16. Data adopted from Hill et al. (2020).

Articulated lorry	
H_2 production via SMR [g CO_2-eq/MJ]	109.4
Fuel - WTT [g CO_2-eq/tkm]	118

Lower medium car	
H_2 production via SMR [g CO_2-eq/MJ]	109.4
Fuel - WTT [g CO_2-eq/vkm]	124

Producing hydrogen from electrolysis is on the other hand considered as a renewable hydrogen production pathway, given that the electricity is of renewable origin. Hydrogen is in this process produced with an electrolyser, where input electricity and water yields a net output of hydrogen gas (U.S department of energy 2022b). After production the gas is compressed and/or liquefied to be further distributed and used in vehicles. An efficiency of 1.56 in the form of MJ electricity required per MJ produced hydrogen is reported by Hill et al. (2020), enabling an own choice of electricity mix.

Additional impact originating from production of facility and infrastructure are taken from Bekel and Pauliuk (2019), which have made an impact assessment on battery and fuel cell electric vehicles including infrastructure. The authors have included two types of facilities for H_2 production via electrolysis, on-site and central production. A mix of these two is assumed, with GWP values comprising electrolyser, compressor and water supply for the on-site alternative and electrolyser, compressor, storage and water supply for the centralised. All this relate to the WTT stage, why they are included here and not in infrastructure. Summarised GWP of this, given by Bekel and Pauliuk (2019) in their supplementary material, is 1.21 g CO_2-eq/vkm. This needs to be recalculated to the functional unit of this study, done by multiplying by their assumed lifetime vkm of 150 000 and divide by the lifetime tkm or vkm assumed in this study. Resulting values are presented in table A16.

Table A18: Well-to-tank GWP for H_2 produced via electrolysis used in FCEV articulated lorry and lower medium car, calculated per tkm and vkm respectively with TTW efficiencies found in table A16.

Articulated lorry		**Source**
H_2 production infrastructure [g CO_2-eq/tkm]	0.02	Adopted from Bekel & Pauliuk (2019)
Electricity use in H_2 production [MJ/MJ final fuel]	1.56	Hill et al. (2020)
Swedish electricity mix [g CO_2-eq/kWh]	26	Energimyndigheten (2021b)
Fuel - WTT [g CO_2-eq/tkm]	12.2	

Lower medium car		**Source**
H_2 production infrastructure [g CO_2-eq/vkm]	0.8	Adopted from Bekel & Pauliuk (2019)
Electricity use in H_2 production [MJ/MJ final fuel]	1.56	Hill et al. (2020)
Swedish electricity mix [g CO_2-eq/kWh]	26	Energimyndigheten (2021b)
Fuel - WTT [g CO_2-eq/vkm]	13.5	

A.2.2.3 Infrastructure

There are currently five hydrogen refuelling stations in operation in Sweden (Vätgas Sverige n.d). To enable a life cycle comparison between the propulsion systems the infrastructure required for the hydrogen supply needs to be included in the analysis. Since no large-scale infrastructure exists, it is difficult to derive a value on GWP based on existing supply systems. Data have therefore been taken from a German study investigating potential impact from H_2 supply infrastructure, if it is to be implemented (Bekel & Pauliuk 2019). In their scenario it is assumed that hydrogen refuelling stations will be distributed similarly and with the same number of stations as biogas refuelling stations are for the biogas vehicle fleet in Germany. A division of infrastructure impact per vehicle has from the methodology been determined and the results have been applied to this study. However, the electricity usage in downstream transport and distribution has been taken from Hill et al. (2020). This to be able to vary the electricity mix, since the report present values in MJ electricity per MJ H_2 produced (Hill et al. 2020). Bekel & Pauliuk (2019) do present GHG emissions from electricity used in downstream transport and distribution with a German electricity mix per vehicle kilometre, wherefore it was found more sufficient to use values from Hill et al. (2020). Specifications on infrastructure are found in table A19 and for the SMR production pathway, transport of the fuel is already included in the value. Therefore no additional transports need to be added. However, electricity and distribution infrastructure are added as an infrastructure post. Regarding electrolysis, both transport, distribution and infrastructure need to be added since the value found in table A18 only includes on-site production and no surrounding processes. The constituting posts and impact per tkm and vkm are found in table A19.

Table A19: GWP of infrastructure for FCEV articulated lorry and lower medium car, calculated per tkm and vkm respectively with TTW efficiencies found in table A16.

Articulated lorry		**Source**
Infrastructure [g CO_2-eq/tkm]	0.01	Bekel & Pauliuk (2019)
Fuel supply transport for electrolysis [g CO_2-eq/tkm]	0.01	Bekel & Pauliuk (2019)
Electricity use in T&D [MJ/MJ final fuel]	0.04	Hill et al. (2020)
GWP electricity use in T&D [g CO_2-eq/tkm]	0.3	
Total infrastructure electrolysis [g CO_2-eq/tkm]	0.3	
Total infrastructure SMR [g CO_2-eq/tkm]	0.3	

Lower medium car		**Source**
Infrastructure [g CO_2-eq/vkm]	0.4	Bekel & Pauliuk (2019)
Fuel supply transport for electrolysis [g CO_2-eq/vkm]	2.6	Bekel & Pauliuk (2019)
Electricity use in T&D [MJ/MJ final fuel]	0.04	Hill et al. (2020)
GWP electricity use in T&D [g CO_2-eq/vkm]	0.3	
Total infrastructure electrolysis [g CO_2-eq/vkm]	3.2	
Total infrastructure SMR [g CO_2-eq/vkm]	0.6	

A.2.2.4 Maintenance

Maintenance needs during the lifetime of the vehicles have been determined using the report from Hill et al. (2020) and these values are presented in table A20.

Table A20: GWP of maintenance for FCEV articulated lorry and lower medium car. Data from Hill et al. (2020).

Articulated lorry	
Maintenance [g CO_2-eq/tkm]	2.8

Lower medium car	
Maintenance [g CO_2-eq/vkm]	3.0

A.2.3 Battery electric vehicle

A.2.3.1 Vehicle production

For coherence and comparability between the different vehicle types, vehicle data are taken from Hill et al. (2020) and they are presented in figure A21. Note that TTW efficiency for the articulated lorry is recalculated to MJ/tkm with given lifetime tkm and vkm of the vehicle similarly as in equation 1 for ICEV-LBG. Data are only given for production of the entire vehicle including battery by Hill et al. (2020). However, since battery capacity and assumed CO_2-intensity of the battery production also are presented in the report, an own division between vehicle and battery production has been derived. This is simply done by multiplying the capacity in kWh with the CO_2-intensity of the production in kg CO_2-eq/kWh and divide it by lifetime tkm or vkm depending on lorry or car. This is then subtracted from the value for "vehicle production with battery" seen in table A21 in order to receive a value for vehicle production excluding the battery.

Table A21: Vehicle specifications for BEV articulated lorry and lower medium car. Data adopted from Hill et al. (2020).

Articulated lorry	
Lifetime [vkm]	800 000
Lifetime [year]	10
Lifetime [tkm]	6 074 000
Unladen mass [kg]	20 943
Load capacity [tonne]	7.59
TTW efficiency [MJ/km]	5.18
TTW efficiency [MJ/tkm]	0.68
Vehicle production with battery [g CO_2-eq/tkm]	26
Battery capacity [kWh]	940
CO_2-intensity battery production [kg CO_2-eq/kWh]	89
Battery production [g CO_2-eq/tkm]	13.8
Vehicle production [g CO_2-eq/tkm]	12.2

Lower medium car	
Lifetime [vkm]	225 000
Lifetime [year]	15
TTW efficiency [MJ/vkm]	0.57
Vehicle production with battery [g CO_2-eq/vkm]	62
Battery capacity [kWh]	58
CO_2-intensity battery production [kg CO_2-eq/kWh]	89
Battery production [g CO_2-eq/vkm]	22.9
Vehicle production [g CO_2-eq/vkm]	39.1

A.2.3.2 Fuel - WTT

The only fuel used in a BEV is electricity, which is stored in the on-board battery and then used for propulsion. In the base case, a Swedish electricity mix is used with an emission factor of 26 g CO_2-eq/kWh (Energimyndigheten 2021b). This is the emission factor at local grid level, but the charging efficiency also needs to be considered since this is not included in the TTW efficiency from Hill et al. (2020). According to Bekel & Pauliuk (2019), 90% is a commonly used value for efficiency of a stationary charger, which therefore is used in this study as well. The results are presented in table A22.

Table A22: Well-to-tank GWP for BEV articulated lorry and lower medium car, calculated per tkm and vkm respectively with TTW efficiencies found in table A21.

Articulated lorry		**Source**
Swedish electricity mix [g CO_2-eq/kWh]	26	Energimyndigheten (2021b)
Charging efficiency [%]	90	Bekel & Pauliuk (2019)
Fuel - WTT [g CO_2-eq/tkm]	5.5	

Lower medium car		**Source**
Swedish electricity mix [g CO_2-eq/kWh]	26	Energimyndigheten (2021b)
Charging efficiency [%]	90	Bekel & Pauliuk (2019)
Fuel - WTT [g CO_2-eq/vkm]	4.5	

A.2.3.3 Infrastructure

There are several different alternatives for charging a BEV in terms of power levels, implying different charging times. Using cable and connecting directly to the socket allows 2.3 kW, but with a special wall box higher power levels could be reached even for home charging (InCharge 2020). Public chargers often support higher levels to allow shorter charging times. At these levels the chargers are equipped with an off-board charger, supplying the vehicle with DC instead of AC (EFUEL n.d.). Chargers with levels up to 350 kW are found today in Sweden (Elbilsstatistik.se n.d.b).

As the driving range today is limited with a BEV, a vehicle will use different types of chargers with different power levels during its lifetime. When evaluating impact from charging infrastructure, utilisation rate and GHG emissions for each type need to be considered. The infrastructural impact derived from Bekel and Pauliuk (2019) is described in the main report, where 53% of the charging points are located at homes with a power level of 3.7 kW, 19% at companies with a level of 3.7 kW, 26% are public chargers with 22 kW and 1% public chargers with 50 kW power. For the lower medium car the scenario described above is assumed to be representative also for Swedish conditions. The reported value found in the supplementary material expressed in kg CO_2-eq/vkm is thus used, but recalculated from the lifetime vkm assumed by Bekel and Pauliuk (2019) of 150 000 km to the value used in this study of 225 000 vkm. However, this recalculation implies that the lifetime of the infrastructure is prolonged and assumes that no further maintenance is needed with a longer usage.

The articulated lorry of BEV type used in this study has a battery capacity of 940 kWh in the base case, meaning that it is not realistic that the charging mainly will occur with a power level of 3.7 kW. In a report from the Swedish Transport Administration examining the need for charging infrastructure for HDVs, power levels of 50, 350 and 600 kW are assumed when investigating costs for the infrastructure. For long-haul transports, 60% of the energy is assumed to be supplied via depot charging at 50 kW, 30% via semi-public charging at 350 kW and 10% via public charging at 600 kW (Lindgren 2021). These values are used as a reference, with input data from Bekel and Pauliuk (2019).

Due to lack of other data for chargers at these power levels, the 50 kW charger modelled by Bekel and Pauliuk (2020) is scaled linearly with respect to power and multiplied with respective usage in percentage. Impact per 50 kW charger is 0.4 in g CO_2-eq/vkm according to Bekel and Pauliuk (2020), which is recalculated with the assumed usage of 1.33% in their study and then converted from 150 000 vkm to lifetime tkm of the BEV lorry. This is shown in equation 2. Impact is then divided between the different chargers as described earlier. Also in this case it means that the lifetime of the charger is altered. Furthermore, since the value per charger is given by Bekel & Pauliuk (2019) in kg CO_2-eq/vkm and not in absolute vales, it is assumed that the value of 0.95 chargers per vehicle is representative also for trucks.

$$\text{GWP per tkm} = \frac{0.4}{0.0133} * \frac{150000}{6074000} = 0.7 \text{ g } CO_2\text{-eq/tkm} \tag{2}$$

The resulting GWP after calculations is seen in table A23.

Table A23: GWP of infrastructure for BEV articulated lorry and lower medium car. Data adopted from Bekel & Pauliuk (2019).

Articulated lorry	
Charging infrastructure [g CO_2-eq/tkm]	2.9
Lower medium car	
Charging infrastructure [g CO_2-eq/vkm]	3.4

A.2.3.4 Maintenance

The additional impact from maintenance needs for each vehicle type is taken from Hill et al. (2020) and can be seen in table A24. Important to note is that no battery replacement is assumed for lorry or car in the study, based on calculations with respect to battery lifetime, battery capacity, lifetime kilometres of the vehicle and TTW efficiency of the vehicle (Hill et al. 2020).

Table A24: GWP of maintenance for BEV articulated lorry and lower medium car. Data from Hill et al. (2020).

Articulated lorry	
Maintenance [g CO_2-eq/tkm]	2.2
Lower medium car	
Maintenance [g CO_2-eq/vkm]	3.0

A.2.4 Battery electric vehicle with ERS

In table A25 additional vehicle specifications for the BEV-ERS articulated lorry and lower medium car are presented. The values for the lorry are used to determine the unladen mass, in turn used to calculate lifetime tkm. Intermediate values in this calculations are also shown in table A25. The methodology is described in the equations below for the lorry.

$$\begin{aligned}\text{Unladen mass BEV-ERS} &= \text{Unladen mass BEV} - \text{Total mass reduction BEV-ERS} = \\ &= 20943 - 5305 = 15638 \text{ kg}\end{aligned} \tag{3}$$

With calculated unladen mass it is possible to determine the total load capacity from the total gross vehicle weight of 40 tonne, which includes both driver, unladen mass and cargo according to Hill et al. (2020). With a driver mass of 75 kg according to the same study, the total load capacity is calculated as follows:

$$\begin{aligned}\text{Total load capacity} &= \text{Total gross vehicle weight} - \text{Unladen mass} - \text{Driver mass} = \\ &= 40000 - 15683 - 75 = 24287 \text{ kg}\end{aligned} \tag{4}$$

The articulated lorry is assumed to carry 40% of its total load capacity according to Hill et al. (2020). The total lifetime tkm is thereby found by multiplying the total load capacity with the load factor and the total lifetime vkm of 800 000 km as seen below.

$$\begin{aligned}\text{Lifetime tkm} &= \text{Full load capacity} * \text{Load factor} * \text{Lifetime vkm} = \\ &= 24287 * 0.4 * 800000 = 7771891 \text{ tkm}\end{aligned} \tag{5}$$

GWP from vehicle production is calculated with basis in a BEV, where impact from battery production is subtracted with help of known BEV capacity and emission factor of the battery production. An own value of battery production is the calculated for BEV-ERS with help of assumed capacity and the same emission factor of the battery production. This is then recalculated with respect to lifetime tkm or vkm for the BEV-ERS instead of the BEV.

For the lower medium car, the pick-up assessed in part I is assumed to be used and GWP per vkm is found by dividing life cycle emissions found in part I by lifetime vkm of the BEV-ERS. The articulated lorry is however assumed to need a larger pick-up, why a scale factor of 1.5 is adopted for the GWP. This is probably an overestimation, but is used as a conservative assumption. The value is then divided by lifetime tkm.

The capacity of the OBC studied in part I is 40 kW. Even though passenger cars are expected to need around 70 kW, no scaling is made in this case. As mentioned, an overestimation is probably made regarding GHG emissions from the 40 kW OBC, motivating the use of this values together with the uncertainty of what exact capacity that will be needed for cars. HDVs on the other hand will likely need around 200-250 kW, why an up-scaling is required. This is made by linearly scaling the DC/DC converter emissions from 40 kW to 250 kW, which probably is an overestimation. Especially since the linear scaling by mass of the original 40 kW may be an overestimation. Together with Elonroad engineers it is assumed that remaining parts will be less affected by an upscaling, why only the converter is assumed to be affected. GWP of one 250 kW OBC is thus calculated to 7.8 tonne CO_2-eq. This is then divided by lifetime tkm. Resulting values of both pick-up and OBC are found in table A25.

Table A25: Vehicle specifications for BEV-ERS articulated lorry and lower medium car. Data adopted from Hill et al. (2020) together with data from part I of the study. Mass reduction refers to a comparison with BEV.

Articulated lorry	
Lifetime [vkm]	800 000
Lifetime [year]	10
TTW efficiency [MJ/km]	5.18
TTW efficiency [MJ/tkm]	0.53
Lifetime BEV [tkm]	6 074 000
Unladen mass BEV [kg]	20 943
Load capacity BEV [tonne]	7.59
Battery capacity BEV [kWh]	940
Battery capacity BEV-ERS [kWh]	282
Battery pack energy density [Wh/kg]	122
Mass reduction from battery downsizing BEV-ERS [kg]	5393
Mass of OBC and pick-up [kg]	88.3
Total mass reduction BEV-ERS [kg]	5 305
Unladen mass BEV-ERS [kg]	15 638
Lifetime BEV-ERS [tkm]	7 771 891
Load capacity BEV-ERS [tonne]	9.71
Vehicle production without battery and ERS components [g CO_2-eq/tkm]	9.6
CO_2-intensity battery production [kg CO_2-eq/kWh]	89
Battery production [g CO_2-eq/tkm]	3.2
OBC [g CO_2-eq/tkm]	1.0
Pick-up [g CO_2-eq/tkm]	0.04

Lower medium car	
Lifetime [vkm]	225 000
Lifetime [year]	15
TTW efficiency [MJ/vkm]	0.56
Vehicle production without battery and ERS components [g CO_2-eq/vkm]	39.1
Battery capacity [kWh]	17.4
CO_2-intensity battery production [kg CO_2-eq/kWh]	89
Battery production [g CO_2-eq/vkm]	6.9
OBC [g CO_2-eq/vkm]	6.1
Pick-up [g CO_2-eq/vkm]	0.9

A.2.5 Fuel - WTT

Charging efficiency of the ERS is taken from a report studying charging losses of the Evolution road, the pilot project for Elonroad's ERS technology in Lund (Wenander et al. 2021). It is found in the study that the efficiency between feed-in station and vehicle is around 95% for the dynamic charging, however with one vehicle using the infrastructure. It is unclear if this value is decreased if more vehicles are using the ERS as an effect of higher losses due to higher current. This needs to be further investigated in future studies. The efficiency of the DC/DC converter in the OBC is according to upstream vendor 98%, which yields a total ERS charging efficiency of 93%. For stationary charging the efficiency is assumed to be 90% in line with Bekel and Pauliuk (2019). Efficiencies are found in table A26 and calculated GWP from the WTT stage in A27. The calculations are based on the relationship of 60/40 for the articulated lorry and 50/50 for the lower medium car concerning the share of energy supplied via ERS versus stationary chargers, as described in the main report.

Table A26: Charging efficiencies for stationary and dynamic charging.

Charging efficiency		**Source**
Charging efficiency ERS [%]	95	Wenander et al. (2021)
Charging efficiency OBC [%]	98	Data from Elonroad
Total charging efficiency ERS [%]	93	
Charging efficiency stationary [%]	90	Bekel & Pauliuk (2019)

Table A27: Well-to-tank GWP for BEV-ERS articulated lorry and lower medium car, calculated per tkm and vkm respectively with TTW efficiencies found in table A25.

Articulated lorry		**Source**
Swedish electricity mix [g CO_2-eq/kWh]	26	Energimyndigheten (2021b)
Charging efficiency ERS [%]	93	See table A26
Charging efficiency stationary [%]	90	Bekel & Pauliuk (2019)
Share of electricity supply from ERS [%]	60	
Share of electricity supply from stationary [%]	40	
GWP electricity supply via ERS [g CO_2-eq/tkm]	2.5	
GWP electricity supply stationary [g CO_2-eq/tkm]	1.7	
Fuel - WTT [g CO_2-eq/tkm]	4.2	

Lower medium car		**Source**
Swedish electricity mix [g CO_2-eq/kWh]	26	Energimyndigheten (2021b)
Charging efficiency ERS [%]	93	See table A26
Charging efficiency stationary [%]	90	Bekel & Pauliuk (2019)
Share of electricity supply from ERS [%]	50	
Share of electricity supply from stationary [%]	50	
GWP electricity supply ERS [g CO_2-eq/vkm]	2.2	
GWP electricity supply stationary [g CO_2-eq/vkm]	2.3	
Fuel - WTT [g CO_2-eq/vkm]	4.5	

A.2.6 Infrastructure

I this section the assumptions are explained regarding the charging infrastructure and how impact from this life cycle stage is determined.

A.2.6.1 Rail

In the base case, an electrification rate of 60% is assumed according to what is reported by Natanaelsson et al. (2021) for Elonroad's technology. This means that per km ERS, 600 m will be covered by rails. With a rail length of approximately 9.2 m, it means that 66 rails are required per km ERS. Furthermore, a rail lifetime of 15 years is assumed as a base case after consultation with Elonroad engineers. Life cycle GHG emissions related to one rail unit are evaluated in part I of this study and these results are now used as input data.

A.2.6.2 Feed-in station

To supply the rails with DC electricity at desired voltage level, feed-in stations consisting of a transformer and a rectifier are needed along the electrified roads. According to Natanaelsson et al. (2021), one feed-in station is required per 1-1.5 km two-way electrified road with Elonroad's ERS solution. After discussions with engineers at Elonroad and in order to not underestimate, calculations are based on having one feed-in station per km ERS. This is then scaled with respect to 60% electrification rate and to the functional unit only concerning a one-way electrified road. The lifetime of a feed-in station is set to 40 years according to upstream vendor of this component.

A.2.6.3 Utilisation

Impact from infrastructure is as earlier described strongly dependent on the utilisation rate, i.e. how many vehicles that are using the technology during its lifetime. The chosen unit for expressing traffic density is AADT, examined by Natanaelsson et al. (2021). Several different AADT values are investigated for both passenger car and HDV. The AADT values include traffic in two directions, why the AADT is divided by two in order to match the functional unit.

A.2.6.4 Allocation between stationary and dynamic charging infrastructure

The allocation of impact between dynamic and stationary charging is made with respect to driving patterns and accordingly usage. Along with what is investigated by Natanaelsson et al. (2021), 60% of the total electricity is assumed to be supplied from the ERS and 40% from stationary charging for HDVs. This is based on a driving pattern of 60% on the ERS network and 40% outside. With respect to the functional unit, this assumptions practically imply that per km road, 60% is assumed to be ERS and 40% not. After that, an electrification rate of 60% is added, meaning that 36% (360 m per km in average) will be covered by rails and the rest without if studying an arbitrary driven km. In reality, both the electrification rate and the 60/40 relation are parameters with relevance on a larger system level, not observable for a road length of one kilometre.

Natanaelsson et al. (2021) have not included passenger cars in their analysis, but it is likely that the 60/40 relationship is altered in this case. For trucks with a lower weight and shorter driving distance per year, Natanaelsson et al. (2021) concludes that all these trucks drive less than 40% on the ERS network. It is thus reasonable that most passenger cars will drive a large portion of its total distance outside major roads equipped with the ERS technology. On the contrary, a smaller fraction of the driving distance being on the ERS will decrease the incentive of using it in analogous to Natanaelsson et al (2021), assuming that only trucks with 60% of its driving distance on the ERS network will use it. In a base case, the relationship 50/50 is assumed for passenger cars due to lack of more specified data.

Table A28: GWP of ERS infrastructure in the form of rails and feed-in stations.

ERS infrastructure	
Electrification rate [%]	60
Rail	
Rail length per km ERS [m]	600
Length per rail [m]	9.18
Number of rails per km ERS [pcs]	66
GWP per rail [kg CO_2-eq/rail]	2591.6
GWP rails per km ERS [t CO_2-eq/km]	171.0
Lifetime [year]	15
Feed-in station	
Number of stations per km ERS two directions [pcs]	1
Number of stations per km ERS one direction [pcs]	0.5
GWP per station [t CO_2-eq/station]	153.0
GWP stations per km ERS [t CO_2-eq/km]	76.5
Lifetime [year]	40

The parameters in table A28 are used together with AADT to determined GWP of infrastructure per FU for the BEV-ERS according to the equations below. Note that the AADT mentioned in the report denotes AADT in two directions. The number of vehicles passing each rail in each direction is therefore AADT/2. The GWP is calculated as seen below, with parameters corresponding to those seen in table A28. GWP per km driven ERS refers to an arbitrary travelled km on ERS, with electrification rate included.

$$\text{GWP per km driven ERS} = \frac{\text{GWP rails per km ERS}}{\frac{\text{AADT}}{2} * 365.25 * \text{Lifetime rail}} + \frac{\text{GWP stations per km ERS}}{\frac{\text{AADT}}{2} * 365.25 * \text{Lifetime station}} \tag{6}$$

GWP of the ERS infrastructure per FU in g CO_2-eq/tkm from the ERS infrastructure is then calculated as seen below, where the term lifetime vkm/lifetime tkm is used to convert between tkm and vkm.

$$\text{GWP per tkm} = \text{GWP per km driven ERS} * \text{Fraction of total driving distance on ERS} * \frac{\text{Lifetime vkm}}{\text{Lifetime tkm}} \quad (7)$$

GWP per FU in g CO_2-eq/vkm from the ERS infrastructure is calculated as following:

$$\text{GWP per vkm} = \text{GWP per km driven ERS} * \text{Fraction of total driving distance on ERS} \quad (8)$$

A.2.6.5 Stationary charging infrastructure

The stationary charging infrastructure GWP is calculated similarly as for the BEV described in section A.2.3.3, with data from Bekel and Pauliuk (2019). The difference is for the articulated lorry, which is assumed to only use depot chargers of 50 kW. Therefore, the 50 kW charger presented by Bekel and Pauliuk (2019) is used. As described with the dynamic charging, the 60/40 and 50/50 relationship is accounted for also with the stationary chargers.

Table A29: GWP of stationary charging infrastructure for BEV-ERS articulated lorry and lower medium car. Data adopted from Bekel & Pauliuk (2019).

Articulated lorry	
Share of total driving distance outside ERS [%]	40
Share of electricity supplied via stationary charging [%]	40
Stationary charging infrastructure [g CO_2-eq/tkm]	0.2

Lower medium car	
Share of total driving distance outside ERS [%]	50
Share of electricity supplied via stationary charging [%]	50
Stationary charging infrastructure [g CO_2-eq/vkm]	1.7

A.2.7 Maintenance

Table A30: GWP of maintenance for BEV-ERS articulated lorry and lower medium car. Data on vehicles from Hill et al.(2020) and on pick-up from Elonroad.

Articulated lorry	
Maintenance vehicle [g CO_2-eq/tkm]	1.7
Maintenance pick-up [g CO_2-eq/tkm]	0.005
Maintenance [g CO_2-eq/tkm]	1.7

Lower medium car	
Maintenance vehicle [g CO_2-eq/vkm]	3.0
Maintenance pick-up [g CO_2-eq/vkm]	0.3
Maintenance [g CO_2-eq/vkm]	3.3

A.2.8 Sensitivity analysis - material impact from ERS components

A.2.8.1 Recycled aluminium

Figure A1 shows GWP of constituent materials used per rail in the base case together with an increased share of recycled aluminium as a sensitivity analysis. Total life cycle GWP per rail is decreased from 2 592 to 1 477 kg CO_2-eq with this change, taking all life cycle stages into account.

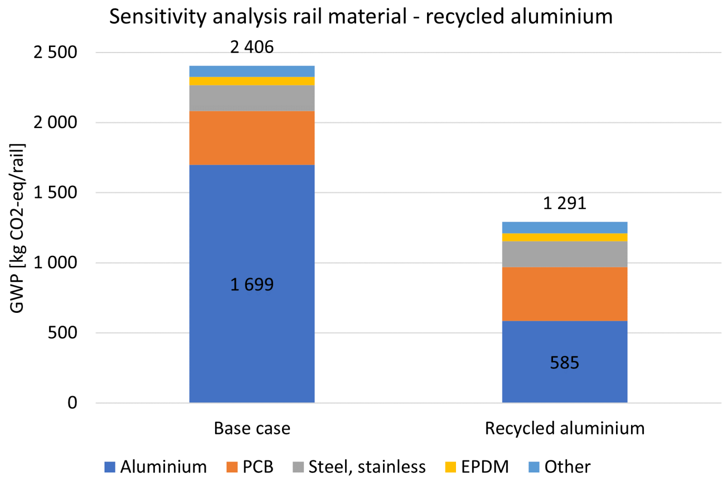

Figure A1: Comparison between base case and sensitivity analysis on increased share of recycled aluminium in total GWP per rail.

A.2.8.2 DC/DC converter in OBC

The following section describes the alternative calculation for determining climate impact from the DC/DC converter in the OBC, which the sensitivity analysis is based on.

In a report examining climate impact of charging equipment for electric vehicles, a model for determining GHG emissions from converter units is presented (Kabus et al. 2020). The report presents an LCI dataset for three different sizes of converters with corresponding Ecoinvent datasets to determine the GWP. In their report the data are aggregated and presented in a different functional unit than of relevance for this report. However, the methodology for estimating GHG emissions from a converter is stated and has been applied to this report as presented below. The DC/DC converter used in the OBC by Elonroad is a 40 kW converter. In the report by Kabus et al. (2020), the closest corresponding dataset is a 50 kW converter. The model to estimate GWP of the converter is found in table A31. The final result with this method yields 101 kg CO_2-eq for one 50 kW converter unit, with a total mass of 1.72 kg. This is not in accordance with the total mass of 28.5 kg that Elonroad's converter weights, but is used for comparison in a sensitivity analysis.

Table A31: Required components and corresponding determination method for climate impact of a 50 kW converter, adopted from Kabus et al. (2020).

Material	**Dataset**	**Total mass [kg]**
MOSFET	Ecoinvent: ”transistor production, wired, big size, through-hole mounting, GLO”	0.12
Diode	Ecoinvent: ”diode production, glass-, for through-hole mounting, GLO”	0.12
Capacitor	Ecoinvent: ”capacitor production, for surface-mounting, GLO”	0.009
Coil	Ecoinvent: ”inductor production, ring core choke type, GLO”	1.05
Transformer		
- Copper, transformer	International Copper Institute (2018)	0.0024
- Ferrite, transformer	Ecoinvent: ”ferrite production, GLO”	0.42
- Process 1, transformer	Ecoinvent: ”inductor production, auxilliaries and energy use, GLO”	0.42
- Process 2, transformer	Ecoinvent: ”wire drawing, copper, RER”	0.0024
Total		**1.7**

A.2.9 Additional sensitivity analyses and altered parameters

Table A32: Specified data on additional sensitivity analyses for articulated lorry. AADT has the unit of vehicles/day.

Changed parameter	**New value**	**Unit**	**Affected life cycle stage**	**New value at AADT 896 [g CO_2-eq/tkm]**
New parameter: Transmission network	33930	kg CO_2-eq/km	Infrastructure	5.7
TTW-efficiency	0.59	MJ/tkm	Fuel - WTT	4.6
TTW-efficiency	0.48	MJ/tkm	Fuel - WTT	3.8
Electrification rate	50	%	Infrastructure	4.3
Changed fraction of total driving distance on ERS	80	%	Infrastructure	6.7
Changed fraction of total driving distance on ERS	40	%	Infrastructure	3.4
Lifetime rails and feed-in stations	10 and 35	years	Infrastructure	7.3
Lifetime rails and feed-in stations	20 and 45	years	Infrastructure	3.9

Table A33: Specified data on additional sensitivity analyses for lower medium car. AADT has the unit of vehicles/day.

Changed parameter	**New value**	**Unit**	**Affected life cycle stage**	**New value at AADT 1000 [g CO_2/vkm]**
New parameter: Transmission network	33930	kg CO_2-eq/km	Infrastructure	41.9
TTW-efficiency	0.62	MJ/vkm	Fuel - WTT	4.9
TTW-efficiency	0.51	MJ/vkm	Fuel - WTT	4.0
Electrification rate	50%	%	Infrastructure	31.3
Changed fraction of total driving distance on ERS	70	%	Infrastructure	51.0
Changed fraction of total driving distance on ERS	30	%	Infrastructure	21.9
Lifetime rails and feed-in stations	10 and 35	years	Infrastructure	52.82
Lifetime rails and feed-in stations	20 and 45	years	Infrastructure	28.08

A.3 Part III

Numerical values from the results are found in table A34. Further data and details on calculations are presented in the coming sections for each bus type.

Table A34: Life cycle GWP from Stockholm bus line 4 per year. Existing system is a bus fleet with 50/50 share of biogas and biodiesel buses.

Life cycle stage	**Existing system [t CO_2-eq/year]**	**BEV [t CO_2-eq/year]**	**BEV-ERS [t CO_2-eq/year]**
Vehicle production	265	466	175
Battery production	0	117	25
Fuel - WTT	926	91	80
Infrastructure	108	19	161
Fuel - TTW	106	0	0
Maintenance	80	109	39
Life cycle GWP	1 485	802	480

A.3.1 Biodiesel bus

Vehicle production impact are recalculated from given value of 153 g CO_2-eq/vkm by Hill et al. (2020) to an absolute value with related lifetime of 675 000 vkm in the same report. This is then divided with the lifetime assumed by Jakobsson and Lindström (2021) of 13 years, which gives a value of 7.9 t CO_2-eq/year. The same methodology is applied to the maintenance part.

The tank-to-wheel efficiency is presented in the unit kg biomass per km (kbm/km) by Jakobsson and Lindström (2021), interpreted as kg biodiesel per km. This is translated into MJ/km with help of the lower heating value of the fuel. Since both FAME and HVO are assumed to be used, LHVs for both these are used and then combined with respect to the portion used of each fuel.

All values used in calculations are found in table A35.

Table A35: Data and parameters used in calculation of GWP for one biodiesel bus.

Biodiesel bus		**Source**
	Vehicle specifications	
Lifetime [year]	13	Jakobsson & Lindström (2021)
Lifetime [vkm]	675 000	Hill et al. (2020)
Lifetime [year]	15	Hill et al. (2020)
TTW efficiency [kbm/km]	0.52	Jakobsson & Lindström (2021)
TTW efficiency [MJ/km]	21.1	Adopted from Jakobsson & Lindström (2021)
Vehicle production [g CO_2-eq/vkm]	153	Hill et al. (2020)
Vehicle production [t CO_2-eq/year]	7.9	
	Fuel - WTT	
Production of FAME100 [g CO_2-eq/MJ]	32.9	Energimyndigheten (2021a)
Production of HVO100 [g CO_2-eq/MJ]	20.4	Energimyndigheten (2021a)
Portion of biodiesel being FAME [%]	50	
Portion of biodiesel being HVO [%]	50	
Heating of bus with biodiesel [l/km]	0.1	Jakobsson & Lindström (2021)
LHV FAME [MJ/l]	33	Engman et al. (2020)
LHV FAME [MJ/kg]	37	Engman et al. (2020)
LHV HVO [MJ/l]	34	Engman et al. (2020)
LHV HVO [MJ/kg]	44	Engman et al. (2020)
Heating of buses [t CO_2-eq/year]	4.1	
Fuel - WTT [t CO_2-eq/year]	29.6	
	Infrastructure	
Distribution and filling stations [g CO_2-eq/MJ]	2.4	Börjesson et al. (2016)
Infrastructure [t CO_2-eq]	2.3	
	Fuel - TTW	
Fuel - TTW [t CO_2-eq/year]	0	
	Maintenance	
Maintenance [g CO_2-eq/vkm]	52	Hill et al. (2020)
Maintenance [t CO_2-eq/year]	2.7	

A.3.2 Biogas bus

A similar approach as for the biodiesel bus is applied, where vehicle production GWP is recalculated from values in g CO_2-eq/vkm via total lifetime vkm by Hill et al. (2020) to annual GWP from lifetime of 13 years according to Jakobsson and Lindström (2021).

Also TTW efficiency is treated similarly as for the biodiesel bus, translated from kg biomass per km to MJ per km via LHV and density at 15 °C.

All data used in calculations are found in table A36.

Table A36: Data and parameters used in calculation of GWP for one biogas bus.

Biogas bus		**Source**
	Vehicle specifications	
Lifetime [year]	13	Jakobsson & Lindström (2021)
Lifetime [vkm]	675 000	Hill et al. (2020)
Lifetime [year]	15	Hill et al. (2020)
TTW efficiency [kbm/km]	0.8	Jakobsson & Lindström (2021)
TTW efficiency [MJ/km]	39.3	Adopted from Jakobsson & Lindström (2021)
Vehicle production [g CO_2-eq/vkm]	156	Hill et al. (2020)
Vehicle production [t CO_2-eq/year]	8.1	
	Fuel - WTT	
Production upgraded biogas [g CO_2-eq/MJ]	12.6	Energimyndigheten (2021a)
LHV upgraded biogas [MJ/ndm^3]	34.9	Energimyndigheten (2022)
Density upgraded biogas [kg/dm^3]	0.711	Energimyndigheten (2022)
LHV upgraded biogas [MJ/kg]	49.1	
Heating of bus with biodiesel [l/km]	0.1	Jakobsson & Lindström (2021)
Heating of bus with biodiesel [t CO_2-eq/year]	4.1	
Fuel - WTT [t CO_2-eq/year]	26.6	
	Infrastructure	
Distribution and filling stations [g CO_2-eq/MJ]	2.4	Börjesson et al. (2016)
Infrastructure [t CO_2-eq/year]	4.3	
	Fuel - TTW	
TTW emissions (methane leakage) [g CO_2-eq/MJ]	0.24	Börjesson et al. (2016)
Fuel - TTW [t CO_2-eq/year]	6.4	
	Maintenance	
Maintenance vehicle [g CO_2-eq/vkm]	41	Hill et al. (2020)
Maintenance [t CO_2-eq/year]	2.1	

A.3.3 BEV

Also for the BEV bus impact from vehicle production and maintenance are recalculated from g CO_2-eq/vkm to CO_2-eq/year via lifetimes. However, an own division between battery and vehicle production is made with respect to values presented by Hill et al. (2020). This is made by using their assumed CO_2-intensity of battery production with their used battery capacity. This total value of 21.4 t CO_2-eq is then subtracted from the vehicle production post, and then expressed in GWP per year.

The maintenance impact is also recalculated from original value presented by Hill et al. (2020) since this includes a battery replacement. This is done by subtracting the estimated impact from one battery produced.

Impact from one stationary charger is taken from Bekel and Pauliuk similarly as in part II. This means that the given GWP value for a 50 kW charger per vkm is divided with its usage in percentage (1.33%) and multiplied with the lifetime vkm in the study (150 000). It is also divided with 0.95 to account for the number of chargers per vehicle.

Numerical values on parameters and assumptions are found in table A37.

Table A37: Data and parameters used in calculation of GWP for one BEV bus using stationary charging.

BEV bus		**Source**
Vehicle specifications		
Lifetime [year]	10	Jakobsson & Lindström (2021)
Lifetime [vkm]	675 000	Hill et al. (2020)
Lifetime [year]	15	Hill et al. (2020)
Battery lifetime [years]	7	Jakobsson & Lindström (2021)
TTW efficiency [MJ/km]	5.4	Jakobsson & Lindström (2021)
Vehicle production (with battery) [g CO_2-eq/vkm]	182	Hill et al. (2020)
Battery capacity in Hill et al (2020) [kWh]	241	Hill et al (2020)
Battery capacity in this study [kWh]	200	
CO_2-intensity battery production [kg CO_2-eq/kWh]	89	Hill et al. (2020)
Vehicle production (without battery) [t CO_2-eq/year]	10.1	
Battery production (200 kWh) [t CO_2-eq/year]	2.5	
Fuel - WTT		
Emission factor Swedish electricity mix [g CO_2-eq/kWh]	26	Energimyndigheten (2021b)
Efficiency stationary charger [%]	90	Bekel & Pauliuk (2019)
Fuel - WTT [t CO_2-eq/year]	2.0	
Infrastructure		
Lifetime stationary charging infrastructure [year]	10	Bekel & Pauliuk (2019)
Stationary charger 50 kW [kg CO_2-eq/charger]	4737	Adopted from Bekel & Pauliuk (2019)
Number of chargers [pcs]	40	Jakobsson & Lindström (2021)
Infrastructure [t CO_2-eq/year]	18.9	
Fuel - TTW		
Fuel - TTW [t CO_2-eq/year]	0	
Maintenance		
Maintenance vehicle [g CO_2-eq/vkm]	35.2	Hill et al. (2020)
Maintenance [t CO_2-eq/year]	2	

A.3.4 BEV-ERS

The same methodology as for the BEV is used also for the BEV-ERS concerning vehicle impact, but with a battery capcity of 60 kWh instead. As described earlier, data are based on a BEV bus and not a BEV-ERS bus in the study by Hill et al. (2020) to be able to model a bus with a relevant battery capacity.

Due to the stationary charging and the ERS charging having different charging efficiencies, a division is made on the share of the energy supplied via each of them. According to Jakobsson and Lindström (2021), ERS buses will depot charge at 6 kW during nights, 10 hours per 24 hours. From total annual driving distance per bus and TTW efficiency, a total annual electricity usage per bus is estimated to around 86 000 kWh. If 60 kWh is assumed to be charged each day via stationary chargers, approximately 22 000 kWh is supplied from these annually. Given these assumptions, around 25% of the total energy is supplied via stationary chargers, which is used as an estimate. GWP from one 6 kW charger is recalculated from Bekel and Pauliuk (2019) similarly as for the 50 kW charger described in the BEV chapter.

Data used in calculations are summarised in table A38, with additional details on the ERS components in table A39.

Table A38: Data and parameters used in calculation of GWP for one BEV-ERS bus. Well-to-tank is abbreviated WTT and tank-to-wheel TTW.

BEV-ERS bus		**Source**
Vehicle specifications		
Lifetime [year]	20	Jakobsson & Lindström (2021)
Lifetime [vkm]	675 000	Hill et al. (2020)
Lifetime [year]	15	Hill et al. (2020)
Battery lifetime [year]	7	Jakobsson & Lindström (2021)
TTW efficiency [MJ/km]	6.8	Jakobsson & Lindström (2021)
Vehicle production (with battery) [g CO_2-eq/vkm]	182	Hill et al. (2020)
Battery capacity in Hill et al. (2020) [kWh]	241	Hill et al. (2020)
Battery capacity in this study [kWh]	60	
CO_2-intensity battery production [kg CO_2-eq/kWh]	89	Hill et al. (2020)
Vehicle production (without battery) [t CO_2-eq/year]	5.1	
Battery production [t CO_2-eq/year]	0.8	
OBC and pick-up [t CO_2-eq/year]	0.2	
Vehicle production total (without battery) [t CO_2-eq/year]	5.3	
Fuel - WTT		
Emission factor Swedish electricity mix [g CO_2-eq/kWh]	26	Energimyndigheten (2021b)
Efficiency stationary charger [%]	90	Bekel & Pauliuk (2019)
Efficiency ERS charging [%]	93	See table A26
Annual electricity usage per bus [kWh/year]	86 365	
Annual electricity supply from stationary chargers per bus [kWh/year]	21 915	
Share of electricity from stationary chargers [%]	25	
Fuel - WTT stationary part [t CO_2-eq/year]	0.6	
Fuel - WTT ERS part [t CO_2-eq/year]	1.8	
Fuel - WTT total [t CO_2-eq/year]	2.4	
Infrastructure - entire system		
Lifetime stationary charging infrastructure [year]	10	Bekel & Pauliuk (2019)
Stationary charger 6 kW [kg CO_2-eq/charger]	79	Adopted from Bekel & Pauliuk (2019)
Number of stationary chargers [pcs]	33	
Stationary charging infrastructure [t CO_2-eq/year]	0.3	
Rails [t CO_2-eq/year]	137.4	
Feed-in stations [t CO_2-eq/year]	23.0	
ERS infrastructure [t CO_2-eq/year]	160.3	
Infrastructure total [t CO_2-eq/year]	160.6	
Fuel - TTW		
Fuel - TTW [t CO_2-eq/year]	0	
Maintenance		
Maintenance vehicle [g CO_2-eq/vkm]	35.2	Hill et al. (2020)
Maintenance vehicle [t CO_2-eq/year]	1.2	
Maintenance pick-up [t CO_2-eq/year]	0.004	
Maintenance total [t CO_2-eq/year]	1.2	

The pick-up is up-scaled compared to the one studied in part I, which also was made for the articulated lorry in part II. This is because the pick-up from part I is designed for a car with lower charging power. As an estimate, it is assumed that the GWP is increased with a factor 1.5.

An up-scaling is also performed for the OBC in order to account for a 100 kW capacity instead of the 40 kW investigated in part I. This is done by linearly scaling the DC/DC-converter GWP with respect to power, i.e. from 40 to 100. This might be an overestimation of the DC/DC-converter impact since a linear relationship is not likely to exist. In other words no other components in the OBC is assumed to be up-scaled, which partly may compensate for that.

Table A39: Detailed data on parameters and values for ERS on bus line 4.

ERS specifications		**Source**
Total ERS distance both directions [km]	7.3	Jakobsson & Lindström (2021)
Electrification rate [%]	30	Adopted form Jakobsson & Lindström (2021)
ERS charging power [kW]	100	Jakobsson & Lindström (2021)
	Rail	
Lifetime rail [year]	15	Jakobsson & Lindström (2021)
Number of rails [pcs]	795	
GWP per rail [t CO_2-eq/rail]	2.6	
GWP all rails per year [t CO_2-eq/year]	137.4	
	Feed-in station	
Lifetime feed-in station [year]	40	Vendor 55
Number of feed-in stations [pcs]	6	Jakobsson & Lindström (2021)
GWP per feed-in station [t CO_2-eq/station]	153.2	
GWP all feed-in stations per year [t CO_2-eq/year]	23.0	
	Pick-up	
Lifetime pick-up [year]	15	Jakobsson & Lindström (2021)
GWP per pick-up [t CO_2-eq/pick-up]	0.2	
Scale factor to bus [-]	1.5	
GWP one pick-up per year [t CO_2-eq/year]	0.02	
	OBC	
Lifetime OBC [year]	15	Jakobsson & Lindström (2021)
OBC capacity [kW]	100	Jakobsson & Lindström (2021)
GWP per 40 kW OBC [t CO_2-eq/OBC]	1.4	
GWP one 100 kW OBC per year [t CO_2-eq/year]	0.2	