38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Lifecycle and national inventory perspectives of Swedish road freight transitioning to net zero emissions

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Executive Summary

This study analyses what the net zero transition of the Swedish heavy truck fleet will mean for overall emissions reductions from a lifecycle perspective (globally) and for Sweden's national emissions inventory. The study considers direct tailpipe emissions and indirect emissions from fuels and vehicle production. The study provides a multi-layered perspective on how the transition of the Swedish heavy-duty transport fleet will potentially affect total emissions under different technological variables, and where emissions end up in terms of geographical regions. Results show the electrification of the Swedish truck fleet could be done without increasing emissions outside the country significantly, but that requires domestic low carbon steel and iron production as well as domestic battery production using renewable electricity. If carbon footprints of these components cannot be reduced significantly, there is a risk that vehicle production emissions will increase and end up in other countries' emissions inventories.

Keywords: Heavy Duty electric Vehicles & Buses, Environmental Impact, Life Cycle Analysis, Vehicle Manufacturing, Public Policy & Promotion

Nomenclature

BEV	Battery electric vehicle
EU ETS	European Union Emissions Trading Scheme
GHG	Greenhouse gas
GVM	Gross Vehicle Mass
H2 ICE	Hydrogen fueled vehicle with internal combustion engine
H2 FCEV	Fuel cell electric vehicle using hydrogen as fuel.
LBG	Liquified biogas
LCA	Life cycle analysis
WTT	Well to tank
WTW	Well to wheel

1 Introduction/Background

Sweden's long term climate target is to have no net greenhouse gas emissions by 2045 and to thereafter reach net negative emissions. Sweden also has a set of interim goals, of which one is to reduce emissions from domestic transports (excluding air transport) by 70% until 2030 compared to the 2010 level. The 2045 target is a sector wide target and includes flexibility mechanisms [15]. However, the Swedish Transport

Administration state that the long-term target means that the transport sector needs to reach zero emissions by 2045 or before [1]. In addition to the nationally set targets, Sweden also have targets according to the EU Burden sharing agreement according to which Sweden's emissions of greenhouse gas emissions by 2030 from the sectors not included in the EU ETS should be 63% lower than the level in 1990. For Sweden, meeting the national 2030 target for domestic transport will mean that also the target for 2030 according to the burden sharing agreement will be met.

1.1 Background

The study presented in this paper is part of a project where a set of target-fulfilling scenarios for the transport sector, meaning that the 2030 target, is met and that the transport sector will contribute its necessary share of fulfillment of the 2045 target. The scenarios include different shares of power trains and fuels and the indirect emissions from fuel and vehicle production are compared. The comparison analyses the total amount of emissions, where, geographically, they occur (in Sweden, in the EU or in rest of the world) and to which sectors they will be accounted for according to the common reporting format (CRF) in the national emissions inventory. The objective of the study is to highlight areas where overall reductions in greenhouse gases may lead to local emissions increases, in particular industrial sectors or geographic regions as well as consider possible policy implications.

In this paper the result for the road freight transport sector is presented. This includes heavy duty trucks (maximum weight > 3.5 tonnes) in Sweden. In Sweden heavy trucks contribute to 98% of road transport work (tonkm). Light duty vehicles only perform about 2% of the transport work and are used for a lot of other purposes than road freight [5].

2 Method

The study contains three parts:

1. Emissions inventory for the base year, set at 2019. The emissions inventory includes:
   a. direct transport emissions, i.e. emissions from tailpipe (tank-to wheel, TTW), which are based mainly on Swedish statistics and Sweden's national inventory
   b. upstream emissions for fuel/electricity production (well-to-tank, WTT), which mainly are based on reports from the Swedish Energy Agency [2,3] and on the Joint Research Centers WTW (well-to-wheel) report [6]
   c. upstream emissions for vehicle production mainly based on information from Swedish truck producers, supplemented by data from publicly available LCA-reports.
2. Scenario definition for target fulfilling direct emissions, stating fuel mixes/technologies applied for HDVs. The development of scenarios also included estimating developments for emissions intensities and emissions reductions for the indirect emissions, i.e. trucks, including production, maintenance and end-of-life, and fuels, including WTT emissions for fuel production.
3. Allocation of emissions into regions and countries of occurrence. Three geographic regions were used; Sweden, the EU+ EEA (including Great Brittain and Norway) and, the rest of the world (RoW).

The study presents direct emissions and direct emissions for 2019, 2030 and 2045. The fuel-related emissions (production etc.) are assumed to occur in the same year as utilization, i.e., the direct emissions. The vehicle-related emissions were annualized by just accounting for the new trucks put on the market in that specific year. All life cycle emissions related to production, maintenance and end-of life were then accounted for in that year.

2.1 Scenarios

The study includes one base case scenario and three additional scenarios for different developments regarding vehicle fleet and energy carriers (fuels) used by HDVs. All scenarios are fulfilling the targets of 70% emission reductions by 2030 and net zero tailpipe emissions in 2045.

The base case scenario is based on long-term scenario from the Swedish Energy Agency which the Swedish Environmental Protection Agency used in the national reporting to the EU and the governments climate accounting for 2024 [4] but have been adjusted in terms of energy use (biofuel and electrification share) to fulfill the mentioned Swedish national climate targets to 2030 and 2045 respectively. The base scenario includes a rapid electrification rate and hence the adjustments made to meet targets were mainly to increase the amounts of biofuels. In Scenario 1 the amounts of biofuels were increased further and thereby allowing for a slower rate in electrification. In Scenario 2 all biofuels were assumed to be produced in Sweden from domestic raw materials, and not as the current (and base year) situation where a significant part of the biofuels and raw materials are imported [3]. In Scenario 3 it was assumed that from 2030 onwards there will be an introduction of hydrogen trucks, both fuel cell electric trucks using hydrogen as energy source, (H2 FCEV) and trucks with an internal combustion engine using hydrogen, ICE-H2.

2.1.1 Fleet projection and energy carriers in the Swedish HDVs

To estimate indirect emissions from trucks the emissions associated with production, maintenance and end-of-life for new trucks that enters the Swedish truck fleet each year were considered. For the heavy trucks there are two producers, producing trucks in Sweden that together stand for over 85% of the market shares.

The life cycle emissions from trucks put on the Swedish market were estimated based on data from these manufacturers. A simplified methodology was used where emissions associated with the production of the most emissions-intensive components and process categories were estimated and then assumptions regarding the development in production technology of these components were used to make estimates of emissions of trucks produced in 2030 and 2045. For future emissions, two sets of assumptions were included, one where the production technologies and sourcing of components develop in accordance with ambitious development routes for emission reductions set by the manufacturers for the Swedish market and one where the development in production technologies of iron and steel and battery packs remains in a state of current conditions.

2.2 GHG emissions intensity of vehicle production

Estimations of emissions related to vehicle production were primarily based on 2023 lifecycle information provided by the two Swedish producers of heavy trucks. The information was provided in the form of emissions data for ICE and BEV trucks, broken down into nine common components and process categories – steel, cast iron, aluminium, plastics, elastomers, other materials (glass, copper, paint, textiles, adhesives), inbound logistics, maintenance, and recovery. For BEV trucks, one additional category for the battery cells was included. The vehicle producers also provided information on how to adjust the emissions estimates for trucks in three vehicle weight categories (further described in the subsection 'fleet segmentation' below). This information was complemented with additional data from publicly available LCA studies to harmonize differences between the information provided by the two producers. One of the truck producers also provided estimated emissions figures for truck production in 2030 and outlining the assumptions that underlined foreseeable sources of emissions reductions.

2.2.1 Fleet segmentation

The heavy truck fleet is segmented into three weight categories, based on Gross Vehicle Mass (GVM) – 16 tonnes, 28 tonnes, 40 tonnes. This segmentation was based on discussions with the two Swedish truck producers. While heavy trucks on Swedish roads can have higher Gross Combination Weights depending on the trailers and loads, they are pulling, this study's analysis of emissions from vehicle production only considers the primarily vehicle – tractors, rigid trucks and articulated trucks. Trailers and other aftermarket superstructures are excluded. For the BEVs different battery sizes were assumed: 300 kWh for 16 tonne GVM, 600 kWh for 28 tonne GVM, 900 kWh for 40 tonne GVM. The fleet analysis for new vehicles produced in 2019 and projections for 2030 and 2045 were also split into these three weight categories.

2.2.2 Emissions breakdown per vehicle

Figure 1 shows the total per vehicle emissions estimates for production, maintenance and end-of-life emissions for all three weight categories for the 2019 base year as estimated in this study. For the ICE vehicles, the increases in production emissions in the higher GVM trucks are due to marginal increases in the amount of steel, cast-iron and aluminium required. These material increases also apply to the BEVs, but the much larger increases for BEVs come from the larger number of battery cells required – 300 kWh, 600 kWh and 900 kWh respectively for the 16, 28 and 40 tonne GVM categories.

Table 1 shows the estimated production, maintenance and end-of-life emissions for a 16 tonne truck for all years, including the corresponding values for the sensitivity analysis where the use of Swedish-made batteries and green hydrogen-based iron and steel were not included (shaded in grey).

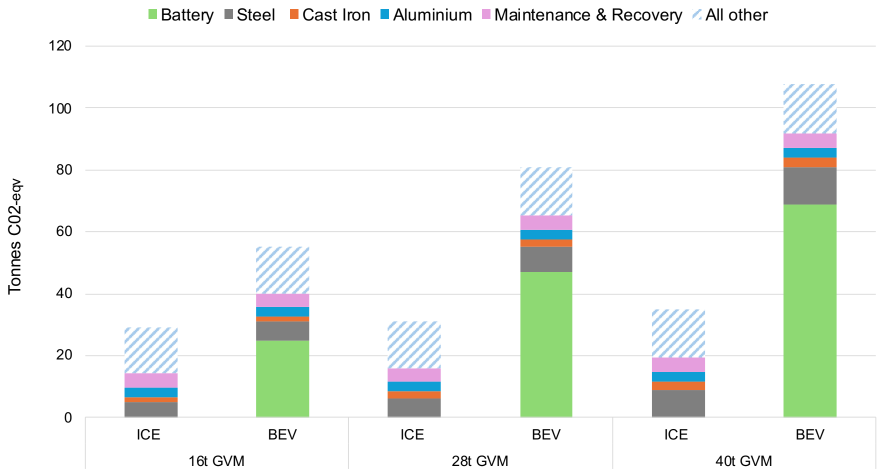

Figure 1. Emissions from production maintenance and end of life for the three HDV weight categories in 2019. The values in this diagram are per vehicle.

Table 1. Emission estimates for ICE and BEV trucks of 16 tonne GVM for 2019 and 2030 divided upon components and processes.

Emissions	**ICE** 16 tonne (assumes Swedish battery production and green hydrogen derived iron and steel from 2030 onwards)			**ICE** 16 tonne (assumptions for batteries, iron and steel kept at same level as in 2019)		**BEV** 16 tonne (assumes Swedish battery production and green hydrogen derived iron and steel from 2030 onwards)			**BEV** 16 tonne (assumptions for batteries, iron and steel kept at same level as in 2019)	
Tonne CO_{2e}/truck	**2019**	**2030**	**2045**	**2030**	**2045**	**2019**	**2030**	**2045**	**2030**	**2045**
Battery cells[a]	n.a.	n.a.	n.a.	n.a.	n.a.	25	3.3	2.8	25	21.9
Steel	5.2	1.6	0.4	5.2	5.2	6	1.8	0.5	5.2	5.2
Cast iron	1.4	0.5	0.2	1.4	1.4	1.6	0.6	0.2	1.4	1.4
Aluminium	3.1	1.9	1.2	1.9	1.2	3.1	1.9	1.2	1.9	1.2
Plastic	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Elastomers	0.7	0.7	0.7	0.7	0.7	1	1	1	1	1
Other[b]	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
Inbound logistics[c]	2.3	1.3	0	1.3	0	2.3	1.3	0	1.3	0
Maintenance[d]	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
End-of-life[e]	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
TOTAL	**29**	**22.4**	**19**	**26.9**	**24.9**	**54.3**	**23**	**19.3**	**27.2**	**25.2**

[a] Battery cells – the estimates only include battery cell production and does not cover the battery pack – which is excluded from the analysis.
[b] Other – this category includes glass, copper, paint, textiles, adhesives.
[c] Inbound logistics – includes estimations of transport emissions associated with the supply chain up to the point a vehicle is fully assembled. Emissions from transport of the vehicle to the end-customer is excluded.
[d]Maintenance – this category is limited to include tyre changes over the course of typical operations, assumed to be 500,000 km over the lifetime of the vehicle. Based on discussions with truck producers, non-tyre related maintenance was excluded due to the environmental insignificance (0.1-0.3% of life cycle) and the difficulty with defining an average maintenance because of the wide range of operations.
[e]End-of-life - is based on a generic model for a heavy-duty vehicle provided by one of the Swedish manufacturers. For the secondary materials emerging from vehicle recovery processes, no credits are considered. No second life of the battery is assumed, meaning that the full production burden is attributed to

the vehicle life cycle.

2.2.3 Emissions reductions over time

In estimating how per vehicle emissions from vehicle production changes for 2030 assumptions that affect the emissions intensity of battery cell production, steel and cast-iron production, aluminium production and inbound logistics were used. Based on discussions with the Swedish vehicle producers, three key assumptions were made that by 2030: i) battery cells for heavy vehicles would be produced in Sweden; ii) a significant proportion of the steel and cast iron in those vehicles would also be produced by green hydrogen processes in Sweden; and iii) a greater share of recycled aluminium would be used in vehicles. Information was received from one of these Swedish vehicle producers that helped us estimate the approximate range of the emissions reductions due to these three assumptions. This resulted in an approximate 86% reduction in the emissions intensity of battery cell production compared to 2019, 70% reduction from steel and iron ore, and 39% reduction from aluminium. Emissions from inbound logistics were estimated to be 43% lower compared to 2019 due to partial decarbonization of the transport vehicle fleet.

In 2045, no further reductions were assumed for battery cells. For steel and cast iron, 100% of the production was assumed to come from green hydrogen processes. In combination with an almost fully decarbonized Swedish electricity grid, this results in emissions for steel and cast iron that are further reduced by approximately 87% compared to 2030. For aluminium it was assumed that the use of recycled content would be further increased and in combination with less carbon intensive European electricity grid this results in an additional 40% emissions reduction compared to 2030. Emissions associated with inbound logistics are assumed to be zero, in line with Swedish national policy targets that tailpipe greenhouse gas emissions from transport will have been fully eliminated by this date. No assumptions were made about emissions reductions from plastics, elastomers, other, maintenance, and end-of-life for 2030 or 2045.

In Figure 2 the results of these assumptions and lowering emissions intensity per vehicle can be seen and compared across the three time periods 2019, 2030 and 2045. In addition, the impacts of two of the key assumptions made on emissions reduction – battery cells produced in Sweden and green hydrogen iron and steel production processes are displayed.

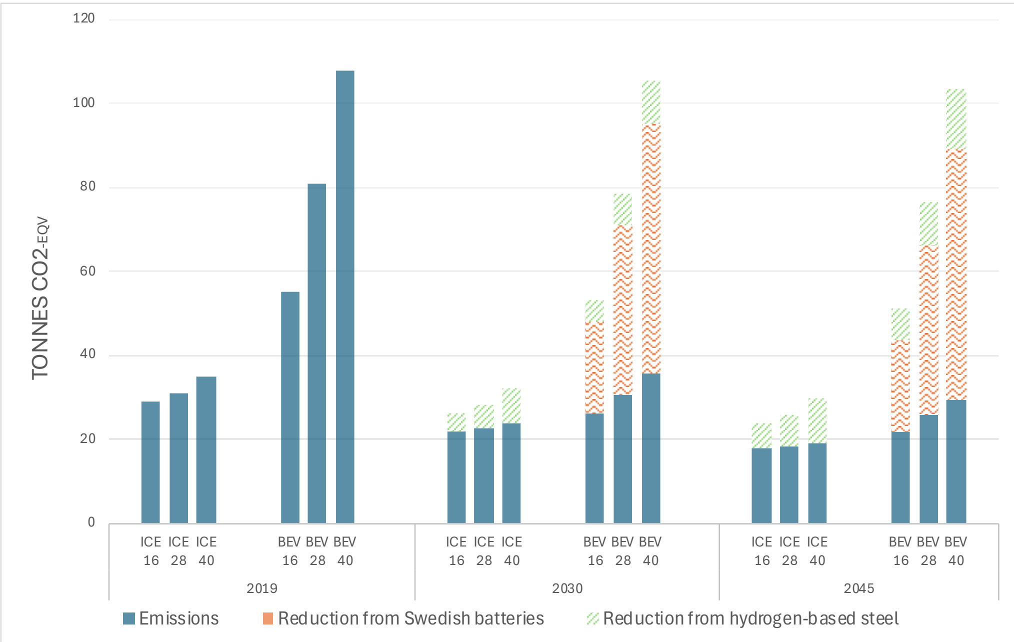

Figure 2 - Emissions per vehicle associated with production, maintenance and end-of-life for new HDV trucks (varying GVM, 16, 28 and 40 tonnes) in 2019, 2030 and 2045 respectively.

2.3 Direct GHG emissions (tail pipe emissions) from HDVs in Sweden

The direct emissions from the HDV trucks, tail-pipe emissions, for 2019 was taken from the Swedish national inventory [16]. For the scenario years, 2030 and 2045, the HDV tail pipe emissions were determined by the target fulfilling scenarios and are therefore the same for all four scenarios.

2.4 Upstream emissions from production of energy carriers (fuels/electricity)

Each scenario has a specific fuel mix for each of the scenario years, see Figure 3. To estimate the indirect emissions from fuels and electricity used by the vehicles, WTW emission factors were estimated. The estimates for the base year were based on the assessment by the Swedish Energy Agency [8]. For the future scenario years 2030 and 2045 respectively, assumptions regarding the development of the production of the fuel in terms of raw materials used, processes pathways and distribution were made, see Table 2. More details on how the WTW emissions were estimated divided upon the different production steps are provided in [12].

Table 2 Emission factors for fuels, (total emission factors and divided upon production steps).

	Emission factor g CO_{2e}/MJ_{fuel}			**References and comments**
	2019	**2030**	**2045**	
Diesel MK1[1], (excl. blend-in biofuels) total	80.3	79.0	76.2	The emissions factor for 2019 is the sum of combustion emissions and indirect emissions based on [10,11]. Reductions in transport and refining assumed over time, described in [12].
Diesel MK1 (excl. blend-in biofuels), TTW/use phase	73.6	73.6	73.6	The emission factor for 2019 includes carbon dioxide, nitrous oxide and methane and is collected from the Swedish national inventory [9]. Assumed to be constant over time.
HVO (mixed sources; tall oil, PFAD, palm oil, slaughterhouse residues), total	8.4	6.5	2.8	The value for 2019 is based on emissions factors for different production pathways from [6] and the actual mix in 2019 according to [2]. In 2045 it is assumed to be second generation fuels.
HVO (from mixed raw materials), TTW/use phase	0	0	0	Biobased carbon dioxide emissions are not accounted for. Nitrous oxide and methane emissions were considered negligible. Same assumptions for all biofuels.
FAME, (from mixed raw materials) total	27.8	23.6	11	The value for 2019 is based on the emission factor given in [3]. Assumed that the WTW emissions factor by 2030 can be 75% of that for the reference fuel.
FAME, TTW/use phase	0	0	0	Same assumption as for TTW/use phase of HVO.
Ethanol, total	28	5.5	2.5	The value for 2019 is based on values from [3] for ethanol used for all purposes. The value for 2030 is based on [3] for ethanol falling within the reduction mandate in 2021, but with further reductions in processing and distribution. The 2045 value is based on production from lignocellulose according to [13].
Ethanol, TTW/use phase	0	0	0	Same assumption as for TTW/use phase of HVO.
Biogas (LBG), total	18.3	13.1	3.6	Values for 2019 based on [3]. Until 2030 reductions are mainly due to lower emissions from electricity. By 2045 the raw materials will be forest residues and the biomethane produced by gasification. Estimates based on [6,17]
Biogas (LBG) use phase	1.4	1.4	1.4	Methane and nitrous oxide emissions from [14].
Electricity	13.0	3.5	0	2019 value based on [3]. Value for 2030 based on the assumption that it can be further halved compared to the level in 2021.

[1] MK1 is the Swedish fuel specification *miljöklass 1*, which is the one dominating the Swedish market and the diesel quality sold at all filling stations [7].

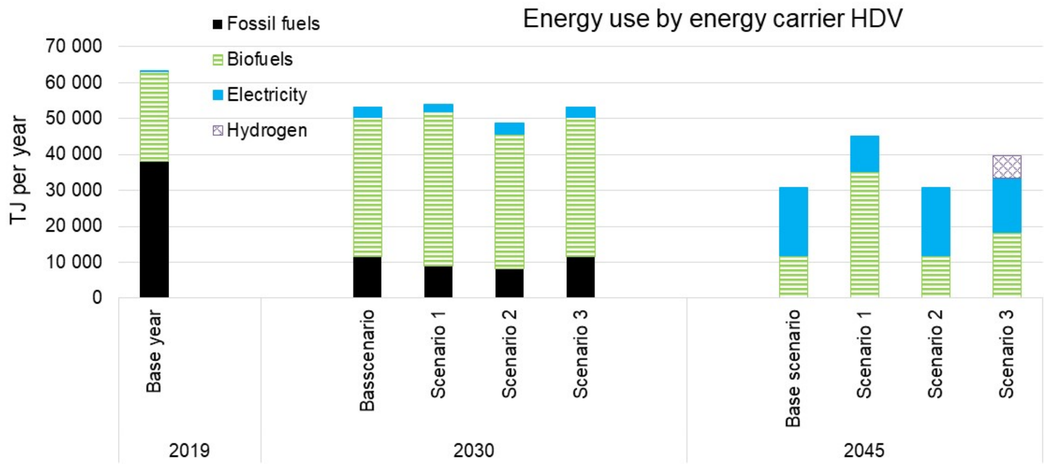

Figure 3 Fuel mixes for HDV in the different scenario-years and scenarios. Note that *fossil fuels* include diesel and for 2019 small amounts of petrol and natural gas whereas *biofuels* include HVO, FAME, ethanol and biogas and for 2019 also small amounts of bio-petrol.

2.5 Geographic divisions of emissions

Emissions from *vehicle production, maintenance and end-of-life* as well as from *upstream emissions from production of energy carriers* have been assigned to three different geographic regions, depending on where they are estimated to be emitted. The three geographic regions included were Sweden, EU (including EEA countries) and Rest of the World (RoW).

2.5.1 Vehicle production, maintenance and end-of-life

An approximated division of emissions into geographic regions was provided by one of the Swedish truck producers. For the study it was assumed that this division holds true for the broader fleet mix of heavy trucks registered in Sweden. The division was provided to from the producer at the component and process category level. In most cases, the emissions from a component and process category were attributed to only one region, except for inbound logistics, elastomers, and battery cells. Inbound logistics emissions were evenly split between Sweden and EU given that these two regions are responsible for overwhelmingly majority of emissions from components and processes in general. Emissions from elastomers were split between EU (production of tyres) and rest of the world (growing of rubber). For battery cells, emissions from 2030 onwards are split between Sweden (cell production) and rest of the world (mining and processing of raw materials). Table 3 shows the country-split of emissions for HDV components and processes for a battery electric truck in 2030.

Table 3 Geographical split of emission estimates for a BEV truck components and processes in 2030 as used in this study.

Heavy duty vehicles - BEV 2030			
Component & process	**Sweden**	**EU**	**Rest of the world**
Battery cells	70%		30%
Steel	100%		
Cast iron	100%		
Aluminium		100%	
Other (glass, copper, paint, textiles, glue, etc.)		100%	
Plastic			100%
Elastomers		25%	75%
Inbound logistics	50%	50%	
Maintenance (tire replacement)		25%	75%
End-of-life	100%		

2.5.2 Upstream emissions from production of energy carriers

The geographic split of the indirect emissions from the upstream production of fossil and bio-based fuels used by the trucks was also estimated. Direct emissions occur in Sweden given that they operate in Sweden (which was the scope of the study). The emission estimates for raw materials production for 2019 were based on the assessments in [2,3]. Sweden has no domestic crude oil extraction, but almost all fuels sold for road vehicles are refined in Sweden. So refining emissions were assumed to occur in Sweden. Geographic location for emissions from crude oil extraction was based on imports in 2019 and for future years it was assumed to stay with a similar division upon the three regions as in 2022, see Table 4. This is a very rough and uncertain estimate since history shows that there have been rapid changes in the sourcing of the crude oil imports to Sweden. For biofuels different assumptions were made for the different biofuels depending on the situation in 2019 and trends to 2022 as well as expected changes in raw materials due to changes in production processes. Table 5 shows the assumptions for the origin of the biofuels in this study.

Table 4 – Geographic origin of crude oil imports to Sweden in 2019 and 2022 and assumptions for 2030, 2045.

		Summarised statistics		Assumptions	
Regions		**2019**	**2022**	**2030**	**2045**
EU +EEA (in 2019: Norway, Denmark, UK)		49	79	80	80
RoW	Africa & Middle-East (Nigeria, Iran)	17	11	10	10
	Americas (USA, Venezuela)	8	8	10	10
	Russia	26	2	0	
Total		100	100	100	100

Table 5 – Geographic origin of feedstock biofuels used in Sweden in 2019, 2022 and assumptions made for 2030, 2045 for base case scenario and scenario 1 and 3. For scenario 2 all biofuels were assumed to sourced from Sweden.

	Share of origin of HVO used in Sweden [%]			
	Statistics		**Assumptions**	
Regions	**2019** / **2021**	**2030**	**2045**	
Sweden	5	11	40	70
EU (+EEA)	41	58	60	30
Rest of the world	54	32		
Total	100	100	100	100
	Share of origin of FAME used in Sweden [%]			
	Statistics		**Assumptions**	
Region	**2019**	**2021**	**2030**	**2045**
Sweden	7	4	5	20
EU (+EEA)	56	42	45	50
Rest of the world	37	54	50	30
Total	100	100	100	100
	Share of origin of biogas, (LBG) used in Sweden [%]			
Region				
Sweden	71	65	65	65
EU (+EEA) (mainly Denmark)	29	32	35	35
Rest of the world	0	3	0	0
Total	100	100	100	100
	Share of origin of ethanol used in Sweden [%]			
	Statistics		**Assumptions**	
	2019	**2022**	**2030**	**2045**
Sweden	13	25	25	75
EU (+ EEA)	50	13	25	25
Rest of the world	37	62	50	0
Total	100	100	100	100

3 Results

The results of the direct and indirect emissions shown in Figure 4 show that emissions of vehicle production do not increase significantly over time, except for in the sensitivity analysis where the battery production and the steel production was not assumed to be less emission intensive in the future. The results in Figure 5 show that in the sensitivity analysis emissions increases due to vehicle production also would occur outside of Sweden. The assumptions based on the vehicle manufacturers were that green steel (low emissions intensity) would be produced in Sweden along with batteries of very low emissions intensity in the production mainly due to the very low emissions of the Swedish electricity mix.

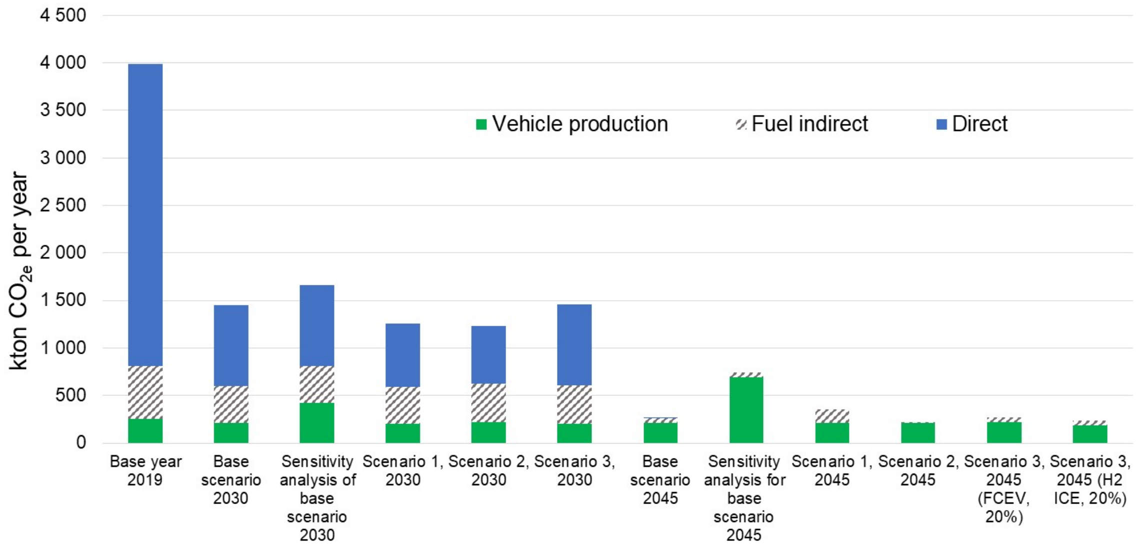

Figure 4 Direct and indirect emissions from Swedish road freight (heavy trucks) in the base scenario, and with a sensitivity analysis in which battery and steel production remains at base year level, along with the other three scenarios. Emissions include tail pipe emissions as well as emissions associated with vehicle production, maintenance and end-of-life and of production of fuel/energy for the use phase.

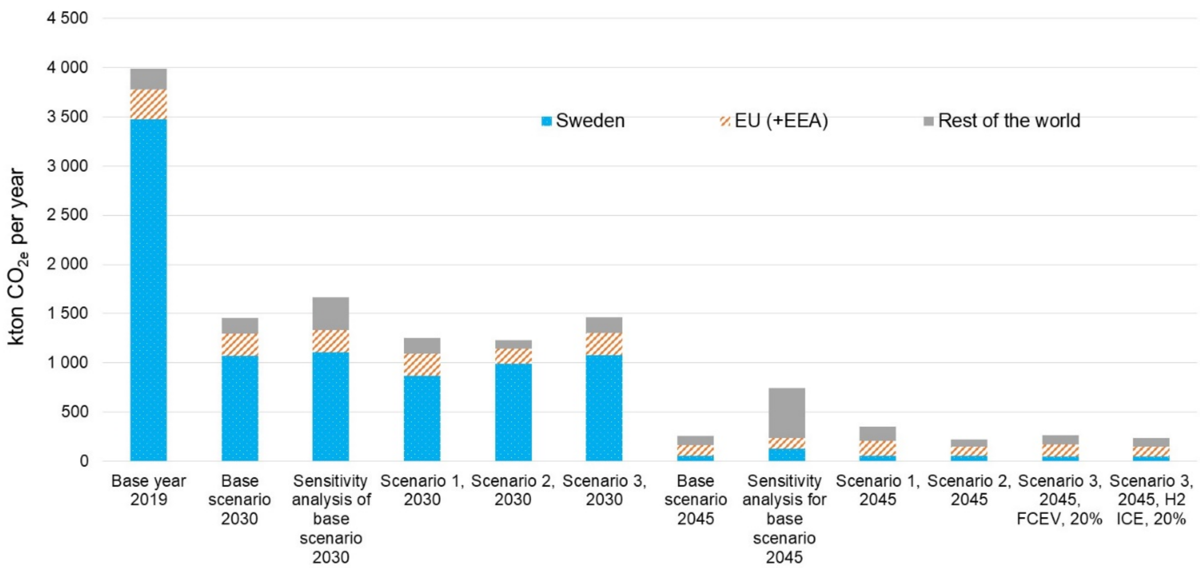

Figure 5 Direct and indirect emissions for Swedish road freight (heavy trucks) divided upon geographical regions. Emissions include tail pipe emissions as well as emissions associated with vehicle production, maintenance and end-of-life and production of fuel/energy for the use phase.

The indirect emissions from fuel and energy production for the use phase of the trucks is very low in all scenarios in 2045. This is due to the assumption that the electricity production will reach net zero emissions in 2045. However, Figure 3 shows that there is a significant amount of electricity being used, and if the emissions factor of the electricity mix would stay at the 2030 level, the fuel production emissions in base case 2045 would be 67 ktons.

4 Discussion

The results show that the transition of the Swedish road freight, i.e. heavy duty trucks towards net zero tail pipe emissions could be done without significant emission increases from vehicle production, but this requires that the production processes of important components and materials like iron and steel and batteries can be produced with low carbon footprints. If production processes for green steel and iron will not come to market and if the carbon footprint of electricity used in battery production will not decrease significantly from the current levels, there is a risk that the electrification of the transport sector will increase vehicle production emissions significantly, and these increases in greenhouse gases will occur in other countries.

In addition, even in a country like Sweden where the carbon footprint of the electricity mix is already among the lowest, it is important the carbon footprint continues to decrease in order to be capable of meeting the net zero emissions targets.

In the larger study of which this paper is only one part, the carbon policies in countries and for sectors where the transition will cause increases are studied. It is important to understand how emissions reducing strategies in one country or region impact the emission levels in other parts of the world.

Acknowledgements

This project has been financed by the Triple F Programme https://triplef.lindholmen.se/triple-f-working-together-fossil-free-freight-transport-system which is hereby acknowledged for the support.

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Presenter Biography

Bobby is an electromobility researcher at the Research Institutes of Sweden (RISE). He holds a Bachelor of Law from the University of New South Wales and a Master of Environmental Management and Policy from Lund University. His work involves partnering with industry and public institutes to solve practical and policy problems to do with charging infrastructure, including vehicle-to-grid, resilience and public policy.

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