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GHG emission comparison of low carbon propulsion alternatives for heavy-duty long haulage

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Summary

This study compares the greenhouse gas (GHG) emissions of low carbon propulsion alternatives for heavy duty long-haulage trucks. The comparison adopts a well-to-wheels (WtW) perspective for the energy/fuel consumption, but also includes battery production. Results show that the availability of electricity produced by low- and zero carbon emission technologies is very important for the sustainable development of heavy road transport since the GHG emission performance of BEV, ERS, FCEV and electrofuels are strongly dependent on this. Further, the relative mobility costs are very sensitive to carbon-based policy instruments related to the GHG intensity of the energy carriers.

Keywords: heavy duty, alternative fuel, electric vehicle, emissions, sustainability

1 Background

The electrification trend is strong in the light vehicle segment, and the battery electric vehicles (BEV) are gaining significant market shares. For heavy-duty long haulage, the choice of zero emission technology is still more open. This study compares different low carbon alternatives for long haulage heavy duty trucks in terms of greenhouse gas (GHG) emissions from a well-to-wheel (WtW) perspective. The alternatives include several biofuels (liquid and gaseous) and different production pathways for these, battery electric vehicles (BEV) using static charging (depot or public fast charging) or dynamic charging (electric road system (ERS)), fuel cell electric vehicles (FCEV) using hydrogen as energy carrier and several electrofuels, see Table 1. The GHG comparison is also used for analysing the impact of a CO_{2e}-price related to the energy carrier of the vehicle on the relative mobility costs as calculated in [1]. The CO_{2e}-related cost is hypothetical at current policy framework, but as an example there is a proposal of including road transports and buildings in the EU ETS (emissions trading scheme) together in a new separate cap. This proposal was communicated by the EU Commission in summer 2021 [2] and could be one way to introduce a CO_{2e}-price for emissions related to fuel/energy carrier in road transport.

2 Objectives and delimitations

The objective of the study is to compare the GHG emissions for different propulsion alternatives for heavy duty long haulage vehicles. The GHG emission comparison includes emissions related to the energy/fuel consumption for propulsion and considers the upstream emissions from producing the fuels/energy carriers as well as combustion emissions. For biofuels, the combustion emissions are assumed to be compensated by the uptake during growth. Further, emissions from land use change were not considered. The comparison includes the battery production (for electrified vehicles). The GHG estimates for the fuels /energy carriers of the different alternatives are also used to evaluate the impact on the relative mobility costs of introducing a CO_{2e}-cost. The study has a time perspective of 2030 and a Swedish perspective, in the sense that e.g., the conditions for implementation of ERS are based on Swedish conditions. The default emission factor for electricity used in the GHG analysis is based on an estimate for Swedish conditions in 2030. However, many of the results are applicable also in a European context and a sensitivity analysis using an estimated GHG intensity for European electricity mix in 2030 is included.

Table 1: Fuels and powertrains included.

Fuel	Description
Diesel	Fossil. Internal combustion engine (ICE) vehicle with compression ignition (CI)
DME	Dimethyl ether from biomass gasification or as electrofuel. ICE-vehicle with CI
ED95	Ethanol from, straw or sugar cane. ICE vehicle, dual fuel 5 % ignition improver
HVO	Hydrogenated vegetable oil, in this study from tall oil. ICE vehicle with CI
RME	Fatty Acid Methyl Esther from rapeseed oil. ICE vehicle with CI
Fischer-Tropsch (FT)-diesel	Synthetic diesel from gasification of biomass or as electrofuel. ICE vehicle with CI
BEV	Battery electric vehicles with a small (600 kWh) or large (1000 kWh) battery
ERS, cat or ind.	Electric road system compatible vehicle with overhead catenary (cat) or inductive (ind.) technology. 250 km range outside ERS-system
H2-FCEV	Hydrogen from electrolysis. Fuel-cell electric vehicle.
LBG/LNG (SI) or HPDI (CI)	Liquefied biogas/natural gas (LBG/LNG) vehicle with spark ignition (SI) engine or with high-pressure direct injection system with common rail injection HPDI.
CBG/CNG (SI)	Compressed biogas/natural (CBG/CNG) gas vehicle with SI engine. For both CBG and LBG cases the biogas is assumed to be produced from gasification of waste wood or via anaerobic digestion of biowaste and manure. LNG and CNG are fossil gas.

3 Methodology and data

The comparisons are made for a heavy-duty truck in 2030 with a maximum permissible weight of 40 tons (HGV40) performing long haulage missions (~640 km/day).

Although there are long term goals (for e.g., 2050) of net zero emissions for all sectors, this will not be reached by 2030. For that reason, the calculations in this study are based on estimated emission for e.g., electricity production in 2030. This means that from a well-to-tank (WtT) -perspective electrified alternatives will not be zero by 2030.

3.1 Estimates of WtW GHG emissions

The calculated GHG emissions (g CO_{2e}/vehicle-kilometre (vkm)) for the different propulsion alternatives are based on emission factors for the different energy carriers/fuels and on estimates of fuel consumption. The estimated energy/fuel consumption for the different alternatives are the same as in [1], originally based on estimates for 2025 [3] and estimates of yearly energy efficiency improvements.

Emission factors used in the calculations and ranges of these estimates along with data sources are given in Table 2. The emission factors for liquid and gaseous fuels are based mainly on the typical values given in Annex V of RED II [4]. The emission factor for Swedish electricity mix in 2030 (used electricity) is estimated based on the method presented by [5], using data on import and exports to Sweden in 2018 [6] and estimated emission factors for the electricity generation of the concerned countries in 2030 based on data from EEA for 2018 and 2020 ([7], [8]) and the assumption that reduction rates in carbon intensity will be the same in 2020-2030 as for the period 2010-2020. Based on the two EEA datasets a higher and lower value was calculated and the average of the two, 5.0 g CO_{2e}/MJ, was used for the carbon intensity of the Swedish electricity mix. The estimated emission factor of the European electricity mix in 2030 is the average between the estimated value of 74.5 g CO_{2e}/MJ by [9] and the estimated value of 30.6 g CO_{2e}/MJ, which, according to [8] is required for Europe to fulfil the 55% reduction target. The emission factors for the electrofuels are based on the estimated value for Swedish electricity mix and the electricity demand according to [10]. The low and high GHG emission estimates for battery production; 61and 106 kg CO_{2e}/kWh battery pack capacity respectively, are based on [11].

Table 2: Emission factors for energy carriers used in GHG comparison

Fuel	Used value g CO_{2e} / MJ	Min/ max values	Reference
Fossil diesel	94.0		Fossil reference according to RED II, Annex V Table A [4].
DME (gasification)	13.2	6.2 /16.8	RED II [4]. typical value for stand-alone unit using forest residues.
CBG (gasification)	9.2	7.8 / 12.3	Gasification of forest residues in stand-alone unit [12], incl. addition according to [4] for biomethane used in transport.
LBG (gasification)	12.4	11 /15.5	Forest residues according to [12]. Addition for lique-faction according to [13].
Swedish electricity mix	5.0	2.6 / 7.3	Own estimate for 2030 based on [5-8].
European electricity mix	52.5	30.6 /74.5	Max value for 2030 from [9], min value based on [8]
ED95 (sugar cane)	27.7		Typical value according to [4] 95 %; 5% renewable diesel[a]
ED95 (straw)	14.3		Typical value according to [4] 95 %; 5 % renewable diesel[a].
CBG (anaerobic digestion)	1.9	-100 / 13.2	Own estimate based on typical values from [4] and assuming a mix of manure (10%) and biowaste (90%). Min corresponds to value for 100% manure, and max corresponds to 100% biowaste according to [4].
RME	32.1	32.1 / 45.1	Swedish value from [14], the typical value from [4] here, as max will not be considered sustainable in 2030.
HVO diesel (tall oil)	17.8	17.8 / 46.7	Both values from [12]. Min value for tall oil-based production and max value based on rapeseed oil.
LNG (fossil)	78.9		Based on [15-16] and [13].
CNG (fossil)	72.4	67.6 /72.6	Used value from [13], min and max values based on [9]
Electrofuels; Swedish, (European) electricity mix			Electricity demand based on [10]
DME	9.4	(138.6)	
CBG	11.0	(146.9)	Addition according to [4] for use in transport
LBG	14.3	(148)	
FT-diesel	10.2	(151.3)	Addition according to [13] for liquefaction.
H2 (hydrogen)	7.2	(111.0)	

[a] The renewable diesel is used as an estimate for the GHG intensity of a renewable ignition improver. Ignition improver is the main component in the 5% addition in the ED95.

3.2 Cost comparison considering CO_{2e}-cost for WtW GHG emissions

The WtW emission factors for the energy carriers are also used in the cost comparison together with the relative mobility costs (based on [1]). The relative mobility costs include vehicle investment and maintenance, energy, energy distribution and infrastructure costs. It does not include salary costs (driver) nor costs for tyres and insurances. The CO_2-cost was set at the level of the Swedish CO_2- tax (in 2018) applied for fossil fuels, 1.16 SEK_{2018}/kg (~113 $€_{2018}$/ton). No other taxes were included.

4 Results

The results of the GHG comparison (see Fig. 1) considering only the WtW emissions of the energy carrier (green and yellow bars) show that: the CBG (digestion) has the lowest emissions followed by the ERS, BEV and the LBG (digestion). The FCEV alternative is very close to these alternatives and its exact ranking is highly dependent on the GHG intensity of the electricity used for the hydrogen production. These results are valid for the electrified alternatives if a Swedish electricity mix is considered. If considering a European electricity mix (yellow bars), and not considering the contribution of emissions from the battery production, puts RME and ED95 in between ERS ind. and the BEVs. If considering the contribution of the battery production the ERS and BEV-cases have higher levels of GHG emissions than all included biofuels (liquid and gaseous) except for RME which comes in-between the large and small battery case.

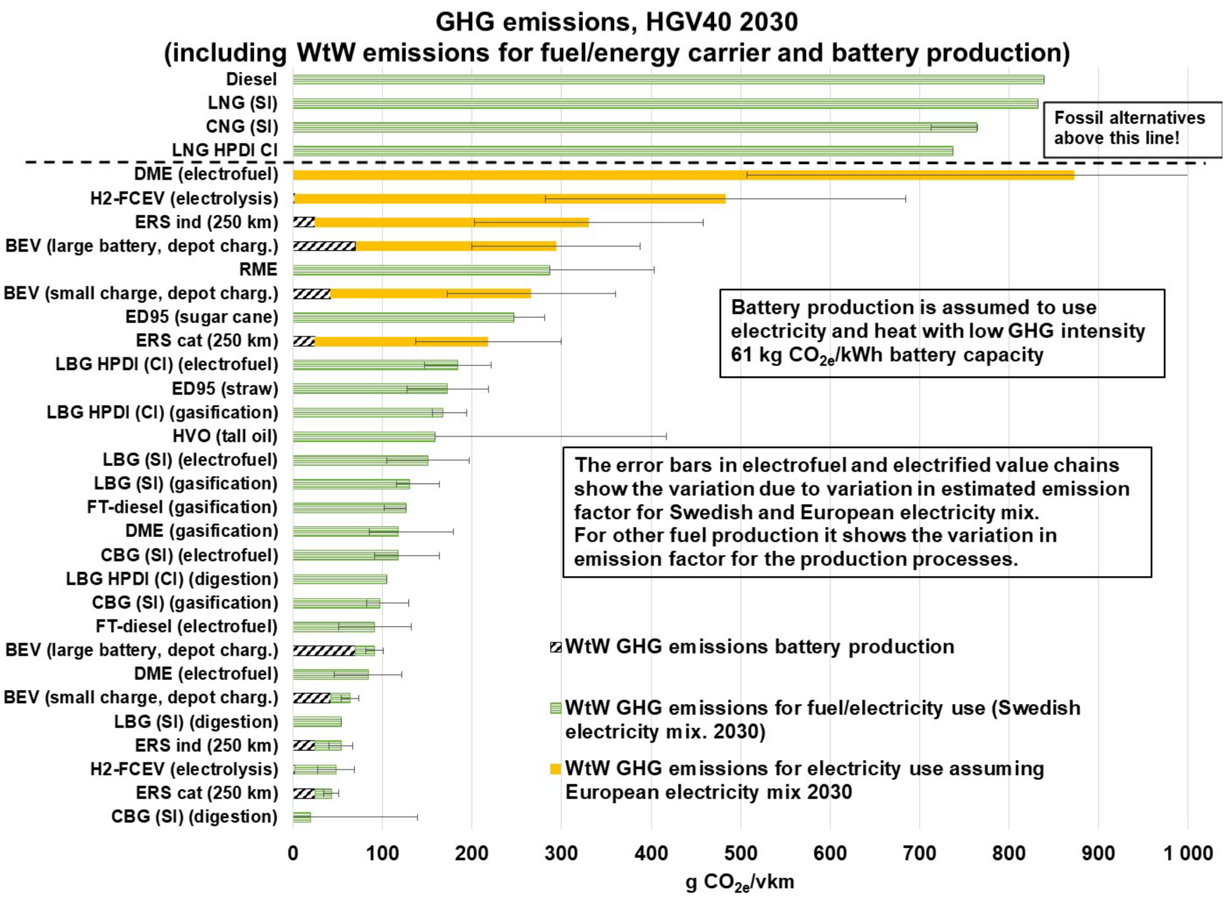

Fig. 1: Estimated greenhouse gas emissions for different propulsion alternatives for heavy duty long haulage trucks including energy utilisation from a WtW-perspective, battery production (in cases of electric propulsion) for 2030. Cases including yellow staples are results for alternatives with significant amounts of electricity used for propulsion or fuel production (electrofuels), applying an emission factor corresponding to estimated European electricity mix in 2030. Note that the error bar CBG (SI) extends to negative values (CO_{2e} credits from digestion) and the error bar for DME (electrofuel) extends to above 1200 but are cut off for readability reasons.

If - in addition - battery production is considered (black and white striped bars in Fig. 1) the analysis shows that:

- The impact of GHG emissions associated with battery production is significant for BEV and ERS cases, even if battery production is assumed to use low emission energy.
- For BEVs, in a case with Swedish electricity mix, the contribution to the overall GHG emissions from the battery production is more significant than the electricity used for propulsion of the vehicle.
- The ranking is altered and both BEVs (large and small battery) are showing higher GHG intensity than the FCEV, and the DME (electrofuel) has lower GHG intensity than the BEV with large battery (referring to cases based on use of Swedish electricity for charging/fuel production).

If the higher end of the GHG emissions from battery production is considered (as shown in Fig. 2) the results show that:

- The ERS cases (with Swedish electricity mix) shows higher emissions than the H2-FCEV and LBG (SI) digestion
- The BEV with the small battery (using Swedish electricity mix for propulsion) shows higher emissions than electrofuels (DME and FT)
- The BEV with the large battery turns worse than several of the biofuels from gasification.
- The impact of considering higher emissions from the battery production on the H2-FCEV is small since the size of the battery in this vehicle is assumed to be small.

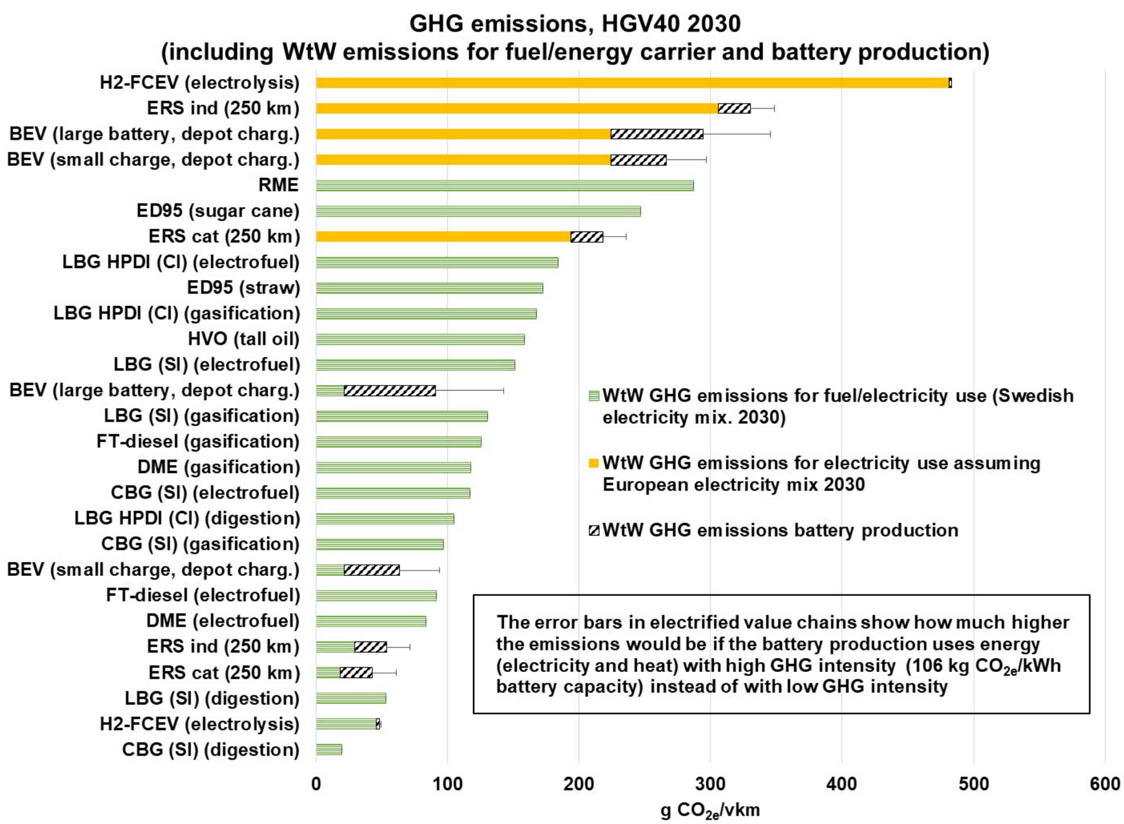

Fig. 2: Estimated GHG emissions for different propulsion alternatives for heavy duty long haulage trucks including energy utilisation from a WtW perspective and battery production (in cases of electric propulsion) for 2030. Indicating variation for CO_{2e} emission intensity of battery production. Note that the ranking of the alternatives in the figure is based on the higher end of the error bars to show the ranking if the battery production uses energy with high GHG intensity.

Note that in Fig. 1 the sensitivity analysis with European electricity mix was done only for the electrofuel with the lowest specific electricity demand (DME). All the other electrofuels will have even higher emissions than the DME case.

The analysis of the impact of a CO_{2e}-price for WtW GHG emissions of the energy carrier (*Fig. 3*) shows that:

- Adding a WtW-based CO_{2e}-cost for the energy carrier impact the ranking of the alternatives significantly.
- At a CO_{2e}-cost of 113 €/ton CO_{2e} the following low-carbon/non-fossil alternatives have lower relative mobility costs than diesel in 2030: BEV, conductive ERS, DME (produced by gasification), ethanol (from sugar cane), RME, HVO, CBG (both produced by gasification and by digestion), LBG (SI) (digestion-based).

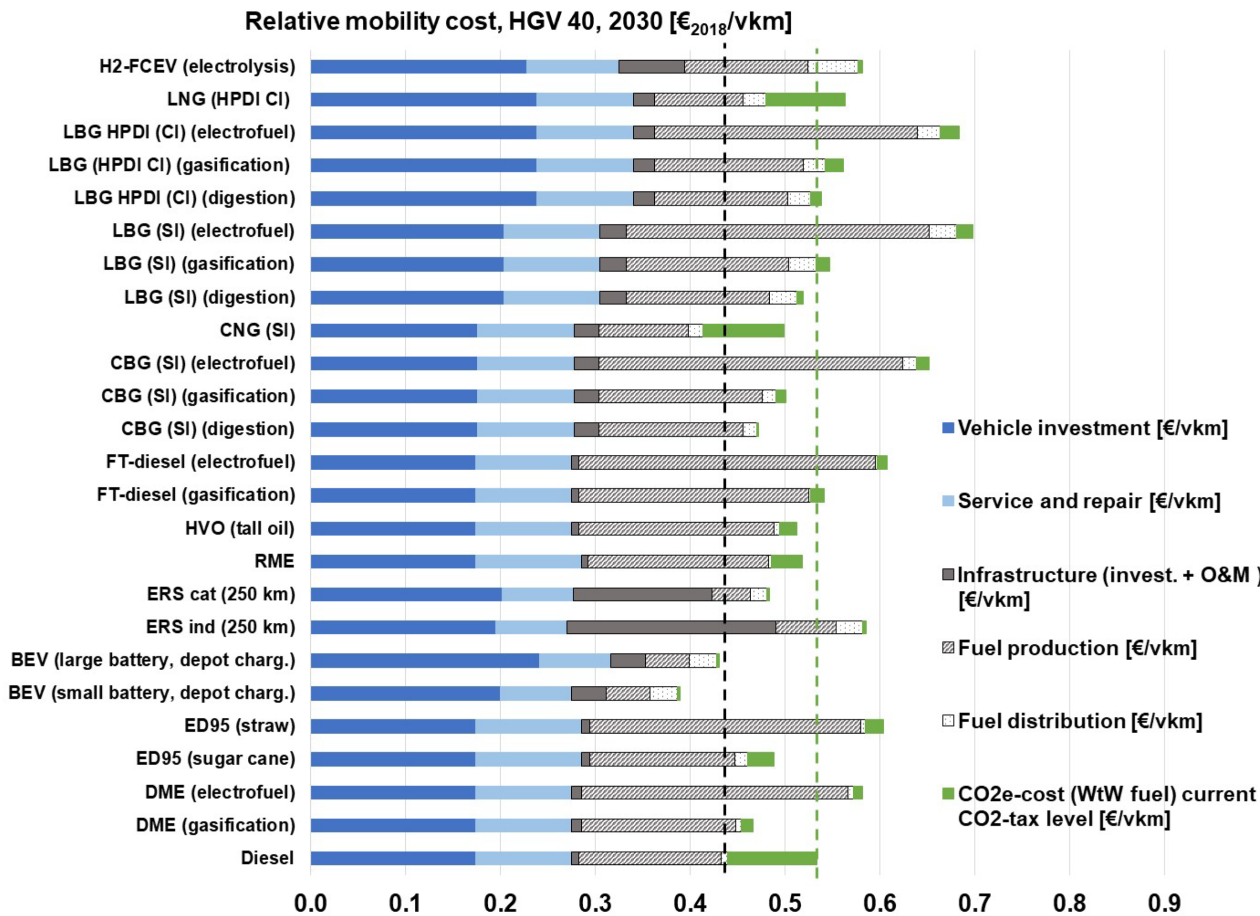

Fig. 3: Relative mobility cost for HGV40 in 2030 including CO_{2e}-cost (at a level of 113 $€_{2018}$/ton). The electricity was associated with the GHG intensity of Swedish electricity mix estimated for 2030. The black dotted line shows level of the relative mobility cost for the diesel case without the CO_{2e}-cost and the green dotted line shows the corresponding level for the diesel case with the CO_{2e}-cost included.

5 Discussion and conclusions

The original study upon which the present work is based [17], and where a slightly higher emission factor for the Swedish electricity mix was used, showed different results, in particular for the electrofuels which show better GHG intensity performance in the present work. Further, the values marked here as low for the emissions associated with battery production might be high estimates. Based on a more recent study [18] the GHG intensity of car battery production in 2021 was 31-57 kg CO_2/kWh in Europe and 51-77 kg CO_2/kWh in China, and further improvements can be expected until 2030. This would further improve BEV and ERS alternatives compared to the other alternatives.

The results show that the availability of electricity produced by low- and zero carbon emission technologies is very important for the sustainable development of heavy road transport since the GHG performance of BEV, ERS, FCEV and electrofuels are strongly dependent on this.

The results also shows that biofuels also can contribute to significant reductions of GHG emissions. The biofuel production is not as dependent as the other alternatives on the availability of renewable electricity.

The CO_{2e}-cost level used in the paper can seem high, but in early February this year, the price of the EU ETS allowances reached an all-time high of almost 95 €/ton which is not so far from that. The power sector is included in the EU ETS.

From the results in Fig. 3 it can also be seen that if the added CO_{2e}-cost would be lower, e.g., half of the suggested level, it would still make several of the alternatives cheaper than diesel. It is also worth noting that the two BEV options already are estimated to be cheaper than diesel without the added CO_{2e}-cost.

The relative mobility costs are very sensitive to carbon-based policy instruments related to the GHG intensity of the energy carriers.

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References

[1] K. Holmgren, S. Heyne; J. Takman, *Cost Structures of Fossil Free Alternatives for Long Haulage Road Freight Transport*, 5th Interdisciplinary Conference on Production, Logistics and Traffic, Darmstadt, Germany, 17-18 March, 2021

[2] EU Commission, *'Fit for 55': delivering the EU´s 2030 Climate Target on the way to climate neutrality*, EU COM 2021/550/final, Brussels, July 14th 2021

[3] M. Röck, M. Rexeis, S. Hausberger, *Tank to wheels report - Heavy duty vehicles,* FVT128/18/Rö EM-I2017/29, JRC/JEC, 2018.10.31

[4] EU Commission, *Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast)*, Brussels, Belgium, 2018

[5] A. Moro, L. Lonza, *Electricity carbon intensity in European Member States: impacts on GHG emissions of electric vehicles*, Transportation Research Part D, doi.org/10.1016/j.trd.2017.07.012, 64(2018), 5-14

[6] SEA, *Energiläget 2019 – en översikt,* ET 2019:2, Swedish Energy Agency, Eskilstuna, Sweden, 2019

[7] EEA, *Greenhouse gas emission intensity of electricity generation in Europe*, European Environmental Agency, ENER038, Copenhagen, Denmark, 2020

[8] EEA, *Greenhouse gas intensity of electricity generation in Europe*, European Environmental Agency, 2021-11-18, www.eea.europa.eu/ims/greenhouse-gas-emission-intensity-of-1 , accessed on 2022-04-22

[9] M. Prussi, et al., *JEC Well-To-Wheels report v5,* doi.org/10.2760/100379, Publications Office of the European Union, Luxembourg, 2020

[10] P. Bokinge, et al., *Nordic P2X for Sustainable Road Transport*, Nordic Energy Research, Oslo, Norway, 2020

[11] E. Emilsson, L. Dahllöf, *Lithium-Ion Vehicle Battery Production - Status 2019 on Energy Use, CO_2 emissions, use of metals, products environmental footprint, and recycling*, C444, IVL Swedish Environmental Research Institute Ltd, Gothenburg, Sweden, 2019

[12] E. Furusjö, J. Lundgren, *Utvärdering av produktionskostnader för biodrivmedel med hänsyn till reduktionsplikten*, 2017:17, f3 The Swedish Knowledge Centre for Renewable Transportation fuels, Gothenburg, Sweden, 2017

[13] D. Hagos, E. Ahlgren, *Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures – Perspectives on gas in transport in Denmark,* Transportation Research Part D: Transport and Environment, https://doi.org/10.1016/j.trd.2018.07.018, 65(2018), 14-35

[14] SEA, *Drivmedel 2018 - Redovisning av rapporterade uppgifter enligt drivmedelslagen, hållbarhetslagen och reduktionsplikten*, 2019:14, Swedish Energy Agency, Eskilstuna, Sweden, 2019

[15] H. Carlsson, *Emissionsfaktorer - För sjöfart och inlandssjöfart – Version 1.0 Slutversion* M4Traffic, Stockholm, Sweden, 2019

[16] S. Brynolf, *Environmental Assessment of Present and Future Marine Fuels* Chalmers University of Technology, Gothenburg, Sweden, 2014

[17] K. Holmgren et al., *Fossilfri framdrift för tunga långväga godstransport på väg - kostnadsfördelning och risker för olika aktörer,* FDOS 12:2021, f3 Swedish Knowledge Centre for renewable fuels, Gothenburg, Sweden, 2021. [In Swedish with English summary]

[18] B. Georg, *A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars*, ICCT The International Council on Clean Transportation, Berlin, Germany, 2021

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