REPORT f3 2018:12

SYNTHESIZING LCA REPORTS ON FUELS FOR HEAVY DUTY TRUCKS

Report from an f3 project

July 2018

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THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

PREFACE

This report is the result of a collaborative project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). f3 is a networking organization, which focuses on development of environmentally, economically and socially sustainable renewable fuels, and

- Provides a broad, scientifically based and trustworthy source of knowledge for industry, governments and public authorities,
- Carries through system oriented research related to the entire renewable fuels value chain,
- Acts as national platform stimulating interaction nationally and internationally.

f3 partners include Sweden's most active universities and research institutes within the field, as well as a broad range of industry companies with high relevance. f3 has no political agenda and does not conduct lobbying activities for specific fuels or systems, nor for the f3 partners' respective areas of interest.

The f3 centre is financed jointly by the centre partners and the region of Västra Götaland. f3 also receives funding from Vinnova (Sweden's innovation agency) as a Swedish advocacy platform towards Horizon 2020. f3 also finances the collaborative research program Renewable transportation fuels and systems (Förnybara drivmedel och system) together with the Swedish Energy Agency. Chalmers Industriteknik (CIT) functions as the host of the f3 organization (see www.f3centre.se).

ACKNOWLEDGEMENT

The report is based on ongoing research projects financed by the Swedish Energy Agency, which are hereby acknowledged.

This report should be cited as:

Cañete Vela, I. et. al., (2018) *Synthesizing LCA reports on transport fuels for Heavy Duty Trucks*. Report No 2018:12, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden. Available at www.f3centre.se.

SUMMARY

Road freight vehicles are key economy enablers, they are employed for the movements of goods, such as food, electronics or raw material. Today's road freight vehicles are mainly fuelled with diesel and use a significant fraction of the global fossil oil production. Without further policy efforts, oil demand from road freight vehicles is projected to increase considerably. Measures to lower greenhouse gas emissions from road freight vehicles include the use of renewable fuels, electrification and the use of fuel cells. All of these alternatives seem viable for medium size distribution trucks, but for heavy duty long-haul trucks the possible alternatives to diesel are less clear.

Life cycle assessment (LCA) can be an important tool to guide policymakers and the direction of technology development. However, from the studies examined in this work, it was recognized that available LCA studies on road freight vehicles do not sufficiently support decision making. Most studies are limited, and therefore, results from different studies are difficult to compare and lead to different recommendations. Problems identified in present studies are: (1) there is only a limited number of available reports on trucks, (2) the definition of the vehicle is unclear, (3) different approaches and system boundaries are applied, (4) studies are focusing on the present situation and do not include future considerations. Furthermore, available studies are typically limited by not including equipment life cycle, end of life, analysis of resource depletion and cost.

Since there is no simple solution to lower greenhouse gas emissions from heavy duty transport it seems obvious that more LCA studies should focus on this sector. Such studies should be complete and well-defined LCAs also including equipment life cycle and end of life. In addition, it is suggested that the analysis include availability of resources as well as incorporate costs. Finally, to better support decision making, also future developments of technologies and society needs to be considered. Building long-term scenarios with zero net greenhouse emissions and where all material is recycled is particularly important to obtain fully sustainable heavy duty transport solutions.

SAMMANFATTNING

Lastbilar för godstransport på väg möjliggör ekonomisk tillväxt, de transporterar varor som mat, elektronik eller råvaror. Dagens lastbilar drivs huvudsakligen med diesel och använder en betydande del av den globala fossila oljeproduktionen. Utan ytterligare politiska ansträngningar förväntas användningen av oljebaserade drivmedel för godstransporter öka betydligt. Åtgärder för att minska utsläppen av växthusgaser från vägfordon inbegriper användningen av förnybara bränslen, elektrifiering och användning av bränsleceller. Alla dessa alternativ verkar vara genomförbara för medelstora fordon, men för tunga långdistansfordon är de möjliga alternativen till diesel mindre tydliga.

Livscykelanalys (LCA) kan vara ett viktigt verktyg för att vägleda beslutsfattare och för att styra den tekniska utvecklingen. Slutsatsen från detta arbete är emellertid att tillgängliga LCA-studier av vägfordon för godstrafik inte ger tillräckligt stöd för beslut. De flesta studier är begränsade och resultat från olika studier är svåra att jämföra och leder till olika rekommendationer. Problem som identifieras i nuvarande studier är: (1) antalet tillgängliga rapporter om lastbilar är begränsat, (2) definitionen av fordonet är oklart, (3) olika metoder och systemgränser används, (4) studier fokuserar på den nuvarande situationen och omfattar inte framtida överväganden. Dessutom är tillgängliga studier vanligen begränsade på så sätt att de inte inkluderar utrustningens livscykel, slutanvändning, analys av resursutarmning eller kostnad.

Eftersom det inte finns någon enkel lösning för att sänka utsläppen av växthusgaser från tunga transporter verkar det uppenbart att fler LCA-studier bör fokusera på denna sektor. Sådana studier bör vara kompletta och väldefinierade samt inkludera utrustningens livscykel och slutanvändning. Dessutom föreslås att analysen även innefattar tillgänglighet av resurser och kostnader. För att bättre kunna stödja beslutsfattandet måste även den framtida utvecklingen av teknik och samhälle beaktas. Att bygga långsiktiga scenarier med noll växthusgasutsläpp och där allt material återvinns är särskilt viktigt för att erhålla fullt hållbara tunga transportlösningar.

CONTENTS

1 INTRODUCTION

The burning of fossil fuels is the fundamental cause of human-induced climate change, and road based transports account for more than 17% of global carbon dioxide emissions. In 2015, more than 40% of road transport-related CO2 emissions were from road freight transport, with a total direct emission of 2.6 Gt that year (IEA 2017).

Road freight vehicles are employed for the movements of goods, such as food, electronics, raw material and other trade. They are a key enabler of economic activity; however, road freight vehicles are a central source of global oil demand today, at around 17 million barrels per day (mb/d) or approximately 18% of the global crude oil demand. Without further policy efforts, oil demand from road freight vehicles is projected to rise significantly (IEA 2017).

In order to achieve the 2 Degree Scenario (2DS) by 2050, efforts to modernise and decarbonise road freight transport are needed. In this report, the challenge of switching to new fuels is addressed. Biofuels, electric batteries and electrofuels are identified as alternatives that have potential to decrease greenhouse gas (GHG) emissions.

GHG emissions from different alternatives should be analysed and compared using life cycle assessment (LCA). However, despite a vast number of LCA reports on fuel production pathways and the utilisation of fuels in vehicles, it is far from clear which alternatives that represent best options.

1.1 GOAL AND SCOPE

The main objectives for the work reported here have been to evaluate to which degree data from LCA studies on Heavy Duty Transport (HDT) can be compared. The ambition has also been to identify differences in underlying parameter assumptions and systems boundaries, aiming to make data more comparable. A specific aim has been to propose general recommendations for future LCA studies on HDT that can make the results comparable and more easily applied by stakeholders. The analysis includes evaluation of selected life cycle stages and system boundaries.

In addition, the work has been directed to give recommendations for prospective analysis. The assumption has been that LCA studies should support decision makers selecting the alternatives that minimize both environmental impact and cost, and in the long term, contributes to achieving the 2 degree target.

The scope of this report is limited to life cycle assessments of HDT published in the last five years, and it has a strong focus on Heavy Freight Trucks (HFT), or, long-distance road transport. Moreover, the report aims to analyze the environmental impacts and cost reported in those studies.

1.2 DEFINITIONS/NOMENCLATURE

BEV Battery electric vehicle.

CNG Compressed natural gas.

EOL End of Life. Final stages of a product's existence.

EPS Energy performance score

GHG	Greenhouse gas
GVW	Gross vehicle weight
HDT	Heavy Duty Transport, including MFT and HFT.
HEV	Hybrid electric vehicle
HFT	Heavy-freight trucks. Commercial vehicles with a GVW greater than 15 t (trailers, long-haul trucks).
HVO	Hydrogenated vegetable oil
LCA	Life Cycle Assessment. A method to assess environmental impacts associated with all the stages of a product's life, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling.
LCV	Light commercial vehicles are pickups. Vans and small trucks with a GVW of less than 3.5 t. LCVs are one of two classes of light-duty vehicles (the other being passenger light-duty vehicles) and are used for the transportation of goods (IEA 2017).
LNG	Liquid natural gas.
MFT	Medium-freight trucks. Commercial vehicles with a GVW from 3.5 t to 15 t (small lorries, rigid trucks, large vans and buses).
NG	Natural gas
PGM	Platinum-group metals
TTW	Tank to Wheel. Analysis that applies to the fuel use in the vehicle.
WTW	Well to Wheel. Analysis referring to specific lifecycle analysis applied to transportation fuels and their use in vehicles. The WTW stage includes resource extraction, fuel production, delivery of the fuel to vehicle, and end use of fuel in vehicle operations.
WTT	Well to Tank. Analysis that includes the fuel production and delivery (transportation, distribution) of the fuel to the vehicle.

2 TODAYS STATUS OF LCA ON TRANSPORT FUELS FOR HEAVY FREIGHT TRUCKS

Life Cycle Assessments (LCA) can be a useful tool to understand and evaluate a holistic environmental perspective on products, helping both environmental management in industry and environmental policy-making in public government to move towards a more sustainable direction (Baumann, Tillman 2004). However, the broad definition (open selection of goal, scope, system boundaries, etc.) of LCA sometimes leads to different problem approaches, and thus results from reports are difficult to compare and can even give inconsistent conclusions (Nordelöf 2017).

Not only the diverse frameworks used in LCA create incomprehension, also the study of emerging technologies, such as alternative fuels (biofuel or electric batteries), makes this problem more noticeable. For instance, the sometimes-confusing debate on electric cars environmental impact is partly a result of not sufficiently comprehensive nor comparable LCA studies.

Additionally, while the life cycle of passenger cars is studied frequently, only a few analyses focus on heavy-duty transports and even less on road freight transport, which generates more than 40% of road transport-related GHG emissions. Therefore, more studies are needed on HDT. This section presents an evaluation of the differences among LCAs approaches and absent information of road freight transport studies.

2.1 RECENT LIFE CYCLE STUDIES ON HDT

Table 1 shows a summary of recent studies which includes life cycle analyses on HDT. As can be observed, although the comparison of different fuels is common among the studies, the vehicle type, technologies and boundaries analysed vary, which leads to differing results.

The results largely depend on the vehicle type and it is important to specify it. For example, the research papers of Ercan and Tatari (2015) and Cooney et al. (2013) performed LCAs on GHG of transit buses. Both conclude that electric batteries help to reduce the emissions and, the same result is stated in Tong et al. 2015 for this type of vehicle, even if a Well to Wheel (WTW) analysis is used. However, comparing distribution trucks is harder due to the fact that some of the studies do not describe the vehicle in detail (Börjesson et al. 2016; Alamia et al. 2016). The results clearly depend on the vehicle type. Tong et al. (2015) shows that, for a trailer, diesel is the technology with lower emissions, while a smaller truck emits less CO_2 if it is electric.

Another important aspect relates to the system boundaries. For instance, the first three studies (Börjesson et al. 2016; Romare and Hanarp 2017; Alamia et al. 2016) compare HDT using diesel, natural gas or biofuels. Although all three studies state that biofuels reduce the GHG emissions, the values differ. One of the reasons is the application of different boundaries, cradle to grave analysis vs. WTW, both with limitations as they are either including the raw material extraction or the end of life. Additionally, the vague description of the vehicles adds uncertainties.

As can be seen, the goals of the studies are also different; while all three refer to GHG, not all include resource use or recycling, essential features for the analysis of emerging technologies such as biofuels or electric batteries. If the aim is to achieve a sustainable 2 degree solution by using LCA as a decision-making tool, not only the GHG emissions should be considered but also material scarcity and recycling (Romare and Hanarp 2017; Ercan and Tatari 2015; Cooney et al. 2013). In addition, the authors of the present report strongly recommend that information on costs should be added to LCA studies to better understand the feasibility of future transport solutions (see section 2.2).

Table 1. Summary of recent studies including LCAs on Heavy Duty Transport.

STUDY	Vehicle type	Aim of study	System boundaries	Conclusions/results
Romare and Hanarp 2017	HDT (16 t)	Comparison of diesel and gas distribution truck (diesel, HVO, bioethanol, CNG and biogas)	Full LCA (cradle to grave), including GHG and resource use	1) The user phase has the highest global warming impact. 2) Biofuel gives a 50-90% reduction of CO_2-eq compared to fossil fuel. 3) It is important to consider material scarcity.
Börjesson et al. 2016	LCV & HDT*	Comparison of existing and potential methane-based systems (NG and biogas)	WTW, including energy, GHG and cost (extraction and transport of raw material not included).	1) Biomethane can reduce 80-90% of GHG emissions in comparison with fossil fuels 2) The cost for WTW is around 15-20% higher for biogas than for NG.
Alamia et al. 2016	HDT*	Comparison of bio-methane derived fuels, bio-CNG and bio-LNG vs their fossil equivalents.	WTW, including GHG.	The use of biofuel can reduce GHG emissions by 43-67%.
Tong et al. 2015	HDT (4-40 t)	Comparison of different vehicle sizes and technologies (for HFT diesel HEV and NG).	WTW, including GHG.	Results depend on the vehicle type. HEVs fuelled by diesel, and conventional diesel vehicles generate the lowest amounts of GHG emissions for HFT**. For transport buses (20 t) BEVs give the lowest amount of GHG emissions.
Nahlik et al. 2016	HDT (10-40 t)	Comparison of diesel, LNG and hybrid trucks	LCA, including GHG and energy (EOL not included).	Results show different performance depending on the vehicle. GHG emissions of MDT are double the emissions of HDT. The CO_2 emissions are similar for all technologies, but the energy efficiency is better for NG.
Ercan and Tatari 2015	HDT bus	Comparison of public transport buses fuelled by diesel, biodiesel, CNG, LNG, as well as HEV (fuelled by diesel) and BEV	LCA***, including GHG and cost.	1) BEV and hybrid powered buses have lower local emissions, however the dependency on fossil fuel for electricity generation can be significant for the total emissions. 2) LNG powered transit buses gave the largest CO_2 eq emissions. 3) Electric buses are the most expensive of all buses included in the study. 4) Recycling of batteries is important.
Cooney et al. 2013	HDT bus	Comparison of transit buses: electric and diesel	LCA***, including GHG and cost.	1) Variations in the electricity grid should be considered prior to recommending the use of battery-driven electric buses for reduction of CO_2 emissions. 2) Recycling of batteries is important. 3) Electric buses are the most expensive of all buses included in the study.

**Weight is not specified.*
***The raw material to produce all the energy carrier is always natural gas, NG.*
****End of Life is considered but there is no numerical study (only quantitative).*

2.2 LIMITED LCAS

Comparisons of fuels and powertrains for vehicles normally focus on GHG emissions using Well to Wheel (WTW) analysis (Romare and Hanarp 2017). An illustration of the complete life cycle is given in Figure 1. The WTW analysis includes resource extraction, fuel production, delivery of the fuel to a vehicle, and end use of fuel in vehicle operation. In other words, WTW studies the life cycle of the energy carrier (i.e. fuel or electricity). Although that approach has been useful for fossil fuels, it may not be sufficient to evaluate new transport solutions where the impact from the equipment life cycle can be significant (Nordelöf 2017).

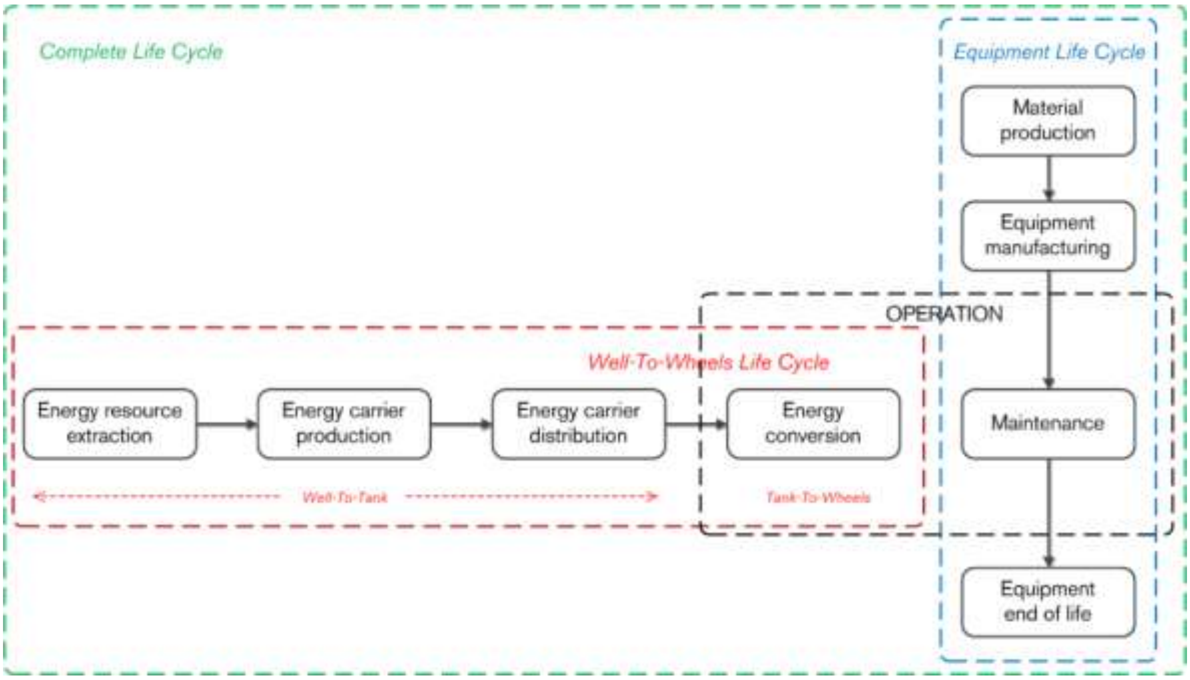

Figure 1. Complete Life Cycle (Nordelöf 2017).

As shown in table 2, available studies on trucks give only a partial overview of the life cycle, i.e. WTW. Not considering 'gate-to-grave' industrial processes lead to uncertainties (Reap et al. 2008a, 2008b) and when the full life cycle is examined new considerations arise:

- For the electric passenger car, the emissions from the electric powertrain production (battery, motor, control system, etc.) can become equal to the WTW emissions. Production of an internal combustion engine only generates 26% of the full life cycle emissions (Nordelöf 2017). The percentage is estimated to be smaller for trucks than for cars as a result of longer driving distances.
- Most often, information about EOL is missing and information needed to fully close the loop of many materials and parts of the powertrain is unknown (i.e. battery, magnets, high-pressure tanks) (Ercan and Tatari 2015; Cooney et al. 2013; Nordelöf 2017).
- The assessment by Romare and Hanarp (2017) includes EOL. It also highlights that use of resources plays an important role when focusing on long-term implications of environmental impacts. Not only should the focus be on global warming, but there is also a need to understand the risks when using rare materials, and establish strategies to ensure that they are returned to the loop after being used in products.

Table 2 illustrates that GHG emissions and energy use are very often studied but other impact categories, such as resource depletion and cost, are rarely explored.

Table 2. Life cycle stages and impact categories included in the studies for trucks. All studies concern current time.

STUDY	LCA phases included			Impact categories included				Geographic scope
	WTW	Life cycle	EOL	GHG	Energy	Resource	Cost*	
Romare and Hanarp 2017	yes	yes	yes	yes	?	yes	no	Sweden - EU
Börjesson et al. 2016	yes	no	no	yes	yes	no	yes	Sweden - EU
Alamia et al. 2016	yes	no	no	yes	yes	no	no	Sweden – Nordic countries
Tong et al. 2015	yes	no	no	yes	no	no	no	US

** Cost is not traditionally included in LCA, but it is included here to illustrate the general absence of this information.*

Availability of resources is an important issue when assessing sustainability. Indeed, scarcity may be of particular importance to include in an LCA if a technology's introduction induces new or significant additional demand on a resource (Miller and Keoleian 2015). For instance:

- Materials which currently play a key role in vehicle electrification, such as lithium and rare earth metals, are not covered by life cycle impact methods (Romare 2017).
- Emissions of toxic substances from the manufacturing stages is an environmental aspect to be studied (Cooney et al. 2013). This can be a possible disadvantage for electric powertrains.
- For internal combustion engine vehicles (ICEV), the small electric starter motor and catalytic converters in the conventional propulsion system have negative environmental impact (Nordelöf et al. 2014).
- Biomass availability may become critical if biofuels are deployed at a large-scale.

Another relevant aspect is the cost estimation. This feature only appears in one of the studies (Börjesson et al. 2016), but it is essential for the decision-making and for the understanding of the potential impact of different technologies. However, many costs are still uncertain or unknown:

- In Börjesson et al (2016), the full electric truck was not considered in the in the scope due to the lack of information on cost and performance, such as charge infrastructure and battery.
- Börjesson et al. (2016) estimates that the WTW cost of using biofuels is around 15-20% higher than conventional trucks, while real data is missing.
- Distribution costs for hydrogen, CO_2, and electrofuels are not considered in the majority of LCA or WTW analyses (Brynolf et al. 2017).
- Many studies state a much higher price for electric HDT buses than for diesel buses; however, recycling and manufacturing are not included (Ercan and Tatari 2015; Sen et al. 2017; Cooney et al. 2013).

2.3 GHG EMISSIONS

The bar charts in Figure 2 illustrate the CO_2-eq emissions of the WTW analyses for different fuels (diesel, natural gas and biogas) in the investigated studies (Romare and Hanarp 2017, Börjesson et al. 2016, Alamia et al. 2016 and Tong et al. 2015). On average, diesel trucks release slightly more GHG emissions (expressed as CO_2-eq) than trucks fuelled with natural gas. All reports show a significant reduction of GHG emissions by the use of biogas.

However, the emissions values of the fuels are diverse. For example, the WTT diesel emissions of Romare and Hanarp (2017), Börjesson et al. (2016) and Alamia et al. (2016) are different although all of them are calculated assuming conditions relevant for Sweden. WTT analysis includes the fuel production and delivery of the fuel to the vehicle and it should be similar if the studied location or region is the same. In a similar manner, WTT emissions for natural gas vary substantially.

Also for the Tank to Wheel (TTW) assessment, the results vary. TTW emissions depend on the fuel use in the vehicle, the vehicle technology, size and driving cycle (city/highway and full/empty vehicle).

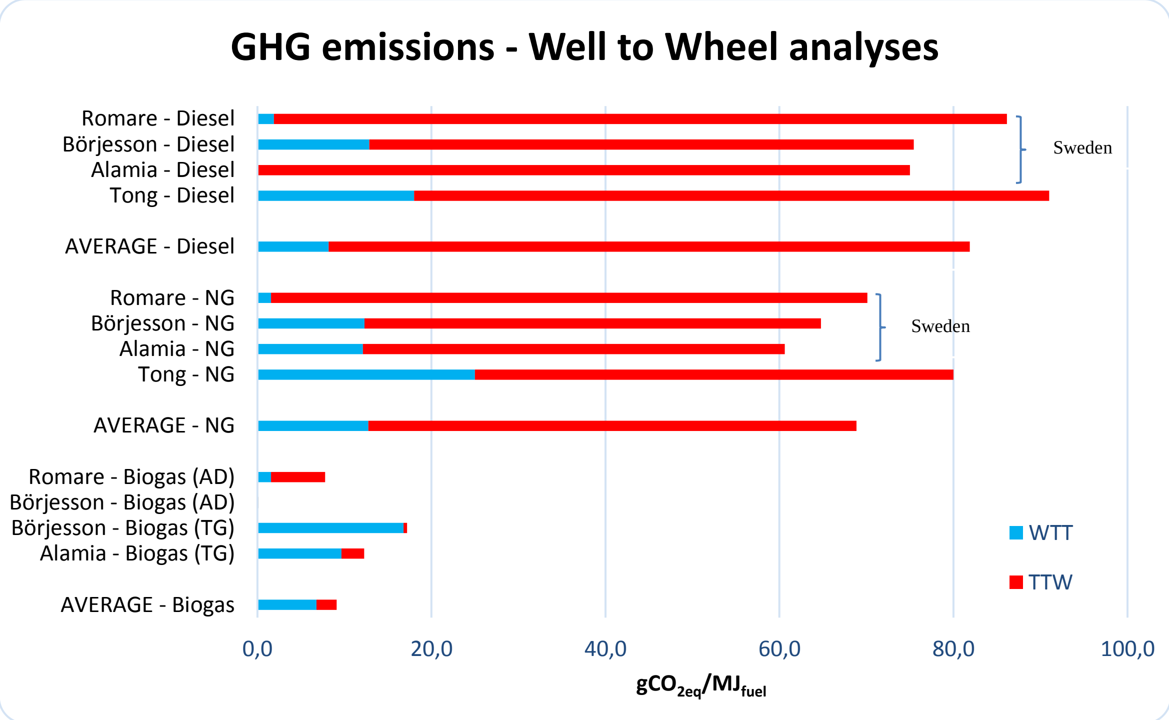

Figure 2. CO_{2eq} emissions for different Well to Wheel analyses, Natural Gas (NG), Anaerobic Digestion (AD), Thermal gasification (TG).

The emissions from biogas production are more complex to analyse than emissions from production of diesel and natural gas. Biogas production based on anaerobic digestion might give negative or positive emissions depending on the method of evaluation (energy allocation or system expansion). Also, values for emissions from biogas production based on thermal gasification differ, even though evaluated for the same production plant (GoBiGas).

Overall, looking at the results in Figure 2, it can be concluded that the CO_2-eq emissions from biogas use are substantially lower than the emissions from use of natural gas or diesel.

2.4 RESOURCE DEPLETION

Looking at the GHG emissions and using a WTW approach, it is clear that biogas gives environment benefits compared to diesel and natural gas. However, taking depletion of resources into account, the total impact is less clear, which is illustrated in this section. Only the study of Romare and Hanarp (2017) includes EOL/recycling of the truck life cycle.

Figure 3 shows results from Romare and Hanarp's study (2017), which analyses the life cycle impact (cradle to grave) using an energy performance score, EPS, a weighting methodology that takes into account the emissions as well as the resource depletion. For HDT, the smallest total impact is obtained with the diesel powertrain, followed by biogas and natural gas. This difference in the EPS score is due to the gas engine catalyst, which requires considerable amounts of platinum-group metals (PGM). Since they are very uncommon in the earth's crust, they denote a higher depletion of reserves. It should be pointed out, however, that not all natural-gas vehicles require special catalysts and can thus contribute to lower life cycle impact also using the EPS methodology.

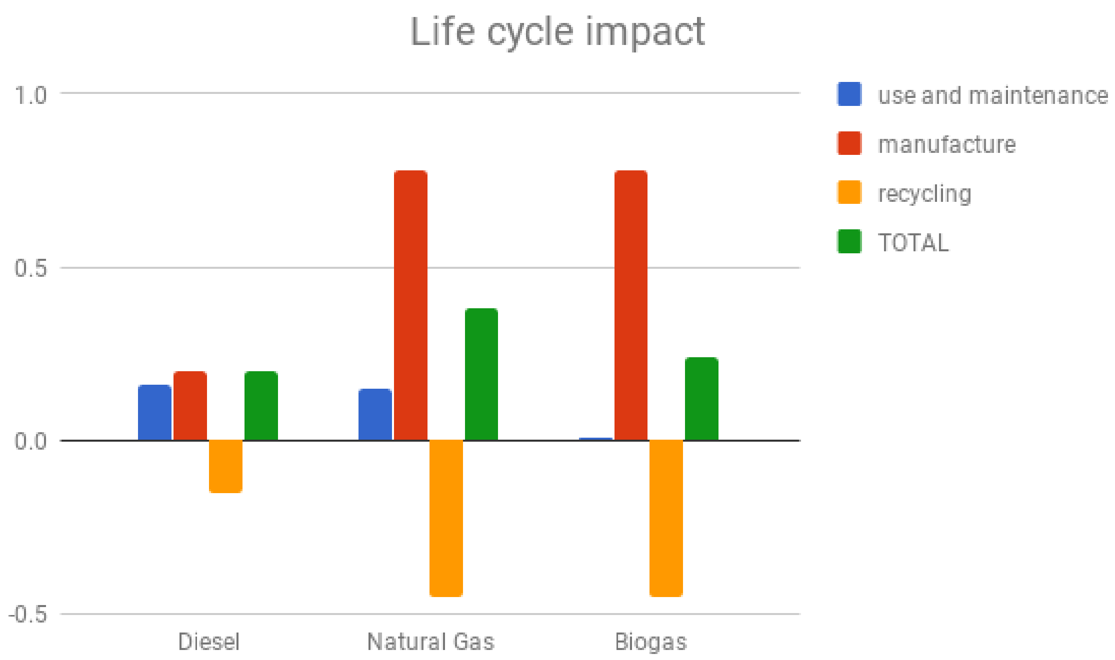

Figure 3. Life cycle impact of different fuels for trucks using the EPS methodology (adapted from Romare and Hanarp, 2017).

The results in Figure 3 illustrates that the environmental impact of different technologies strongly depends on assumptions and systems boundaries used in the LCA study.

2.5 UNCERTAINTY OF DATA FOR NEW TECHNOLOGIES

Commonly, when estimating the environmental impact of vehicles with internal combustion engines, WTW analysis has been considered sufficient, and the impact of the equipment life cycle has been considered marginal. However, the emissions during EOL could be high also for some of those vehicles, thus, it should be reconsidered to take the EPS into account, as illustrated in the previous section.

With the introduction of batteries, and possibly other materials for an electric vehicle propulsion systems, the assumption of a negligible emissions from the equipment life cycle is no longer valid. There are large uncertainties in the underlying data, but estimations for an electric medium duty distributions truck, using results from Romare and Dahllöf (2017), indicate GHG emissions from the equipment life cycle that are 5-16 times higher than for conventional vehicles. Additionally, the resulting total life cycle emissions depends heavily on the battery lifetime, the driving distance and emissions from the electricity generation.

3 DISCUSSION AND CONCLUSIONS ON AVAILABLE LCA STUDIES

The challenge of lowering GHG emissions from HDT has been addressed in the literature. Nevertheless, available reports do not sufficiently support the decision-making process because results are difficult to compare and lead to different recommendations.

From the studies examined in this project, various barriers were identified that interfere with the decision-making:

- **Limited amount of work has been carried out.** As opposed to car LCAs, only a small number of reports cover HDT, and only a few include long-haul trucks or trailers.
- **The definition of the vehicle is unclear.** The examined studies frequently refer to HDT without specifying size or type. It is often missed that heavy-duty vehicles are machines that transport goods or people. There is a very big difference between a city bus and a long-haul truck, which fundamentally can influence the results of an LCA.
- **Study approaches and system boundaries differ.** The comparison of different fuels is common among the examined studies, but the system boundaries vary and often only WTW is considered. The technologies evaluated also differ, e.g. the selection of WTT pathways: (for example, ethanol production varies depending on feedstock (wheat/sugarcane) and energy used for the process (natural gas/biomass)).
- **LCAs have a limited scope**. Examined reports have a strong focus on WTW life cycles, often omitting the equipment life cycle. GHG emissions are always examined, but not the resource use and costs. Therefore:
    - Overlooking the ***equipment life cycle*** could generate large bias on the emissions (for example, the electric powertrain production emissions can be equal to those from the WTW life cycle). By leaving out EOL, the possibilities of closing the loop of many material and parts of emerging technologies cannot be estimated.
    - Neglecting ***resource depletion*** devaluates an important source for environmental impact, as well as the risks connected to the use of rare materials, or fuels based on biomass with limited availability.
- **Cost is commonly not included in LCAs.** Including cost in LCA studies would add important information needed for decision making. Several studies state that the equipment price for alternative technologies will be higher than for e.g. diesel. Cost for recycling, remanufacturing and infrastructures are not commonly estimated and are highly uncertain.
- **Limited considerations regarding future technology development.** Although alternative fuels require technological change and take time to be fully adopted, all of the examined studies are based on the current time and on the actual technologies. Typically, LCA studies do not include the role of technology development, future cost nor the long-term availability of raw materials.

Most existing LCAs compare technologies at early phases of development but the long-term potential is typically not considered. However, if the technology is modelled for the future, further technical refinements and possibly large-scale production can influence the results (Arvidsson et al. 2017). Emerging transport technologies, however, involve uncertain changes and are difficult to assess with LCA.

Despite the inherent uncertainty, anticipating the consequences of a transformative technology at an early stage may allow for more successful mitigation of future problems. Therefore, scenario forecasting should be utilised to further complement present LCA, addressing factors that are both highly uncertain yet have a large impact on LCA results (Miller and Keoleian 2015).

This type of future-forecasting analysis can be addressed with, for example, Prospective LCA, where the most important aspects of using this assessment are the following (Arvidsson et al. 2017):

– *Technology alternatives:* Different transportation technologies can be compared in terms of vehicle type or movement of goods (tons by km), when using fossil fuels, biofuels, hydrogen fuel, fuel cells, and electric motors (Nordelöf et al. 2014).

– *Foreground System:* Different strategies must be considered when modelling the future, for example, scenarios should include technical development as well as the adoption-scale (Nordelöf 2017).

– *Background system:* Modelling of background systems includes assumptions for future generation of electricity and for future extraction of limited material resources. It is important to avoid a temporal mismatch between the foreground and background systems, both systems must have similar scenario approach (Arvidsson et al. 2017).

4 RECOMMENDATIONS FOR FUTURE LCA

Recommendations given in this section are based on the assumption that LCA should be an important tool to guide the development of future heavy duty transport technologies. Stakeholders involved need as much background as possible to select the alternatives that minimize the environmental impact and costs as well as having the potential to replace a substantial fraction of the presently used fossil diesel fuel.

4.1 CRITICAL CRITERIA FOR EVALUATION

Given that the analysis covers the full life cycle there are three critical criteria for selecting vehicle transport solutions:

1. GHG emissions
2. Cost
3. Sustainable resource potential

The emission of GHG gases is one of the most challenging problems of our time and solutions have to take the total global emissions into account. There are also several other vehicle-related emissions, some of which have a direct harmful effect on human health and/or on the environment. The assumption here is that such emissions are, or will be, regulated to sustainable levels by legislation, however, all emissions should be considered during the full life cycle.

Long-term costs will remain as the most important factor for selecting a certain transport solution. However, in order to obtain sustainable solutions, all costs have to be included from an LCA perspective. One cost category that is often omitted in studies is the infrastructure for fuelling and/or charging.

The sustainable resource potential represents the potential to replace the presently used fossil fuels by other energy carriers, but should also take depletion of material resources into account. Some solutions that are favourable in terms of GHG emissions and cost might have limited resource potential. Such solutions can however still be good options if they do not impact the present vehicle technology or infrastructure negatively. For instance, it is known that the potential to replace the presently used fossil diesel with biofuels is limited to around 20% (Volvo Trucks 2007). This means that even a large-scale introduction of biofuels will not be sufficient. However, today's biomass-based fuels could in the future be produced based on renewable electricity. Electrofuels are assumed to have the potential to replace a large fraction of today's fuels but the cost of production must become competitive. The cost of adapting vehicles, for most alternative fuels, is believed to be marginal.

It is important to highlight that other commonly used criteria for evaluation are included indirectly by those recommended here. One commonly used criteria is "energy efficiency", which typically suggests electrified propulsion as the optimal future alternative. The reasons for putting the focus on energy efficiency are the indirect effects on emissions, the cost for fuels and the limited supply of fuels. However, all these direct effects are included in the criteria selected here.

Also, energy efficiency is not well defined. The common interpretation of energy efficiency is the efficiency of conversion of energy in some basic form to mechanical energy useful to drive a vehicle. This interpretation is useful for estimating the performance of a vehicle having a well-defined energy storage system. However, when estimating the WTT efficiency, problems arise when defining system boundaries, e.g. when reallocating energy contained in fuel production bi-products. Since the release of pure energy typically does not give any direct negative impact it does not have to be reduced because of environmental reasons.

4.2 TRANSPARENCY AND REUSE OF CONSENSUS DATA

A reason for that many LCA studies are limited is the large effort needed to make the full analysis. In addition, access to underlying data is often limited and/or data is uncertain. The recommendation from this study is to perform the work stepwise and, where data is missing, reuse already available results in a structured way. Following Nordelöf (2017), sufficiently complete studies should include WTW as well as the equipment life cycle (see Figure 1). The WTW study should be broken down and provide numbers for:

- Energy resource extraction,
- Energy carrier production,
- Energy carrier distribution including infrastructure for filling, and
- Energy conversion.

The equipment life cycle analysis should similarly report separate results for:

- Material production,
- Equipment manufacturing,
- Maintenance, and
- Equipment End of Life.

The advice for future LCA work is to refine uncertain parts of existing LCA studies and/or to generate new data representing novel technologies or processes. One example of an ongoing activity with the objective to facilitate the comparison of present and future vehicle propulsion systems is the JRC - Joint Research Centre-EUCAR-CONCAWE collaboration (JRC 2014). The outcome of the work is WTT, TTW and TTW reports including results for a large range of fuels presented in a form that can be reused for different applications. An important aspect of the work is that all results are discussed between experts representing academia, automotive and fuel providers. Even if some numbers are results from compromises, the importance of reaching consensus is a key enabler for further efficient utilisation of the data.

4.3 PROSPECTIVE ANALYSIS

Prospective (or in the future) LCA will include many assumptions but should have the ambition to generate the best possible background for today's decision makers.

The probably most important long-time scenario is represented by zero or negative GHG emissions and complete recycling of material. The selected technologies will be those providing the best cost/performance ratio for given boundary conditions representing fully sustainable transport solutions. The important effect of depletion of resources can possibly be taken into account when estimating future costs. The basic assumption of a fully circular use of material should allow a certain use of virgin resources corresponding to an expected increase of activities.

To estimate the performance and cost of future technologies a further break-down of the analysis is the recommended procedure. Vehicle performance estimates, like drive range, can be made using basic numbers representing energy density (kWh/kg and kWh/m^3) and propulsion system energy conversion efficiency (%). Similarly, cost estimates can be made for the energy carrier, including distribution and infrastructure for filling, (€/kWh), energy storage (€/kWh) and propulsion system (€/kW). Since decisions for future transport solutions to a large degree depend on assumptions for energy carrier, energy distribution, filling, storage and propulsion system, LCA might give important guidelines just by providing such basic numbers representing the present technology, together with reasonable assumptions for the future development.

4.4 SUMMARY OF RECOMMENDATIONS

HFT includes trucks that deliver goods in a certain expected time schedule. When comparing different HFT transport solutions we recommend the following:

- GHG emissions, cost and sustainable resource potential are the critical criteria when evaluating HFT solutions.
- The comparison should be done by the “work done” principle, i.e. metrics per tkm. The studied vehicles should have the same capability to deliver goods within a defined time.
- Boundaries and limitations should be clearly defined. The inclusion of vehicle production and EOL is recommended especially for electrified powertrains. Any exclusion of parts that are expected to be significant should be clearly indicated, e.g. the vehicle itself or fuel infrastructure. Whenever essential data is missing the use of best available existing data is recommended.
- Sensitivity analysis is recommended for uncertain cases, e.g. recycling.
- For future scenarios, all relevant changes impacting the result should be considered, including e.g. the development of fuel production technology (e.g. improved electricity grid) and the development of future vehicle/infrastructure technologies.

REFERENCES

Alamia, Alberto; Magnusson, Ingemar; Johnsson, Filip; Thunman, Henrik (2016): Well-to-wheel analysis of bio-methane via gasification, in heavy duty engines within the transport sector of the European Union. In *Applied Energy* 170, pp. 445–454. DOI: 10.1016/j.apenergy.2016.02.001.

Arvidsson, Rickard; Tillman, Anne-Marie; Sandén, Björn A.; Janssen, Matty; Nordelöf, Anders; Kushnir, Duncan; Molander, Sverker (2017): Environmental Assessment of Emerging Technologies. Recommendations for Prospective LCA. In *Journal of Industrial Ecology* 80 (7), p. 40. DOI: 10.1111/jiec.12690.

Baumann, Henrikke; Tillman, Anne-Marie (2004): The hitch hiker's guide to LCA. An orientation in life cycle assessment methodology and application / Henrikke Baumann & Anne-Marie Tillman. Lund, Sweden: Studentlitteratur.

Börjesson, Pål et al. (2016) Methane as vehicle fuel – A well-to-wheel analysis (MetDriv). Report No 2016:06, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden, available at www.f3centre.se.

Brynolf, Selma; Taljegard, Maria; Grahn, Maria; Hansson, Julia (2017): Electrofuels for the transport sector. A review of production costs. In *Renewable and Sustainable Energy Reviews* 81, pp. 1887–1905. DOI: 10.1016/j.rser.2017.05.288.

Cooney, Greg; Hawkins, Troy R.; Marriott, Joe (2013): Life Cycle Assessment of Diesel and Electric Public Transportation Buses. In *Journal of Industrial Ecology* 451 (7179), n/a-n/a. DOI: 10.1111/jiec.12024.

Ercan, Tolga; Tatari, Omer (2015): A hybrid life cycle assessment of public transportation buses with alternative fuel options. In *Int J Life Cycle Assess* 20 (9), pp. 1213–1231. DOI: 10.1007/s11367-015-0927-2.

IEA (2017): The Future of Trucks. With assistance of IEA/STO/ETP/EDT GORNER Marine: IEA.

JEC (2014): Joint Research Centre - Institute for Energy and Transport (IET). Edited by European Commission. Available online at http://iet.jrc.ec.europa.eu/about-jec/downloads, checked on 1/19/2018.

Miller, Shelie A.; Keoleian, Gregory A. (2015): Framework for analyzing transformative technologies in life cycle assessment. In *Environmental science & technology* 49 (5), pp. 3067–3075. DOI: 10.1021/es505217a.

Nahlik, Matthew J.; Kaehr, Andrew T.; Chester, Mikhail V.; Horvath, Arpad; Taptich, Michael N. (2016): Goods Movement Life Cycle Assessment for Greenhouse Gas Reduction Goals. In *Journal of Industrial Ecology* 20 (2), pp. 317–328. DOI: 10.1111/jiec.12277.

Nordelöf, Anders (2017): Using life cycle assessment to support the development of electrified road vehicles. Component data models, methodology recommendations and technology advice for minimizing environmental impact. Graduate School of Energy and Environment. Chalmers University of Technology, Division of Environmental Systems Analysis.

Nordelöf, Anders; Messagie, Maarten; Tillman, Anne-Marie; Ljunggren Söderman, Maria; van Mierlo, Joeri (2014): Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? In *Int J Life Cycle Assess* 19 (11), pp. 1866–1890. DOI: 10.1007/s11367-014-0788-0.

Reap, John; Roman, Felipe; Duncan, Scott; Bras, Bert (2008a): A survey of unresolved problems in life cycle assessment. Part 1. In *Int J Life Cycle Assess* 13 (4), pp. 290–300. DOI: 10.1007/s11367-008-0008-x.

Reap, John; Roman, Felipe; Duncan, Scott; Bras, Bert (2008b): A survey of unresolved problems in life cycle assessment. Part 2. In *Int J Life Cycle Assess* 13 (5), pp. 374–388. DOI: 10.1007/s11367-008-0009-9.

Romare, Mia. & Dahllöf, Lisbeth. (2017): The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries. A Study with Focus on Current Technology and Batteries for light-duty vehicles. No. C 243 IVL.

Romare, Mia. & Hanarp, Per. (2017): Comparison of diesel and gas distribution trucks - a life cycle assessment case study. Report No 2017:16, f3 The Swedish Knowledge Centre for Renewable Transportation Fuels, Sweden.

Sen, Burak; Ercan, Tolga; Tatari, Omer (2017): Does a battery-electric truck make a difference? – Life cycle emissions, costs, and externality analysis of alternative fuel-powered Class 8 heavy-duty trucks in the United States. In *Journal of Cleaner Production* 141, pp. 110–121. DOI: 10.1016/j.jclepro.2016.09.046.

Tong, Fan; Jaramillo, Paulina; Azevedo, Inês M. L. (2015): Comparison of life cycle greenhouse gases from natural gas pathways for medium and heavy-duty vehicles. In *Environmental science & technology* 49 (12), pp. 7123–7133. DOI: 10.1021/es5052759.

Volvo Trucks (2007): Alternative Fuels - The way forward. Avilable: https://www.volvotrucks.com/content/dam/volvo/volvo-trucks/markets/global/pdf/our-trucks/Alternative_fuels_The_way_forward.pdf

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