REPORT f3 2013:29

# WELL-TO-WHEEL LCI DATA FOR FOSSIL AND RENEWABLE FUELS ON THE SWEDISH MARKET

Report from an f3 project

**Authors**:

Lisa Hallberg (IVL – Swedish Environmental Research Institute)

Tomas Rydberg (IVL – Swedish Environmental Research Institute)

Lisa Bolin (SP Technical Research Institute of Sweden)

Lisbeth Dahllöf (Volvo Group)

Helen Mikaelsson & Eva Iverfeldt (Scania)

Johan Tivander (Chalmers University of Technology)

THE SWEDISH KNOWLEDGE CENTRE FOR RENEWABLE TRANSPORTATION FUELS

# PREFACE

This report is the result of a cooperation project within the Swedish Knowledge Centre for Renewable Transportation Fuels (f3). The f3 Centre is a nationwide centre, which through cooperation and a systems approach contributes to the development of sustainable fossil-free fuels for transportation. The centre is financed by the Swedish Energy Agency, the Region Västra Götaland and the f3 Partners, including universities, research institutes, and industry (see www.f3centre.se)

Partners involved in this project:

| **Lisa Hallberg** | **IVL** | **Project manager, LCI-data gathering and modelling.** |
|---|---|---|
| **Tomas Rydberg** | IVL | Project supervisor |
| **Felipe Oliveira** | IVL | LCI-data gathering and modelling |
| **Åke Sjödin** | IVL | Emission factors for the use of fuels in vehicle |
| **Lisa Bolin** | SP | LCI-data gathering and modelling |
| **Frida Røjne** | SP | LCI-data gathering and modelling |
| **Sara Palander** | Chalmers | CPM coordinator |
| **Johan Tivander** | Chalmers | Responsible for data documentation format and CPM database |
| **Nils Brown** | KTH | Investigation of different methods* |
| **Lisbeth Dahllöf** | Volvo Group | Emission factors for the use of fuels in vehicles |
| **Per Salomonsson** | Volvo Group | Emission factors for the use of fuels in vehicles |
| **Helen Mikaelsson** | Scania | Emission factors for the use of fuels in vehicles |
| **Eva Iverfeldt** | Scania | Emission factors for the use of fuels in vehicles |

* The work carried out by Nils Brown was presented at a Workshop on Environmental product declarations and guarantees of origin, held at IVL in Stockholm in November 2013. The workshop was arranged within the f3 project "Beyond LCI: EPD-conforming LCA:s for vehicle fuels" in which Nils Brown's contribution is included.

In addition, the following persons have been involved: Magnus Swahn (The Network for Transport and Environment (Nätverket för transporter och miljön, NTM) and Ebba Tamm (Svenska Petroleum och Biodrivmedel Institutet, SPBI).

Also, the following fuel producing companies have contributed to the project: Lantmännen Energi, SEKAB, Perstorp Oxo, and Preem.

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# EXECUTIVE SUMMARY


The purpose of this project has been to gather and compile the best available environmental data for vehicle fuels on the Swedish market, for use in environmental assessments, such as LCA etc. The main deliverable is a database, published by f3 and also distributed by CPM - Swedish Life Cycle Center.

Life cycle inventory data (LCI-data) for well-to-tank (production of the fuel) as well as tank-to-wheel (combustion of the fuel in a vehicle) have been gathered from different available LCA studies and other sources. No LCA modelling has been carried out in the project except for some minor calculations in some cases.

The fuels studied are fuels used in heavy duty vehicles (trucks and buses) and data sets for the following fuels are published in the database; ED95, Fossil diesel, RME, HVO, biogas and natural gas.

The reference unit for the reported LCI-data is 1 MJ fuel.

When assessing the impact from using different fuels in vehicles, the consumption of the fuel needs to be considered in addition to the environmental data for the fuel. Note that the fuel consumption in heavy duty vehicles can differ widely due to other factors than the fuel type, namely vehicle type and driving conditions.

The actual figures are presented in the database and not in the report. However, an illustration of the results for the fuel data sets based on global warming potentials [g CO2-eq/MJ fuel] is presented.

For **well-to-tank**, there are for most fuels two different scenarios; allocation and system expansion. For fossil diesel and natural gas there is only one scenario. The different scenarios published are the scenarios available in the original data sources.

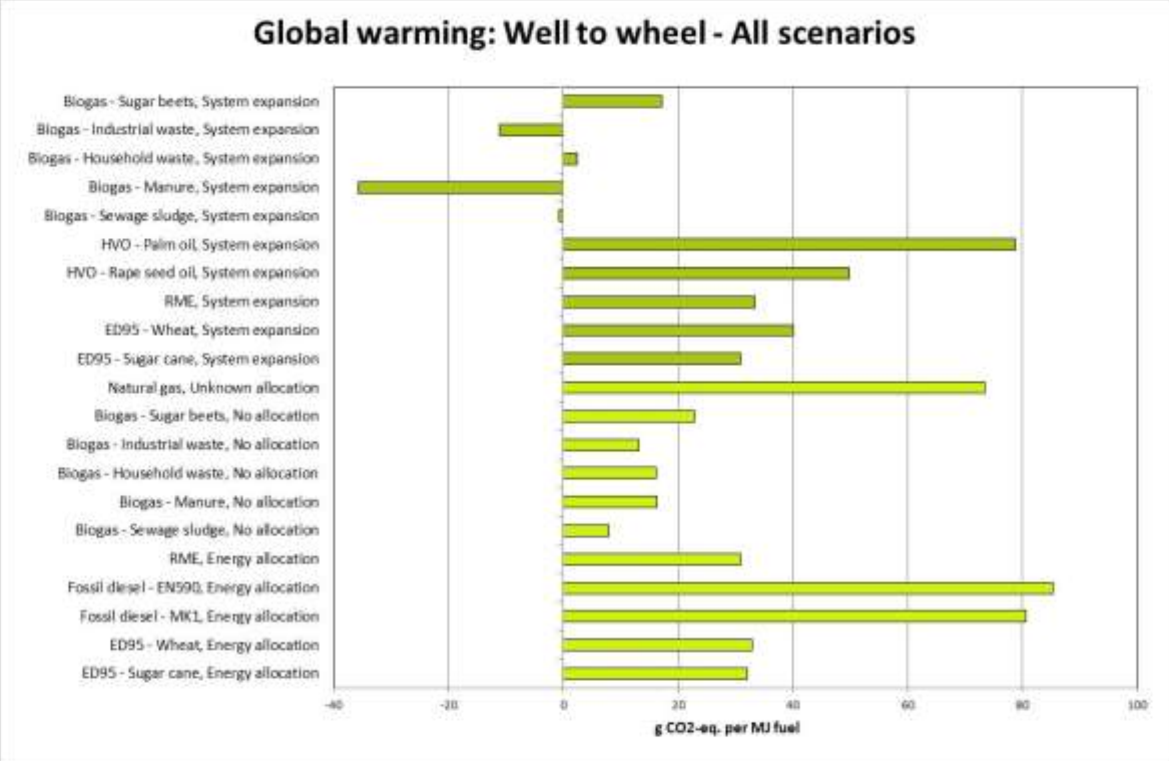
For well-to-tank, the biofuels ED95, RME and HVO show a larger impact than the fossil diesel. Biogas, regardless of the production process, shows a similar impact as the natural gas.

For **tank-to-wheel**, two data sets for each fuel are presented; Euro V and Euro VI engine. The data sets differ concerning the emissions of methane ($CH_4$), nitrogen oxides ($NO_x$), non-methane volatile organic compounds (NMVOC) and particles (PM), while emissions of fossil carbon dioxide ($CO_2$), carbon monoxide (CO), nitrous oxide ($N_2O$) and sulphur dioxide ($SO_2$) are the same irrespective of Euro class.

For the biofuels biogas and HVO, the fossil carbon dioxide ($CO_2$) is assumed to be zero. The global warming impact however is not zero, since there are small emissions of the other greenhouse gases ($CH_4$ and $N_2O$). For RME a very small part (1 of 19 carbon atoms) in the fuel is of fossil origin, which means that some fossil $CO_2$ is generated as well. For ED95 the fossil $CO_2$ comes from the components (not from the ethanol).

All biofuels have a global warming impact of less than 10 grams of $CO_2$-eq/MJ, while the fossil fuels vary between 60-75 grams of $CO_2$-eq/MJ.

The total picture is obtained when looking at the results for the **well-to-wheel**.




For most biofuels, the total well-to-wheel impact is much lower than for the corresponding fossil fuels. The impact from ED95 and RME is less than 40% of the impact from diesel. The biogases (no allocation) show an impact of between 10 – 30% of the impact from natural gas. If considering the system expansion from the use of biogases, the savings from biogas will be even higher.

The only biofuel showing an impact within in the same range as the corresponding fossil fuel is HVO from palm oil, which has more or less the same impact as diesel has. The HVO from rape-seed oil is however significantly lower (40%) compared to fossil diesel.

Some bars show negative values, which is due to the use of system expansions.

**General conclusions**

- The choice of methodology (e.g. energy allocation or no allocation versus system expansion) can have large influence on the LCI results (data).
- The choices of the alternative material and/or energy which are assumed to replace the generated by-products and/or energy are of large importance.
- For ED95 and RME there are small differences between the two scenarios energy allocation and system expansion.
- For the biogases, it is the opposite situation. The system expansion results in much lower values (often even negative). This is an expected result since the corresponding “allocation” scenario, allocates the entire impact to the biogas.

**Comments**

- The amounts of data sets available on vehicle fuels (or fuel components) are poor, especially for biofuels.
- More data sets for different fuels/fuel components, and also data sets based on site specific data, are required.
- Most LCA-studies only reports energy use and greenhouse gas emissions. In order to carry out a more complete environmental assessment, other impact categories should be considered as well.
- Of the data in this study, the data on HVO from palm oil (well-to-tank) are assessed to be the most uncertain. The data are based on several quite extensive LCA-studies, but too much generic background data are used by the authors of these reports. The studies are also quite old. When looking at the results from another data source (JEC (2013)), a well-known study from JRC, EUCAR and CONCAWE, the reported figure for HVO palm oil is 48 g $CO_2$-eq/MJ, to be compared with 77 g $CO_2$-eq/MJ reported in this f3 study. The main reason for not publishing the JEC (2013) data was that no other impacts than global warming is reported in JEC (2013).
- Data on Brazilian sugar cane ethanol were only available for impact categories, and it has furthermore not been possible to assess how well they reflect the actual production.
- No well-to-tank data at all were found for the following fuels; HVO from tall oil (relevant for the Preem Evolution diesel), HVO from other raw materials (e.g. animal fats), ethanol from other raw materials than sugar cane, sugar beets and wheat, Liquefied biogas and natural gas (LBG and LNG) and Compression of biogas and natural gas to CBG and CNG.
- When assessing the impact from using different fuels in vehicles, the consumption of the fuel needs to be considered in addition to the environmental data for the fuel. Note that the fuel consumption in heavy duty vehicles can differ widely due to other factors than the fuel type, namely vehicle type and different driving conditions.

# SAMMANFATTNING

Syftet med projektet har varit att inventera, samla in, tolka och sammanställa de miljödata för svenska fordonsbränslen som finns tillgängliga och som är mest lämpliga för att användas i olika typer av miljöbedömningar, exempelvis i LCA-beräkningar. Resultatet har varit en databas som publiceras av f3 och i CPM-databasen hos CPM – Svenska Livscykelcentret.

Den livscykelinventeringsdata (LCI-data) för "well-to-tank" (produktion av bränslet) samt för "tank-to-wheel" (förbränning av bränslet i ett fordon) som sammanställts har samlats in från tillgängliga LCA-studier och från andra källor. Inga LCA-modelleringar har genomförts i projektet förutom mindre beräkningar i några fall.

De studerade bränslena är bränslen som används i tunga fordon (lastbilar och bussar). Datamängder för följande bränslen har publicerats i databasen: ED95, Fossil diesel, RME, HVO, biogas and naturgas.

Referensenheten för rapporterade LCI-data är 1 MJ bränsle.

Förbrukning av bränsle i fordonet måste också inkluderas vid en bedömning av effekten av att använda olika bränslen i ett fordon. Observera att förbrukningen kan variera beroende på typ av bränsle, typ av fordon och förhållandena för transporten.

Data i form av konkreta siffror presenteras i databasen och inte i rapporten. Däremot illustreras i rapporten resultaten för bränsledatamängderna baserat på växthuseffekt
[g $CO_2$-ekvivalenter(ekv)/MJ bränsle].

För **"well-to-tank"** finns för det flesta bränslen två olika scenarier; allokering och systemexpansion. För fossil diesel och naturgas finns endast ett scenario. De scenarier som publicerats är de som finns tillgängliga i originalreferenserna.

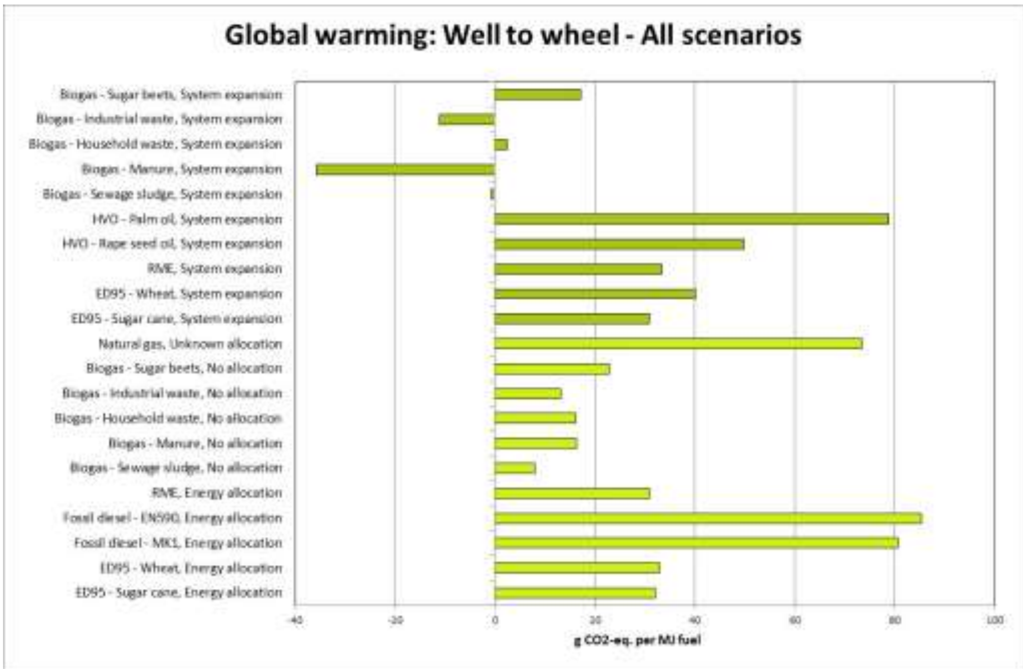
För well-to-tank, uppvisar biobränslena ED95, RME och HVO en högre miljöbelastning än den fossila dieseln gör. Biogas, oavsett produktionsprocess, ligger på ungefär samma nivå som naturgas.

För **"tank-to-wheel"**, finns två datamängder per bränsle; för Euro V respektive Euro VI motor. Data skiljer sig med avseende på emissioner av metan ($CH_4$), kväveoxider ($NO_x$), icke metaninnehållande flyktiga kolväten (NMVOC) och partiklar (PM), medan emissioner av fossil koldioxid ($CO_2$), kolmonoxid (CO), lustgas ($N_2O$) och svaveldioxid ($SO_2$) är desamma oavsett Euroklass.

För biobränslena biogas och HVO är de fossila koldioxidemissionerna antagna att vara noll. Det finns dock emissioner av de andra växthusgaserna ($CH_4$ and $N_2O$), varför bidraget till växthuseffekten inte är noll. För RME är en liten del (1 av 19 kolatomer) i bränslet av fossilt ursprung, vilket betyder att lite fossil $CO_2$ bildas utöver de andra växthusgaserna. För ED95 kommer den fossila koldioxiden från tillsatserna (inte från etanolen).

Alla biobränslena uppvisar ett bidrag till växthuseffekten på mindre än 10 gram $CO_2$-ekv/MJ, medan de fossila bränslena varierar mellan 60-75 gram $CO_2$-ekv/MJ.

Den totala bilden erhålls när man tittar på resultatet för **”well-to-wheel”**.




Ur det totala livscykelperspektivet är miljöbelastningen för de flesta biobränslena mycket lägre än för motsvarande fossila bränslen. ED95 och RME uppvisar en miljöbelastning som är mindre än 40% av den för fossil diesel. Jämför man biogaserna (ingen allokering) med naturgas så ligger dessa på mellan 10-30% av miljöbelastningen för naturgas. Besparingen från biogas blir ännu högre om man beaktar systemexpansion.

Det enda biobränsle som uppvisar en miljöbelastning som ligger på ungefär samma nivå som motsvarande fossila bränsle är HVO från palmolja. HVO från rapsolja däremot ligger betydligt lägre (40%) jämfört med fossil diesel.

Vissa bränslen uppvisar negativa resultat, vilket beror på att systemexpansion har använts.

**Generella slutsatser**

- Valet av metod (energiallokering, ingen allokering eller systemexpansion) kan ha stor påverkan på resultaten.
- Valet av alternativt material och/eller alternativ energi som antas ersätta genererade biprodukter och/eller genererad energi, är av stor betydelse.
- För ED95 och RME är skillnaden liten mellan de tillämpade scenarierna energiallokering och systemexpansion.
- För biogaserna gäller det motsatta. Med systemexpansion erhålls mycket lägre miljöbelastning (ofta till och med negativ). Detta är ett väntat resultat eftersom all miljöbelastning allokeras till huvudprodukten i scenariot ”ingen allokering”.

**Kommentarer**

- Datautbudet (antalet datamängder) för tillverkning av fordonsbränslen är knapert, speciellt för biobränslen.
- Fler datamängder behövs för olika bränslen och bränslekomponenter, men också mer specifik data baserad på verkliga anläggningar.
- Många LCA-studier redovisar enbart energianvändning och växthusgaser. För att göra en mer fullständig miljöbedömning krävs fler miljöaspekter än så.
- Av de data som publiceras in denna rapport bedöms HVO från palmolja (”well-to-tank”) vara de mest osäkra. Dessa data baseras på flera omfattande LCA-studier, som dock både är ganska gamla och använder mycket generiska bakgrundsdata. Jämförs resultaten med en annan välkänd datakälla (JEC (2013)), rapporterar denna studie 48 g $CO_2$-ekv/MJ medan motsvarande siffra publicerad i denna f3-studie är så hög som 77 g $CO_2$-ekv/MJ. Huvudorsaken till att inte publicera data från JEC (2013) är att inga andra miljöpåverkanskategorier än växthuseffekt rapporteras i denna studie.
- Data för brasiliansk sockerrörsetanol fanns enbart tillgänglig i form av miljöpåverkanskategorier. Det har vidare inte varit möjligt att bedöma hur väl dessa data speglar den faktiska produktionen.
- För följande drivmedel har inga data hittats; HVO från tallolja (relevant för Preem Evolution diesel), HVO från andra råvaror (t.ex. kött- och fiskrester), etanol från andra råvaror än sockerrör, sockerbetor och vete, vätskeformig biogas och naturgas (LBG and LNG) samt komprimering av biogas och naturgas till CBG och CNG.
- När man analyserar miljöpåverkan från användning av olika bränslen i fordon måste även fordonets bränsleförbrukning beaktas. Notera att tunga fordons bränsleförbrukning kan variera avsevärt beroende på andra faktorer än bränsletyp t.ex. typ av fordon och körbetingelser.

# ABBREVIATIONS

| | |
|---|---|
| LCA | Life cycle assessment |
| LCI | Life cycle inventory |
| WTT | Well-to-tank, the production of the fuel cradle-to-gate |
| TTW | Tank-to-wheel, the combustion of the fuel in a vehicle |
| WTW | Well-to-wheel = WTT+TTW, i.e. the whole perspective from cradle-to-combustion in an engine |
| GWP | Global warming potential, expressed as amount of carbon dioxide ($CO_2$) equivalents in gram or kilogram. |
| ED95 | Ethanol fuel with about 94 w-% denaturised hydrous ethanol |
| FAME | Fatty acid methyl ester (biodiesel) |
| RME | Rape seed methyl ester i.e. a type of FAME |
| HVO | Hydrotreated vegetable oil |
| CNG | Compressed natural gas |
| CBG | Compressed biogas |
| MK1 | Diesel according to “Miljöklass 1” |
| EN590 | Diesel according to the European standard EN590 |

# CONTENTS

# 1 GOAL AND SCOPE

Commercial fuels in the market are blended out of various constituents. Biomass-based components are part of practically all commercial fuels today (ethanol fuels, RME/HVO in diesel, CNG/CBG mixtures). With an increasing demand for environmental communication business-to-business as well as business-to-consumer there is also an increasing demand for generic, well-acknowledged best available environmental data for vehicle fuels, both in terms of production (well-to-tank, WTT), as well as emissions from use in vehicles (tank-to-wheel, TTW).

## 1.1 PURPOSE OF THE PROJECT

The purpose of this project has been to gather and compile the best available environmental data for vehicle fuels on the Swedish market, for use in environmental assessments (such as LCA etc.) within the transport sector as well as other sectors. The purpose of the study has been to publish data which are available and it has not been possible to estimate any lacking emissions. The full project results are presented in a separate database (see section 1.6).

## 1.2 FUELS STUDIED

The studied fuels are used in heavy duty vehicles (trucks and buses). The fuels are divided into the groups; Diesel fuels (Table 1), and Methane fuels (Table 2).

**Table 1. Diesel fuels included in the study.**

| "Diesel fuels" | Fossil | Remark |
|---|---|---|
| ***ED95 - Sugar cane*** | Partly | Ethanol (renewable) and additives which are of fossil origin. |
| ***ED95 - Wheat*** | Partly | Ethanol (renewable) and additives which are of fossil origin. |
| ***Fossil diesel - MK1*** | Yes | According to the Swedish MK1: "Miljöklass 1" (EC1 Environmental class 1). |
| ***Fossil diesel – EN590*** | Yes | According to the EN590 standard. |
| ***Rapeseed methyl ester (RME)*** | Partly | RME can be used as a fuel component in fossil diesel or as a fuel product as such. A small share of its carbon content is of fossil origin. |
| ***Hydrotreated Vegetable Oil - Rapeseed oil*** | No | HVO's can be used as a fuel component in fossil diesel or as a fuel product as such. |
| ***Hydrotreated Vegetable Oil - Palm oil*** | No | HVO's can be used as a fuel component in fossil diesel or as a fuel product as such. |

As far as possible, the data for the fuels reflect fuels on the Swedish market. An exception is the fossil diesel EN590, which represents European conditions both for well-to-tank and tank-to-wheel.

**Table 2. Methane fuels in the study.**

| ”Methane fuels” | Fossil | Remark |
|---|---|---|
| ***Biogas - Sewage sludge*** | No | Used as a component in a biogas mix. |
| ***Biogas - Manure*** | No | Used as a component in a biogas mix. |
| ***Biogas - Household waste*** | No | Used as a component in a biogas mix. |
| ***Biogas - Industrial waste*** | No | Used as a component in a biogas mix. |
| ***Biogas - Sugar beets*** | No | Used as a component in a biogas mix. |
| ***Natural gas*** | Yes | |

Except for the fuel products/components listed in Table 1 and Table 2, the database also contains the ethanol data sets presented in Table 3.

**Table 3. Ethanol data sets included in the study.**

| Ethanol data sets | Fossil | Remark |
|---|---|---|
| ***Ethanol from sugar cane*** | No | Used in the LCA modelling of ED95 - Sugar cane. |
| ***Ethanol from wheat*** | No | Used in the LCA modelling of ED95 - Wheat. |
| ***Ethanol from sugar beets*** | No | Just published in the database since it was available. |

## 1.3 REFERENCE UNIT

The reference unit for the reported LCI-data is 1 MJ fuel.

## 1.4 REPORTED PARAMETERS

Available life cycle inventory data (LCI-data) for well-to-tank (production of the fuel cradle-to-gate) as well as tank-to-wheel (combustion of the fuel in a vehicle) have been gathered. In the **well-to-tank** (WTT) analysis, the reported parameters vary depending on which parameters were included in the original data source. The inputs of energy resources are in some cases in the referred literature either not reported at all or reported as primary energy demand. In some cases there are data on the use of energy resources, such as crude oil, natural gas, hard coal and uranium.

Common emissions to air from WTT are:

- fossil carbon dioxide ($CO_2$),
- methane ($CH_4$),
- nitrous oxide ($N_2O$),
- carbon monoxide (CO),
- nitrogen oxides ($NO_x$),
- sulphur dioxide ($SO_2$),
- non-methane volatile organic compounds (NMVOC), and
- particles (PM)

Common emissions to water from the well-to-tank are:

- nitrate,
- nitrogen,
- ammonia,
- ammonium, and
- phosphate.

In some referred literature, only the impact categories global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photo-oxidant formation potential (POCP) are reported.

The reported emissions for the TTW data sets are fossil carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), carbon monoxide (CO), nitrogen oxides ($NO_x$), sulphur dioxide ($SO_2$), non-methane volatile organic compounds (NMVOC) and particles (PM).

## 1.5 PROJECT PROCEDURE

The data have been collected from different available LCA studies and other sources and have been interpreted, documented and inserted to a database. In some cases the figures have been recalculated from another reference unit to the reference unit 1 MJ. In these cases a physical property such as heat value or density has been used. No LCA modelling has been carried out in the project except for some minor calculations for ED95 and HVO, for further details see these sub-sections in section 2.2.2.

## 1.6 THE DATABASE

Available life cycle inventory data (LCI-data) for well-to-tank (production of the fuel cradle-to-gate) as well as tank-to-wheel (combustion of the fuel in a vehicle) have been gathered in the project. The data compiled in the project are published in a database, with separate files for each fuel, the WTT data (divided on scenarios) and for the TTW data (based on Euro V and Euro VI engines).

The file names are presented in appendix A.

The database is published separately on the f3 website.

The data has also been imported to the CPM database distributed by CPM - Swedish Life Cycle Center. Access the database here: http://lifecyclecenter.se/tools-data/cpm-lca-database/.

The detailed documentation of the data (system boundaries, assumptions, allocations, underlying data sources used by the original reference/report, etc.) can only be found in the database. This means that for details concerning the methodological aspects, the documentation in the database is required. This report serves to complement the database with brief descriptions of each studied fuel, and references to each data source. See section 2.2 for the WTT analysis and section 2.3 for the TTW analysis. The database should be considered as the main deliverable from the project.

# 2 FUEL LCI DATABASE

## 2.1 PHYSICAL PROPERTIES OF THE STUDIED FUELS

The physical properties of the fuels are presented in Table 4.

**Table 4. Physical properties of the fuels included in the project.**

| Data set in database | Heat value [MJ/kg] | Density [kg/m3] | Remark |
|---|---|---|---|
| ***ED95*** | 25.7 [(a)] | 818 [(a)] | Same for ED95 irrespective of ethanol origin e.g. Sugar cane, Wheat etc. |
| ***Fossil diesel - MK1*** | 43.3 [(b)] | 815 [(b)] | |
| ***Fossil diesel – EN590*** | 42.6 [(b)] | 840 [(b)] | |
| ***Rapeseed methyl ester (RME)*** | 38.0 [(c)] | 833 [(c)] | |
| ***Hydrotreated Vegetable Oil (HVO)*** | 44.1 [(d)] | 780 [(d)] | Same for HVO irrespective of ethanol origin e.g. Rapeseed oil, Palm oil etc. |
| ***Biogas*** | 46.9 [(e)] | 0.74 [(e)] | Same for all biogases irrespective of origin. |
| ***Natural gas*** | 47.9 [(f)] | 0.814 [(f)] | Based on values for gas sold in the south of Sweden. |

a) These are the properties for the ED95 fuel. The ethanol part has a heat value of 25.4 MJ/kg and a density of 807 kg/m$^3$ (Mattebo 2013).
b) SPBI (2010)
c) Perstorp (2013)
d) Mikkonen et. al. (2012, p. 15).
e) The heat value is 34.74 MJ/Nm$^3$ and the density is 0.74 kg/Nm$^3$. (Johansson 2013)
f) This is based on a heat value of 39.0 MJ/Nm$^3$ and a density of 0.814 kg/Nm$^3$, average for 2013 for Swedish natural gas (Swedegas 2013).

## 2.2 WELL-TO-TANK DATA

Available LCI-data for the production of the fuels (WTT) are published in the database (see section 1.6).

### *2.2.1 Scenarios for WTT data*

For several of the fuels there are two scenarios for WTT; one concerning the type of allocation method and one addressing system expansion (in which the environmental savings due to by-products and/or generated energy are considered). When allocation has been applied it is energy allocation. In some cases no allocation is performed, meaning that the entire environmental impact has been allocated to the fuel. In this project all scenarios available in the original data sources were applied, i.e. the choice of allocation method or whether or not to perform system expansion (and how) were not made by the participants of this project.

The different scenarios addressed in the data sets are presented in Table 5.

**Table 5. Scenarios for the data sets.**

| Data set in database | Allocation scenario | System expansion scenario |
|---|---|---|
| ***ED95 - Sugar cane*** | Energy allocation | Yes |
| ***ED95 - Wheat*** | Energy allocation | Yes |
| ***Fossil diesel - MK1*** | Energy allocation | No |
| ***Fossil diesel – EN590*** | Energy allocation | No |
| ***Rapeseed methyl ester (RME)*** | Energy allocation | Yes |
| ***Hydrotreated Vegetable Oil - Rapeseed oil*** | No | Yes |
| ***Hydrotreated Vegetable Oil - Palm oil*** | No | Yes |
| ***Biogas - Sewage sludge*** | No allocation | Yes |
| ***Biogas - Manure*** | No allocation | Yes |
| ***Biogas - Household waste*** | No allocation | Yes |
| ***Biogas - Industrial waste*** | No allocation | Yes |
| ***Biogas - Sugar beets*** | No allocation | Yes |
| ***Natural gas*** | Unknown allocation | Yes |
| ***Ethanol from sugar cane*** | Energy allocation | Yes |
| ***Ethanol from wheat*** | Energy allocation | Yes |
| ***Ethanol from sugar beets*** | Energy allocation | Yes |

### *2.2.2 WTT data for each fuel*

The data sources used for the WTT data are presented in the sub section for each fuel. One common data source is Börjesson et.al (2010), but other data sources have been applied as well.

A well-known data source, which has not been applied is JEC (2013), a study from JRC, EUCAR and CONCAWE, which reports both WTT and TTW data. The reasons why are described below.

The JEC (2013) study uses marginal data for fossil fuels and electricity – a methodological approach, which was not considered as applicable here in this study. Furthermore, only greenhouse gas emissions and energy use are reported, which is not considered to be sufficient enough. Furthermore, the time perspective is 2020-2025, while this study focuses on the current situation.

#### *ED95*

ED95 is an ethanol based fuel used in dedicated, adapted diesel engines (trucks and buses).

In Sweden ED95 is produced by SEKAB, Domsjö, Örnsköldsvik. The ethanol for ED95 can be produced from different raw materials such as wheat, sugar beet, sugar cane etc., but since 2012 SEKAB only purchases ethanol from Brazilian sugar canes, since it is considered to be the most sustainable (Indevall 2013).

The composition of ED95 is 94 w-% denaturised hydrous ethanol and 6 w-% components. The components serve as ignition improver, lubricant and denaturant. SEKAB has provided the exact composition and chemical information about the components as well all relevant physical properties such as densities, heat values and fossil carbon contents (Mattebo 2013). These data are however confidential.

Two LCA models of the ED95 fuel was made; based on Brazilian sugar cane ethanol and based on ethanol from wheat. The models include the upstream production of the raw materials, but not the ED95 production itself.

Since the composition is confidential, only the LCI-results from these models were published in the database. For the production of ethanol (WTT), data from Börjesson et.al (2010) were used for both sugar cane and wheat ethanol.

The ignition improver and lubricant are produced by AkzoNobel Surface Chemistry (Martinsson 2013). The LCA data for the production, could however not be provided within the timeframes of this project. Instead, data were found in a Master thesis performed for AkzoNobel Surface Chemistry (Changa Rodriguez 2003). Although these data were from 2003 they were the most recent data available.

Data for the denaturant were found in the Ecoinvent database (2013).

For both the two ED95 data sets (sugar cane and wheat) two different scenarios have been published; one where the emissions are allocated between the ethanol and the by-products based on the energy content, and one where system expansion is applied to include the benefits from the generated by-products.

The data were recalculated from per kg to per MJ of fuel by using a heat value of 25.7 MJ/kg.

### *Fossil diesel*

Fossil diesel is used as a fuel in diesel engines (trucks and buses).

This project has used two data sources for diesel production that were considered to provide the best available data:

- For Swedish MK1 diesel the data from Öman, Hallberg and Rydberg (2011) have been chosen. These are the same data as published in Miljöfaktaboken (Gode et.al 2011).
- For diesel according to EN 590 standard, data from the ELCD Database (2013) were applied. The practitioner of the LCA was PE International (developer of the Gabi software and databases) on behalf of the Institute for Environment and Sustainability (IES), one of the seven scientific institutes of the European Commission’s Joint Research Centre (JRC).

When looking at the GWP for instance, the data applied for MK1 is 27% lower than the ELCD data applied for EN 590.

For the two diesel data sets (MK1 and EN590) only one scenario has been published, where the emissions are allocated between the diesel and the by-products based on the energy content.

The data were already provided per MJ in both data sources (i.e. no recalculation needed).

There are other data on fossil diesel production available, most of them (e.g. the data used in the CEN standard) are only reporting greenhouse gas emissions and energy use, which is not sufficient for LCA calculations. A report from EcoTraffic written for Trafikverket (Ahlvik & Eriksson 2012) also states that there are no significant differences between the two diesel qualities. Since the study only analysis greenhouse gas emissions and energy use, it was not sufficient to be used in the report from this f3 project.

Ahlvik and Eriksson (2012) report roughly 9.3 g $CO_2$-eq/MJ fuel (irrespective of diesel quality). The corresponding figures for the data published in the f3 database are 6.6 (MK1 diesel) and 9.1 (EN 590 diesel).

It is however important to keep in mind that even if we in this project have published WTT data where the EN 590 has higher values than the MK1 quality, the contribution from WTT is only roughly 10% of the total WTW for greenhouse gas emissions.

Another study reporting WTW data for diesel fuels is the WTW LCA from JEC (2007). The JEC study reports even higher values for greenhouse gas emissions, due to application of a different methodological approach using marginal data. Since the study uses a methodological approach, which could not be considered as applicable here in this f3 study, these data were not used. Further-more, only greenhouse gas emissions and energy use are reported in the JEC study, which is not considered to be sufficient enough.

### *RME*

Fatty acid methyl ester (FAME), can be used as a component in fossil diesel or as a fuel as such for dedicated diesel engines (trucks and buses). When used as a diesel component, maximum 7% FAME is allowed according to the “Fuel Quality Directive” (Tamm 2013). In Sweden, mainly rapeseed methyl ester (RME) is used. RME is for instance produced by Perstorp Oxo in Stenungsund.

For the production of RME, WTT data from Börjesson et.al (2010) were used.

For the RME data set two different scenarios have been published; one where the emissions are al-located between the RME and the by-products based on the energy content and one where system expansion is applied to include the benefits from the generated by-products.

The data were already provided per MJ (i.e. no recalculation needed).

### *Hydrotreated Vegetable Oil (HVO)*

Hydrotreated Vegetable Oil (HVO) can be used as a component in fossil diesel. The Swedish and European standards for diesel allow for a blending of up to approximately 20% HVO in diesel as well as 7% FAME/RME.

HVO can be used as a fuel as such for dedicated diesel engines. According to an HVO handbook published by Neste oil (Mikkonen et.al 2012), exhaust after treatment device will be easier when engine-out particulate and NOx emissions are lower and ash content of the fuel negligible. To at-tain full benefits of the fuel and engine, the fuel injection system may need recalibration due to the lower density and higher cetane number of HVO (Mikkonen et.al 2012).

Hydrotreated Vegetable Oil (HVO) can be produced from e.g. tall oil, rapeseed oil, palm oil, camelina oil, jatropha oil, soybean and animal fats. Preem is using tall oil as raw material while the other big producer of HVO, Neste Oil, uses other raw materials such as palm oil (64.5%), waste and residues (35.1%) and other vegetable oils (0.3%) (Neste Oil 2012). On the Swedish market, mainly rapeseed oil and animal fats are used by Neste Oil as base for the HVO.

Data for process steps relevant for HVO production (WTT) were found in several publications. Since none of these contained the desired system boundaries for fuel HVO, an LCA model had to be compiled. This was carried out for HVO from rapeseed oil and from palm oil respectively. The modelling was made more or less exactly as in the original data sources i.e. by using the same assumptions and upstream data.

For the agriculture rapeseeds and oil palms and for the oil processing from rapeseeds and oil palm fruit bunches, detailed data from Schmidt (2007) were used. This reference had in turn used both site specific data as well as database data from the Ecoinvent database (2013). The oil palms are grown in Malaysia and the rapeseeds are based cultivation in Denmark.

For the hydro treatment process (i.e. production of HVO at Neste oil), data from two reports were used: Arvidsson & Persson (2008) and Reinhardt et.al (2006).

No data have been found for the production of HVO from animal fats or any other raw materials used in HVO production.

For the two HVO data sets (rapeseed oil and palm oil) only one scenario has been published, where system expansion is applied to include the benefits from the generated by-products.

The data were recalculated from per kg to per MJ of fuel by using a heat value of 41.1 MJ/kg.

### *Biogas*

For the production of biogases data from Börjesson et.al (2010) were used. The data for biogas from sewage sludge are however based on Palm and Ek (2010). The data were already provided per MJ (i.e. no recalculation needed).

The upgraded biogas is sometimes used as a fuel itself in vehicles, but in the south of Sweden the biogas is often injected to the natural gas grid, and thus mixed with natural gas. Depending on the substrate that the biogas is produced from, how well the process is running, and how efficient the purification of the gas is, the heat value and density of the gas will vary. Based on this it is hard to say what the properties of biogas in general are. However, in this study density and heat values were needed to convert some of the data to the reference unit. Data on density and heat value have been obtained from FordonsGas Sverige (Johansson 2013), who does regular measurements in order to assure that they meet the quality required in the Swedish biogas standard (SS 155438).

According to Fordonsgas Sverige (Johansson 2013) the heat value on the gas they buy varies between 9.67-9.77 kWh/Nm$^3$. In calculations where the heat value is needed, Fordonsgas Sverige uses 9.7 kWh/Nm$^3$ (34.7 MJ/Nm$^3$). The density of the gas also varies between production sites, mostly due to variations in gas impurities. FordonsGas Sverige is using the density 0.74 kg/Nm$^3$ when a general figure is required. In this study the density and heat value provided by FordonsGas Sverige is used in all calculations.

When performing LCA on biogas production an important issue is what is done with the digestate. For every substrate two different scenarios have been used; one traditional with all emissions allocated to the biogas production (the "no allocation scenario") and one where system expansion is used to include the benefits of using digestate instead of mineral fertilizer. In the system expansion case, the digestate from the biogas production is replacing mineral fertilizer. This gives a significant lower emission level since production of mineral fertilizer causes quite a lot of environmental impact e.g. concerning the global warming potential. For the system expansion cases the environmental impact is only available per impact category. The data could not be disaggregated for each emission substance.

#### *Natural gas*

For the production of natural gas, WTT data from Boustead (2005) were used. The data were recalculated from 'per kg' to 'per MJ' of fuel by using a heat value of 47.9 MJ/kg.

The heat value and density for the natural gas comes from Swedegas, and refers to gas sold from the gas network in the south east of Sweden. Heat value and density of natural gas do vary between different places mostly because of the content of hydrocarbons other than methane.

For the natural gas data set there is only one scenario published, in which the allocation method used for allocating the emissions between the natural gas and the by-products is unknown.

## 2.3 TANK-TO-WHEEL DATA

Data for combustion of fuels used for propulsion of a vehicle (TTW) are published in the database (see section 1.6).

The data are reported for fuels used in vehicles equipped with Euro V or Euro VI engines.

The emissions factors per MJ of fuel refer to the use of fuel in heavy duty vehicles, i.e. vehicles used for transport of goods and for buses.

### *2.3.1 General principle for deriving the TTW emission factors*

The reported emission factors should be considered as generic data. It should be noted that the emissions for a specific vehicle might differ from those generic data, e.g. the limit values for certification of engines have been used as basis for deriving some of the emission factors. The duty cycles used for certification are defined to cover the whole range of typical loads of an engine in different operations. The operation of a specific vehicle can however differ from the duty cycle used in the certification, resulting in different emissions than calculated with the generic emission factors.

Emissions of $CO_2$ and $SO_2$ are directly dependent of the composition of the fuels. The emission factors have been calculated from the carbon and sulphur content based on the composition of typical fuels in the Swedish market in 2013. The references vary depending on fuel. The calculations and references are presented in appendix B.

Emissions of carbon monoxide (CO), total hydrocarbons (THC), nitrogen oxides ($NO_X$) and particles (PM) from engines are regulated in directive 2005/55/EC for Euro V engine and Regulation (EC) No 595/2009 for Euro VI engines. In addition, emissions of methane ($CH_4$) and non-methane volatile organic compounds (NMVOC) are regulated for gas fuelled engines (other types of fuels have significant lower emissions of $CH_4$). In order to derive the emissions factors from the limit values in the legislation, some conservative assumptions have been made:

- The limits in the legislations are maximum emissions in grams per energy delivered from the engine (g/kWh). In order to calculate emissions factors per energy unit of the fuel into the engine, a value for the engine efficiency has to be assumed. The efficiency differs between different engine load points/operations. As a conservative approach the efficiency in the best point has been used for calculation of the emission factors (observe that a higher engine efficiency results in higher emission factors).
- Certification of the engine involves testing of the engine in a test bench using agreed duty cycles. The limit values are specified for two types of duty cycles, for a steady state duty cycle and for a transient duty cycle. The emission factors have been derived using the transient cycles in the Euro V and Euro VI regulations. (The transient cycle has been changed between Euro V and Euro VI. However, no significant effects on the generic emission factors are expected from this change).

Nitrous oxide ($N_2O$) emissions and methane ($CH_4$) emissions from other than gas-fuelled engines are not regulated in the European regulations. There are only a few reports of non-regulated emissions of $CH_4$ and $N_2O$ from heavy duty vehicles, therefore two generic assumptions have been made to estimate the emissions:

- The emissions of $CH_4$ are maximum 10% (JEC 2013) of the total hydrocarbons for all fuels except natural gas and biogas.
- Emissions of $N_2O$ are approximately 50 mg/kWh. This is a rough estimate based on limited data. The emissions of $N_2O$ depend on the type of technology applied for $NO_X$-reduction, which can vary between different manufacturers and engine types, rather than the fuel type.

### 2.3.2 Data sources for fuel consumption

In order to quantify emissions as total emissions in grams, grams emission per km transport or grams per tonne-km transported goods etc., the published emission factors have to be multiplied with a value for the fuel consumption.

The fuel consumption in heavy duty vehicles can differ widely depending on both the type of vehicle, different driving conditions (the road slope, the speed, traffic conditions etc.) and vehicle load etc. For example, the fuel consumption (litres/100 km) can easily differ more than 100% depending on the driving conditions and load for a long haulage mission. No generic values for fuel consumption in a heavy duty vehicle are therefore provided in this report.

We recommend using the following sources for the fuel consumption, in the following order:

1. Measured fuel consumption, in case of studying a specific vehicle and a specific route.
2. Calculated fuel consumption using calculation programs that are capable to consider the parameters important for the specific route and the driving conditions studied (the speed, slope, payload etc.).
3. Generic or typical values for the type of transport studied, in cases when more specific values are lacking.

There is yet today no common defined method on how to measure fuel consumption in heavy duty vehicles, thus great care should be taken when comparing data on fuel consumption from different sources.

### *2.3.3 Data sources for TTW emission factors*

Data on emission factors are derived based on limit values for maximum emission during certification of engines. For non-regulated emissions, the generic emission factors have been assumed based on judgement by vehicle manufacturers.

Detailed information concerning the compilation of the emission factors, assumptions made and used data sources can be found in the published database (see description in section 1.6).

Data on properties and composition of the different fuels are based on information from fuel producers (sections 2.1 and 2.2).

### *2.3.4 TTW fuel data sets*

For the tank-to-wheel stage, the number of data sets is smaller (Table 6) since the same emissions are generated irrespective of the origin of e.g. the ethanol or the biogas, which is not the case for well-to-tank.

**Table 6. Tank-to-wheel data sets.**

| Data set in database | Remark |
|---|---|
| ***ED95*** | Same for ED95 irrespective of ethanol origin e.g. Sugar cane, Wheat etc. |
| ***Fossil diesel - MK1*** | |
| ***Fossil diesel – EN590*** | |
| ***Rapeseed methyl ester (RME)*** | |
| ***Hydrotreated Vegetable Oil (HVO)*** | Same for HVO irrespective of ethanol origin e.g. Rapeseed oil, Palm oil etc. |
| ***Biogas*** | Same for all biogases irrespective of origin. |
| ***Natural gas*** | |

### *2.3.5 Emission factors*

The emission factors for the tank-to-wheel stage are presented in Table 6. Since the emissions of $CO_2$, $N_2O$, CO and $SO_2$ are not affected by emission class they are therefore labelled Euro V, VI. For the other emissions, separate emission factors for Euro V and Euro VI engines are reported.

**Table 7. Emission factors [kg/MJ] Tank-to-wheel.**

| Data set in database | $CO_2$ | $CH_4$ | | $N_2O$ | CO | $NO_x$ | | $SO_2$ | NMVOC | | PM, unspecified | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Engine** | **Euro V, VI** | **Euro V** | **Euro VI** | **Euro V, VI** | **Euro V, VI** | **Euro V** | **Euro VI** | **Euro V, VI** | **Euro V** | **Euro VI** | **Euro V** | **Euro VI** |
| ***ED95*** | 7.29E-03 | 6.57E-06 | 1.91E-06 | 6.11E-06 | 4.78E-04 | 2.39E-04 | 5.49E-05 | 2.33E-07 | 5.91E-05 | 1.72E-05 | 3.58E-06 | 1.19E-06 |
| ***Fossil diesel - MK1*** | 7.20E-02 | 6.72E-06 | 1.96E-06 | 6.11E-06 | 4.89E-04 | 2.44E-04 | 5.62E-05 | 1.39E-07 | 6.05E-05 | 1.76E-05 | 3.67E-06 | 1.22E-06 |
| ***Fossil diesel – EN590*** | 7.43E-02 | 6.72E-06 | 1.96E-06 | 6.11E-06 | 4.89E-04 | 2.44E-04 | 5.62E-05 | 2.82E-07 | 6.05E-05 | 1.76E-05 | 3.67E-06 | 1.22E-06 |
| ***Rapeseed methyl ester (RME)*** | 5.08E-03 (1) | 6.72E-06 | 1.96E-06 | 6.11E-06 | 4.89E-04 | 2.44E-04 | 5.62E-05 | 1.58E-07 | 6.05E-05 | 1.76E-05 | 3.67E-06 | 1.22E-06 |
| ***Hydrotreated Vegetable Oil (HVO)*** | 0 | 6.72E-06 | 1.96E-06 | 6.11E-06 | 4.89E-04 | 2.44E-04 | 5.62E-05 | 1.36E-07 | 6.05E-05 | 1.76E-05 | 3.67E-06 | 1.22E-06 |
| ***Biogas*** | 0 | 1.22E-04 | 5.56E-05 | 5.56E-06 | 4.44E-04 | 2.22E-04 | 5.11E-05 | 8.52E-07 | 6.11E-05 | 1.78E-05 | 3.33E-06 | 1.11E-06 |
| ***Natural gas*** | 5.73E-02 | 1.22E-04 | 5.56E-05 | 5.56E-06 | 4.44E-04 | 2.22E-04 | 5.11E-05 | 8.35E-07 | 6.11E-05 | 1.78E-05 | 3.33E-06 | 1.11E-06 |

(1) Fossil $CO_2$ calculated based on the fact that 1 of 19 carbon atoms is of fossil origin (from the methanol), see appendix B. However, if it is known that the methanol is of renewable origin, the $CO_2$ emission should be set to zero.

## 2.4 RESULTS – GLOBAL WARMING POTENTIAL

An illustration of the results for the fuel data sets based on Global warming potentials [g $CO_2$-eq/MJ fuel] is presented here. The actual figures are presented in the f3 database.

Three diagrams are presented for the three stages well-to-tank, tank-to-wheel and well-to-wheel (Figure 1-Figure 3).

### *2.4.1 Well-to-tank*

For well-to-tank, there are for most fuels two different scenarios; energy allocation and system expansion. For the biogases there is one scenario with system expansion and one scenario in which no allocation has been performed i.e. where the entire environmental impact has been allocated to the biogas. For fossil diesel and natural gas there is only one scenario, see section 2.2.1.

In the system expansion scenarios, a credit for generated by-products and/or energy has been given to the main product by assuming an alternative material and/or alternative energy source which has replaced the generated by-products and/or energy. This explains the negative bars in some cases.

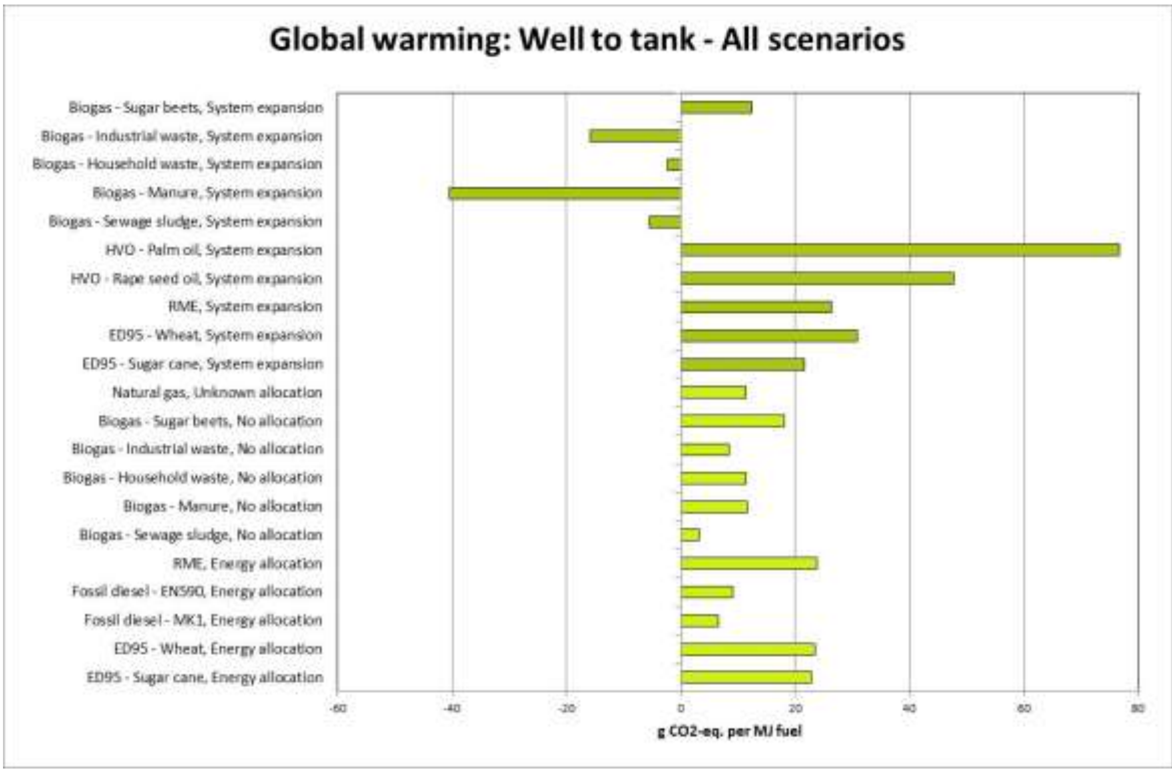



**Figure 1. Global Warming Potential for Well-to-tank [g $CO_2$-equivalents/MJ fuel].**

For WTT, the biofuels ED95, RME and HVO show a larger impact than the fossil diesel. The group of biogas fuels show a similar impact as the natural gas (when applying the “no allocation” scenarios).

The HVO from palm oil and rape seed oil both have a relatively large impact for WTT and it is therefore interesting to compare these results with another data source. In JEC (2013), a well-known study from JRC, EUCAR and CONCAWE, the reported figure for HVO palm oil is 48g $CO_2$-eq/MJ to be compared with 77g $CO_2$-eq/MJ reported in this study. Due to aspects such as too aggregated data and lack of transparency, it has not been possible to assess exactly why there is such a huge difference. One reason could be that the data (on which the compilation for HVO palm oil is based on) are older than those used in the JEC (2013) study. The three studies this compilation was based on were from 2006-2008 (see section 2.2.2). Another qualified guess is that the actual underlying data sources differ.

When looking at the corresponding figures for HVO rape seed oil, the results are however within the same range; the JEC (2013) reports 58g $CO_2$-eq/MJ to be compared with 48g $CO_2$-eq/MJ reported in this f3 study.

The same comparison can be made for RME, which in this f3 study causes only about 27g $CO_2$-eq/MJ while JEC (2013) reports 55g CO2-eq/MJ. For the same reason as mentioned for HVO, it has not been possible to assess why the results differ that much, but we can at least figure out that an important issue such as inclusion of $N_2O$ emissions from agriculture is considered in both studies.

The main reason for not publishing the JEC (2013) data was that no other impacts than global warming is reported in JEC (2013) (see section 2.2.2).

### *2.4.2 Tank-to-wheel*

For TTW, two data sets for each fuel are presented; Euro V and Euro VI engine. The data sets differ concerning the emissions of methane ($CH_4$), nitrogen oxides ($NO_x$), non-methane volatile organic compounds (NMVOC) and particles (PM), while emissions of fossil $CO_2$, carbon monoxide (CO), nitrous oxide ($N_2O$) and sulphur dioxide ($SO_2$) are the same irrespective of Euro class.

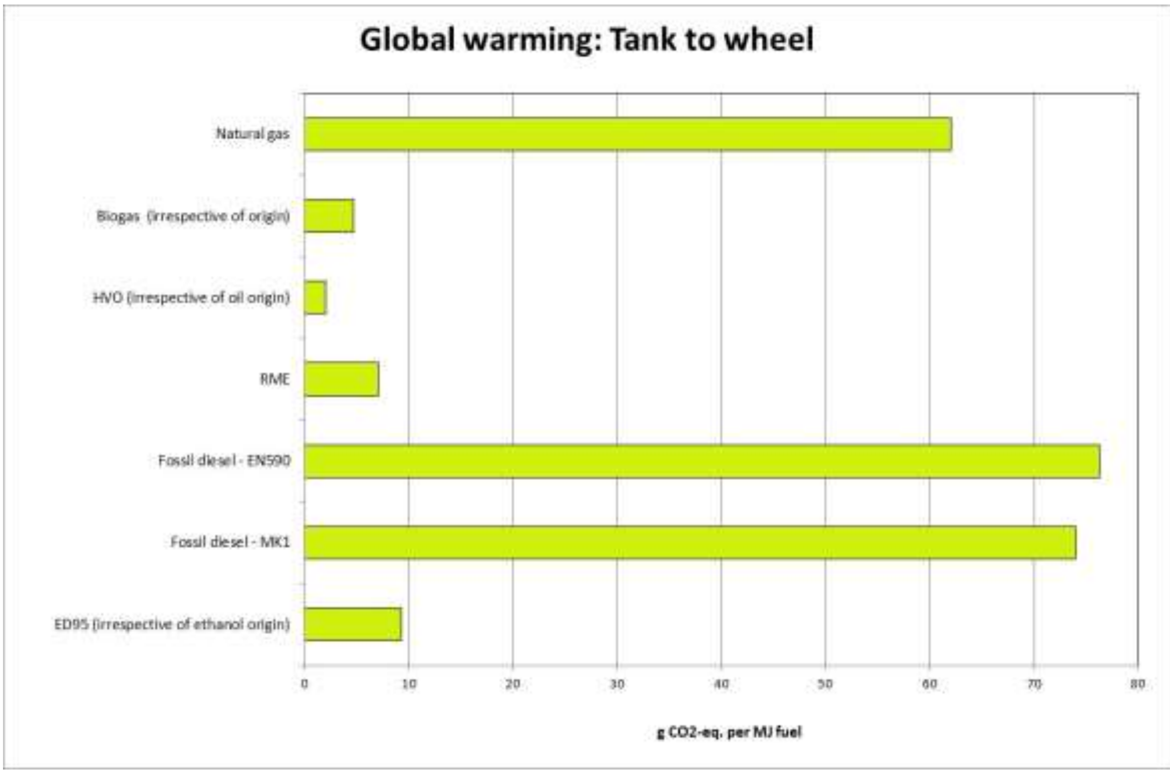



**Figure 2. Global Warming potential for Tank-to-wheel [g $CO_2$-equivalents/MJ fuel].**

For biogas and HVO, the fossil $CO_2$ is assumed to be zero. The global warming impact, however, is not, since there are small emissions of the other greenhouse gases ($CH_4$ and $N_2O$). For RME a very small part (1 of 19 carbon atoms) in the fuel is of fossil origin, which means that some fossil $CO_2$ is generated as well. For ED95 the fossil $CO_2$ comes from the components (not from the ethanol).

All biofuels have a global warming impact of less than 10g $CO_2$-eq/MJ, while the fossil fuels vary between 60-75g $CO_2$-eq/MJ.

### *2.4.3 Well-to-wheel*

The total picture is obtained when looking at the results for the well-to-wheel.

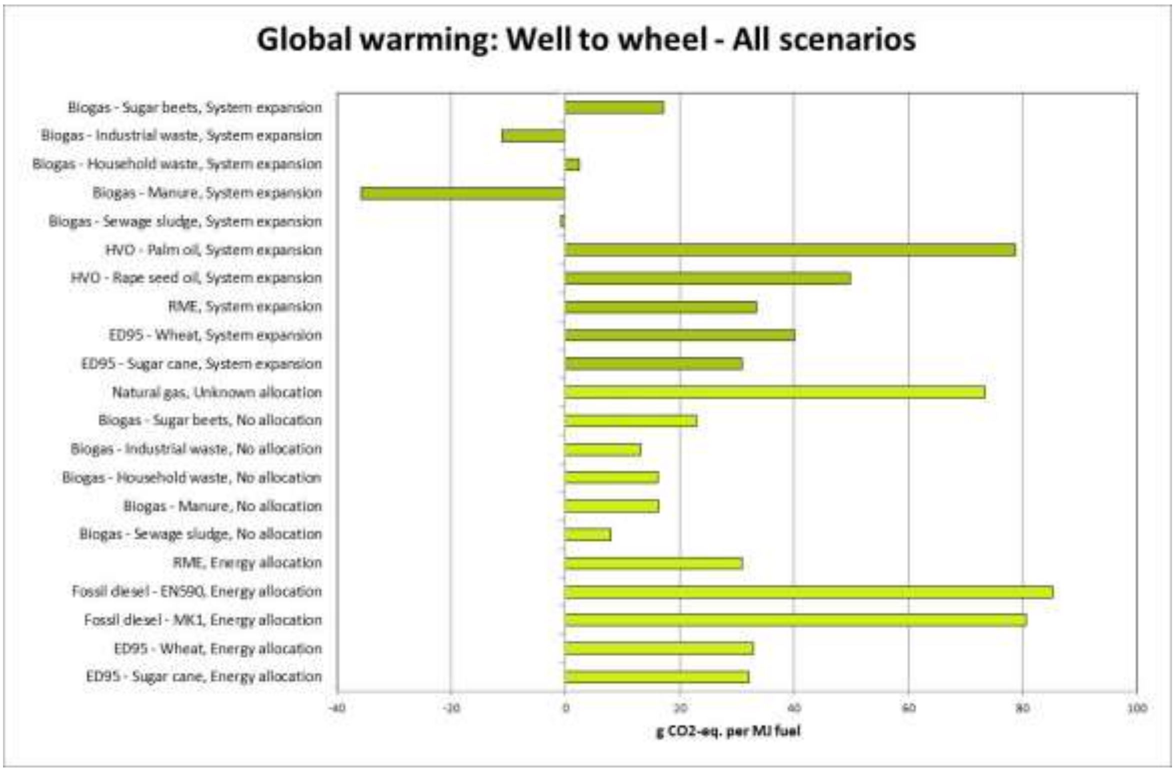



**Figure 3. Global warming potential for Well-to-wheel [g $CO_2$-eq/MJ fuel].**

For most biofuels, the total global warming impact in the well-to-wheel analysis is much lower than for the corresponding fossil fuels. The impact from ED95 and RME is less than 40% of the impact from diesel. The biogases (no allocation) show an impact of between 10-30% of the impact from natural gas. If considering the system expansion from the use of biogases, the savings from them will be even higher.

The only biofuel showing an impact within in the same range as the corresponding fossil fuel is HVO from palm oil, which has more or less the same impact as diesel has. The HVO from rape-seed oil is however significantly lower (40%) compared to fossil diesel.

# 3 CONCLUSIONS

The purpose of this study is to publish the best available environmental data for vehicle fuels but not to analyse the results in order to draw conclusions on which fuel to prefer from an environmental point of view.

## 3.1 GENERAL CONCLUSIONS

- The choice of methodology (energy allocation or no allocation versus system expansion) can have large influence on the LCI results (data). Whether the allocation/no allocation or the system expansion will provide the "best" results, depends on the specific case.
- The choice of the alternative material and/or energy which is assumed to replace the generated by-products and/or energy is of large importance.
- For ED95 and RME there are small differences between the two scenarios energy allocation and system expansion.
- For the biogases, the results are the opposite, meaning that system expansion results in much lower values (often even negative). This is an expected result since the corresponding "allocation" scenario, allocates the entire impact to the biogas.

## 3.2 COMMENTS

- The amounts of data sets available on vehicle fuels (or fuel components) are poor, especially for biofuels. Production technologies are developing, new fuels/components are introduced and fuels/components from different countries/regions are introduced as well. The available data sets are often based on too generic background data etc.
- More data sets for different fuels/fuel components, and also data sets based on site specific data, are required.
- Most LCA-studies only report energy use and greenhouse gas emissions. In order to carry out a more complete environmental assessment, other impact categories should be considered as well.

## 3.3 FINAL REMARKS

- Of the data in this study, the data on HVO from palm oil (well-to-tank) are assessed to be the most uncertain. The data are based on several quite extensive LCA-studies (see section 2.2.2), but too much generic background data are used by the authors of these reports. The studies are also quite old. When looking at the results from another data source (JEC (2013)), a well-known study from JRC, EUCAR and CONCAWE, the reported figure for HVO palm oil is 48g $CO_2$-eq/MJ to be compared with 77g $CO_2$-eq/MJ reported in this f3 study. The main reason for not publishing the JEC (2013) data was that no other impacts than global warming is reported in JEC (2013).
- Data on Brazilian sugar cane ethanol were only available for impact categories, and it has furthermore not been possible to assess how well they reflect the actual production.
- No well-to-tank data at all were found for the following fuels; HVO from tall oil (relevant for the Preem Evolution diesel), HVO from other raw materials (e.g. animal fats), ethanol

from other raw materials than sugar cane, sugar beets and wheat, Liquefied biogas and natural gas (LBG and LNG) and Compression of biogas and natural gas to CBG and CNG.

- There are certainly many more examples of fuels/components for which data are required.
- When assessing the impact from using different fuels in vehicles, the consumption of the fuel needs to be considered in addition to the environmental data for the fuel. Note that the fuel consumption in heavy duty vehicles can differ widely due to other factors than the fuel type, namely vehicle type and different driving conditions.

# APPENDIX A: FUEL LCI DATABASE CONTENT

## f3: Fuel LCI Database content

*Project* — *f3: WELL-TO-WHEEL LCI DATA FOR FOSSIL AND RENEWABLE FUELS ON THE SWEDISH MARKET*

**Comment** — Available life cycle inventory data (LCI-data) for well to tank (production of the fuel) as well as tank to wheel (combustion of the fuel in a vehicle) have been gathered in the project. The data are published in a database delivered to f3, distributed as Excel files.

| No | Fuels/fuel components | Well to tank | | Tank to wheel |
|---|---|---|---|---|
| | | Allocation scenario<br>Excel file name | System expansion scenario<br>Excel file name | Euro X (X = V and VI)<br>Excel file name |
| **"Diesel fuels"** | | | | |
| **D1** | **ED95 - Sugar cane** | D1.1_ED95 - Sugar cane, cradle-to-gate, energy allocation, impact categories only - f3 fuels | D1.2_ED95 - Sugar cane, cradle-to-gate, system expansion, impact categories only - f3 fuels | D1&2_ED95 combustion in heavy duty truck or bus, Euro X, tank-to-wheel - f3 fuels |
| **D2** | **ED95 - Wheat** | D2.1_ED95 - Wheat, cradle-to-gate, energy allocation - f3 fuels | D2.2_ED95 - Wheat, cradle-to-gate, system expansion, impact categories only - f3 fuels | |
| **D3** | **Fossil diesel - MK1** | D3_Diesel MK1, cradle-to-gate, energy allocation - f3 fuels | Not relevant | D3_Fossil diesel - MK1 combustion in heavy duty truck or bus, Euro X, tank-to-wheel - f3 fuels |
| **D4** | **Fossil diesel - EN590** | D4_Diesel EN590, cradle-to-gate, energy allocation - f3 fuels | Not relevant | D4_Fossil diesel - EN590 combustion in heavy duty truck or bus, Euro X, tank-to-wheel - f3 fuels |
| **D5** | **Rapeseed methyl ester (RME)** | D5.1_Rapeseed methyl ester (RME), cradle-to-gate, energy allocation - f3 fuels | D5.2_Rapeseed methyl ester (RME), cradle-to-gate, system expansion, impact categories only - f3 fuels | D5_RME combustion in heavy duty truck or bus, Euro X, tank-to-wheel - f3 fuels |
| **D6** | **Hydrotreated Vegetable Oil - Rape seed oil** | Not relevant | D6_Hydrotreated Vegetable Oil (HVO) - Rape seed oil, cradle-to-gate, system expansion, well-to-tank - f3 fuels | D6&7_HVO combustion in heavy duty truck or bus, Euro X, tank-to-wheel - f3 fuels |
| **D7** | **Hydrotreated Vegetable Oil - Palm oil** | Not relevant | D7_Hydrotreated Vegetable Oil (HVO) - Palm oil, cradle-to-gate, system expansion, well-to-tank - f3 fuels | |
| **Ethanol components for fuels** | | | | |
| **E1** | **Ethanol from sugar cane** | E1.1_Ethanol from sugar cane, cradle-to-gate, energy allocation - f3 fuels | E1.2_Ethanol from sugar cane, cradle-to-gate, system expansion, impact categories only - f3 fuels | Not relevant, since only used as a fuel component. |
| **E2** | **Ethanol from wheat** | E2.1_Ethanol from wheat, cradle-to-gate, energy allocation - f3 fuels | E2.2_Ethanol from wheat, cradle-to-gate, system expansion, impact categories only - f3 fuels | Not relevant, since only used as a fuel component. |
| **E3** | **Ethanol from sugar beets** | E3.1_Ethanol from sugar beets, cradle-to-gate, energy allocation - f3 fuels | E3.2_Ethanol from sugar beets, cradle-to-gate, system expansion, impact categories only - f3 fuels | Not relevant, since only used as a fuel component. |
| **"Methane fuels"** | | | | |
| **M1** | **Biogas - Sewage sludge** | M1.1_Biogas from sewage sludge, cradle-to-gate, no allocation - f3 fuels | M1.2_Biogas from sewage sludge, cradle-to-gate, system expansion, impact categories only - f3 fuels | M1-M5_Biogas combustion in heavy duty truck or bus, Euro X, tank-to-wheel - f3 fuels |
| **M2** | **Biogas - Manure** | M2.1_Biogas from manure, cradle-to-gate, no allocation - f3 fuels | M2.2_Biogas from manure, cradle-to-gate, system expansion, impact categories only - f3 fuels | |
| **M3** | **Biogas - Household waste** | M3.1_Biogas from household waste, cradle-to-gate, no allocation - f3 fuels | M3.2_Biogas from household waste, cradle-to-gate, system expansion, impact categories only - f3 fuels | |
| **M4** | **Biogas - Industrial waste** | M4.1_Biogas from industrial waste, cradle-to-gate, no allocation - f3 fuels | M4.2_Biogas from industrial waste, cradle-to-gate, system expansion, impact categories only - f3 fuels | |
| **M5** | **Biogas - Sugar beets** | M5.1_Biogas from sugar beets, cradle-to-gate, no allocation - f3 fuels | M5.2_Biogas from sugar beets, cradle-to-gate, system expansion, impact categories only - f3 fuels | |
| **M6** | **Natural gas** | Natural gas, cradle-to-gate, unknown allocation - f3 fuels | Not relevant | M6_Natural gas combustion in heavy duty truck or bus, Euro X, tank-to-wheel - f3 fuels |

# APPENDIX B: TTW EMISSION FACTORS FOR $CO_2$ & $SO_2$

## B.1 FOSSIL $CO_2$ EMISSIONS

Fossil $CO_2$ emissions are calculated from the fossil carbon content in the fuel;

**$CO_2$ = C content [kg/kg fuel] * 3.67**

The CO2 emission factors are presented in Table 8. The emissions are recalculated from ‘per kg’ to ‘per MJ’ fuel using the heat values presented in the table in section 2.1.

**Table 8. Emission factors [kg/MJ fuel] for fossil $CO_2$ emissions.**

| Data set in database | kg CO2/MJ | Reference |
|---|---|---|
| ***ED95*** | 0.00729 | SEKAB, Roger Mattebo, personal communication 2013. |
| ***Fossil diesel - MK1*** | 0.07200 | SPBI (2010) |
| ***Fossil diesel – EN590*** | 0.07430 | SPBI (2010) |
| ***Rapeseed methyl ester (RME)*** | 0.00508 | Stefan Lundmark, Perstorp Oxo (2013). |
| ***Hydrotreated Vegetable Oil (HVO)*** | 0 | - |
| ***Biogas*** | 0 | - |
| ***Natural gas*** | 0.0573 | Jerksjö & Martinsson (2010). |

### *ED95*

From the data provided by SEKAB (see section 2.2.2) an average fossil carbon content of 5.11 w-% was derived. The heat value of ED95 is 25.7 MJ/kg. Recalculating to per MJ of fuel, 0.00729 kg of fossil $CO_2$ per MJ is obtained.

### *Fossil diesel - MK1*

The SPBI website publishes the $CO_2$ emission per litre of fuel (2.54 kg $CO_2$/l) and a density of 0.815 kg/l and a heat value of 35.8 MJ/l. This corresponds to a heat value per kg of 43.3 MJ/kg and to a carbon content of 85.0 w-%. Recalculating to per MJ of fuel, 0.0720 kg of fossil $CO_2$ per MJ is obtained.

### *Fossil diesel – EN590*

The SPBI web site publishes the $CO_2$ emission per litre of fuel (2.66 kg $CO_2$/l) and a density of 0.840 kg/l and a heat value of 35.8 MJ/l. This corresponds to a heat value per kg of 42.6 MJ/kg and to a carbon content of 86.4 w-%. Recalculating to per MJ of fuel, 0.0743 kg of fossil $CO_2$ per MJ is obtained.

### *Rapeseed methyl ester (RME)*

According to Perstorp, there is 1 fossil carbon for each C18 chain. The fossil carbon comes from the methanol. The carbon content is calculated = 1x12/(1x12+18x12) = 5.26 w-%. The heat value is 38.0 MJ/kg (Perstorp, 2013). Recalculating to per MJ of fuel, 0.00508 kg of fossil $CO_2$ per MJ is obtained. However, if it is known that the methanol is of renewable origin, the $CO_2$ emission should be set to zero.

### Hydrotreated Vegetable Oil (HVO)

For HVO the fossil $CO_2$ has been assumed to be zero.

### Biogas

For biogas the fossil $CO_2$ is by definition zero.

### Natural gas

The emission factor applied (0.057 kg $CO_2$/MJ natural gas) was found in Jerksjö et al. (2010) referred to in Miljöfaktaboken 2011.

## I Sulphur dioxide ($SO_2$) emissions

$SO_2$ emissions are calculated from the sulphur content in the fuel;

**$SO_2$ = S content [kg/kg fuel] * 2**

The $SO_2$ emission factors are presented in Table 9. The emissions are recalculated from per kg to per MJ fuel using the heat values presented in the table in section 2.1.

**Table 9. Emission factors [kg/MJ fuel] for $SO_2$ emissions.**

| Data set in database | kg $SO_2$/MJ | Chosen sulphur content |
|---|---|---|
| *ED95* | 2.33E-07 | The legislative limit is 10 mg/kg (10 ppm) (Dir 2009/30/EC), but here a typical value of 3 ppm is chosen. |
| *Fossil diesel - MK1* | 1.39E-07 | The legislative limit is 10 mg/kg (10 ppm) (Dir 2009/30/EC), but here a typical value of 3 ppm is chosen. |
| *Fossil diesel – EN590* | 2.82E-07 | The legislative limit is 10 mg/kg (10 ppm) (Dir 2009/30/EC), but here a typical value of 6 ppm is chosen. |
| *Rapeseed methyl ester (RME)* | 1.58E-07 | The legislative limit is 10 mg/kg (10 ppm) (EN 14214), but here a typical value of 3 ppm is chosen. |
| *Hydrotreated Vegetable Oil (HVO)* | 1.36E-07 | The legislative limit is 10 mg/kg (10 ppm) (Dir 2009/30/EC), but here a typical value of 3 ppm is chosen. |
| *Biogas* | 8.52E-07 | For biogas and natural gas there is a standard (SS 15 54 38) for biogas which has been applied for both biogas and natural gas. Here the legislation limit for vehicle gas based on biogas is 20 ppm sulphur in Sweden. |
| *Natural gas* | 8.35E-07 | For biogas and natural gas there is a standard (SS 15 54 38) for biogas which has been applied for both biogas and natural gas. Here the legislation limit for vehicle gas based on biogas is 20 ppm sulphur in Sweden. |

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