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Evaluation of Alternative Fuels from a Heavy-duty Vehicle Perspective

Master Thesis at Volvo Group Trucks Technology

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Volvo FH-series. Volvo Trucks - Sweden

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Abstract

The European Union set a target goal in October 2014 to reduce the domestic greenhouse gas (GHG) emissions with 40 % by the year 2030, when compared to the 1990 levels. Another goal for the year 2030 is to increase the production and use of renewable energy sources and to increase the energy savings with 27 %. The transport industries around the world are facing large challenging problems phasing in a more biofuel based vehicle fleet to meet these goals.

This thesis was performed at Volvo Group Trucks Technology with a focus on finding the most suitable biofuels from the group FAME, HVO-diesel, synthetic diesel (FT-diesel), DME, methane fuels (biogas, bio-SNG), ethanol and methanol for the time perspective of 2030-2050. A method study of previous studies with focus on biofuels and the pros and cons of each method was performed to find the most suitable criteria for fuel evaluations.

The criteria found most suitable for the needs of Volvo GTT were biomass feedstock potential for the production of biofuels, production and distribution cost for each individually produced fuel, GHG-emissions from a WTW-perspective and vehicle adaptations that could possibly be necessary when changing from a fossil diesel fuel to a biobased fuel.

From the result acquired, it appeared that all fuels are relevant for Volvo GTT's continued work in finding potential biofuels that should be ventured in the future. The first generation biofuels, however, have generally gotten less distinctive results when compared to the BtL-fuels. This indicates a trend that leans more towards a residue-based fuel feedstock than a crop-based one. This trend can be seen both in the potential and the cost analysis of the result and fits well with the indications given by the IEA Blue Map Scenario.

For future work it is recommended to look further into the area of biofuel potential with the land use efficiencies for each crop and to expand the GHG-emission influences on the North American market through the GHGenius WTW-analysis.

Key words: Biofuels, Biomass Feedstock Potential, Cost analysis, GHG WTW analysis, vehicle adaptations,

Utvärdering av alternativa bränslen för användning i tunga fordon
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Sammanfattning

Europeiska Unionen satte i oktober i år ett mål för att minska de inhemska växthusgasemissionerna med 40 % före 2030 jämfört med 1990 års nivåer. En ökning av produktion och användning av förnyelsebara energikällor samt att minska energianvändningen i Europa med 27 % var två mål till som sattes av EU. Detta innebär att den globala transportindustrin har en stor utmaning med att fasa in sin verksamhet mot en mer biobränslebaserad fordonsflotta.

Detta arbetet utfördes på Volvo Group Trucks Technology och fokuserade på att undersöka de lämpligaste biobränslena i gruppen FAME, HVO-diesel, syntetiskt framställd diesel (FT-diesel), DME, metanbränslen (biogas, bio-SNG), etanol och metanol med tidsperspektivet 2030-2050. En granskning av tidigare studier med fokus på biobränslen och dess för- och nackdelar användes för att hitta de lämpligaste kriterierna för bränsleutvärderingen.

Kriterierna som ansågs vara lämpligast för Volvo GTT:s behov var råvarupotential för produktionen av biobränslena, produktions- och distributionskostnaden för respektive bränsle, växthusgasemissioner från ett WTW-perspektiv samt eventuella fordonsadaptioner som kan behövas vid byte från fossil diesel till biobränslet i fråga.

Utifrån resultaten som erhölls med utgångspunkt i de olika kriterierna framgick att alla bränslen för Volvos GTT:s fortsatta arbete kring potentiella releventa biobränslen för framtiden. Första generationens biobränslen har dock fått mindre utmärkande resultat överlag jämfört med andra generationens biobränslen (förgasningsbränslena), vilket påvisar en trend som lutar mot mer avfallsbaserade bränslen än grödbaserade, i det undersökta tidsspannet. Denna trend stämmer för potentialberäkningarna liksom kostnadsuppskattningarna och stämmer överlag med indikationerna som IEA Blue Map Scenario också påvisar.

För framtiden rekommenderas att studera potentialen hos biobränslen med landanvändningen hos respektive gröda i åtanke samt att expandera växthusgasernas utsläppspåverkan till Nordamerika genom GHGenius WTW-analys.

Nyckelord: Biobränslen, biobränslepotential, kostnadsanalys, växthusgasemissioner, WTW-metod, fordonsadaption

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I would also like to thank my family and my friend Alvean for being the best comfort during my most confused moments. Last of all, I would like to dedicate this report to Jens. The last time we spoke, it was of doing our Master Thesis together. This for you my friend.

Caroline Hallung, 12th of January, 2015

Acronyms and Abbreviations

BTL	Biomass to Liquid
CNG	Compressed Natural Gas
CI	Compression Ignition
DI	Direct Inject engine
DME	Dimethylether
ETP	Energy Technology Perspective
EU	European Union
FAME	Fatty-acid Methyl Ester
FAO	Food and Agriculture Organisation of the United Nations
FT	Fischer-Tropsch
FVV	Forschungsvereinigung Verbrennugnskraftmaschinen e.V
GHG	Greenhouse Gas
GTT	Volvo Group Trucks Technology
GWP	Global Warming Potential
HPDI	High Pressure Direct Inject engine
HVO	Hydrogenated Vegetable Oils
ICE	Internal Combustion Engine
IEA	International Energy Agency
ILUC	Indirect Land Use Change
JEC	Joint Research Centre, EUCAR & Concawe
LHV	Longer Heavier Goods Vehicle or Lower Heating Value
LNG	Liquefied Natural Gas
MSW	Municipal Solid Wastes
NPP	Net Primary Production
RED	Renewable Energy Directive
SI	Spark Ignition
SNG	Substitute Natural Gas
TTW	Tank-To-Wheel
VCE	Volvo Construction Equipment
WTT	Well-to-Tank
WTW	Well-to-Wheel
WHO	World Health Organisation

Units

EJ	Exajoule (10^{18} J)
GJ	Gigajoule (10^{9} J)
Mtoe	Million tonnes of oil equivalents = 41.6 GJ

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Introduction

One of the main challenges the transport industries face today is the transition from fossil-based to alternative fuel-based vehicle fleet. The EU has agreed on reducing the domestic greenhouse gas (GHG) emissions by 40 % by the year 2030, compared to the year 1990. Another EU goal is the shared increase of renewable energy sources and energy efficiency with 27 % by the year 2030. The transport sector plays a significant role in these reductions and face considerable challenges in meeting these goals. [1]

Volvo Group is one of the world's leading manufacturers of buses, trucks, construction equipment and engines for marine and industrial applications. The largest part of the Volvo Group carbon footprint is related to use of it's products, and therefore the fuel efficiency and alternative fuels are high priorities.

The area of responsibilities for Volvo Group Truck Technologies include completion of the entire vehicle, powertrain engineering, product planning, project and range management, purchasing, vehicle engineering and advanced technology and research.

1.1 Background

Heavy-duty vehicles have certain requirements on the fuels used, for instance when it comes to range, the space requirements for the engine and fuel system, how often service is needed as well as the power and torque of the truck. If a change is to be made, leading to a more alternative fuel driven vehicle fleet that will meet the set requirements, an increase in the complexity and cost of the vehicle may arise.

98 % of the transport used around the world today by the transport industries rely on fossil fuels[2]. Biofuels (mainly ethanol and biodiesel) are used in some markets, mainly

as low blend-ins, e.g 5-10 % ethanol in gasoline and up to 7 % biodiesel in diesel. Due to the currently low price on natural gas, CNG and LNG are also used as fuels to some extent. For heavy-duty trucks, there are some demo projects currently in works such as the Volvo DME project that focus on biofuels.

1.2 Purpose & Goals

The aim of this thesis is to evaluate alternative fuels for long-haul, heavy-duty vehicle applications, by taking into account both sustainability and practical criteria.

The study focuses on biofuels and the specific aim is to point out which fuels that can be available in significant amounts in a long term perspective (2030-2050).

Several specific goals have been defined and are as follows:

- To investigate existing fuel evaluation reports and roadmaps. The pros and cons for each methodology used will be listed.
- Selecting specific evaluation criteria for the evaluation of fuels from a heavy-duty perspective.
- Collecting and analysing of current data for the selected evaluation criteria.

The final result will not pin-point one single fuel that will be recommended for further research but rather give a dimensional analysis of all the researched fuels with a following discussion about the advantages and disadvantages of each.

1.3 Scope

The long-haul, heavy-duty application refers to trucks, driving at high speeds and with few stops for long periods of time. This puts certain requirements on the fuel used, regarding the range and the power to torque ratio.

This thesis will focus on the following fuels: FAME (B100), synthetic diesel (FT-diesel/BtL-diesel), HVO-diesel, DME, methane fuels (bio-SNG/biogas), ethanol and methanol. A survey of the most recent data for the European, North American and Chinese markets as well as on a global basis will be performed with focus on the situation today and for a 2030-2050 scenario.

Hydrogen gas and electricity will be excluded from this thesis as the focus is biobased fuels. Third and fourth generation biofuels (such as genetically modified crops for instance) will also be excluded as they are still in a research phase.

The focus will be concentrated on heavy-duty, long-haul vehicles as the thesis is performed at Volvo GTT and hence does not include light-duty vehicles like cars, motorcycles, mopeds, buses and city-based trucks. This, as light-duty vehicles have been in focus in many other studies, while heavy-duty vehicles for an alternative fuels point of view has been less regarded.

2

Theory

The theory chapter will give a short background to all the fuels that will be discussed in the thesis. In the analysis, a WTW-method will play a central part, taking into account the complete chain from fuel production, distribution and its use.

2.1 Background of fuels and biofuels

From the 19th century and onwards, petroleum fossil fuel products have been used to feed the energy consumption of the world. Calculations made of the present oil reserves predict that these will last about 50 years with the current usage rates. [2] There are many incentives for increasing the production of biofuels around the world. An increased energy demand and a decline in the finite sources are such influencing factors, together with climate changes like global warming, that will have certain dramatic and unpredictable consequences in the future.

A particular factor worth mentioning is the climate changes due to the emissions of CO_2. The EC target set for 2030 is one of many regulations to try and handle the GHG emissions on an European level. The transport industry plays a significant role in contributing to these emissions, but increasing responsibility may also be ascribed to the local communities and even to an individual basis.

Another factor, particularly important in the USA, is the energy security factor for fuels. During the Second World War and the oil crisis of 1973, a natural self-sufficient energy production was necessary. [3] USA has therefore focused a lot of investments in it's ethanol production (e.g from maize) to be independent in case of an oil shortage in the future.

2.1.1 First generation biofuels

The definition of first generation biofuels is the commercially produced fuels made from food and fodder feedstocks, such as seeds and grains, whole crops like sugar cane, cereals, sugar beets and vegetable oils. In order to use food and fodder stocks for biofuel production, conventional food and chemical conversion technologies are used. Ethanol and FAME are the most well-known first generation biofuels. [4]

The first generation biofuel feedstocks that will be discussed in this thesis are:

1. Sugar crops
2. Oilseed crops
3. Grains/cereals
4. Starch crops

Ethanol

Ethyl alcohol (CH_3CH_2OH), more commonly known as ethanol, is a clear and colorless liquid which can be produced either through fermentation of carbohydrates that are converted to sugars, or through synthesis from various gases. [5]

Ethanol is the most commonly used biofuel in the world, with the largest production sites in Brazil and the US. Ethanol is combusted in Otto engines and is widely used as an alternative fuel for the car industry. [6]

The bioethanol feedstock can be classified into three different categories[7]:

1. Starch-based materials like cereals/grains and root-/tuber crops.
2. Sucrose-based materials such as sugar beet, sugarcane and sweet sorghum.
3. Lignocellulosic materials like wood, grasses and straws. (See second generation biofuels).

The EU quality standard for bioethanol blend-in with gasoline is 5 %, so called EN228. The use of EN228 in regular gasoline does not require any engine modifications. E85 refers to a blend-in mixture with 85 % bioethanol and 15% petrol, which does require modifications, and is a commonly used biofuel in Sweden.[8]

FAME

The term of biodiesel usually refers to Fatty-acid methyl ester (FAME), which can be obtained through transesterification of methanol with virgin vegetable oils. The largest producer of biodiesel in the world is Europe with 53 % of the market share.[7] The most common vegetable oil crops that are used to produce FAME are: rapeseed (RME), soybean oil (SME), mustard, palm oil, sunflower oil, castor, coconut, cotton, peanut, and sesame. [9]

The three main process steps when producing biodiesel are[10]:

1. oil extraction from oilseeds through mechanical pressing or solvent extraction
2. transesterification of the virgin oils from the oil seeds
3. transesterification of used fats and oils from residue streams such as slaughterhouse waste and frying or cooking oil

A large advantage with biodiesel is that relatively small modifications will be needed to the diesel engine used. However the fuel used will produce slightly lower power and torque, which will, in turn, mean a higher fuel consumption compared to that of petroleum diesel. The sulfur content of the fuel, the flash point, aromatic content and biodegradability of biodiesel, however, are of a more advantageous nature. [8]

A major driving force for the production of vegetable oils has been the use for non-food purposes, such as biofuel production or as a feedstock for chemicals.[11] The standard for mix-in of biodiesel in diesel is called EN590 and allows for 7 %.[8]

2.1.2 Second generation biofuels

The second generation biofuels are produced from non-food and fodder resources, such as agricultural and forestry residues or from MSW (Municipal Solid Waste). These resources use BTL-tehnologies such as thermochemical conversion or fermentation to produce the biofuel in question.[4]

Bioethanol

Second generation bioethanol is produced from either a lignocellulosic-based feedstock or agricultural residues, which adds additional technical challenges to the production. The challenges include pretreatment steps such as delignification, steam explosion, dilute acid pre-hydrolysis, and enzymatic hydrolysis of the biomass. [8] Because of the more complex feedstock and the following complex treatment steps, the production of second generation ethanol is likely to be more expensive than first generation ethanol.

HVO-diesel

HVO- (Hydrogenerated Vegetable Oils) diesel can be distinguished from FAME-biodiesel in two ways: the production process of the biodiesel in question and the composition of the diesel. HVO is a second generation biofuel when it is produced through hydrotreating of residual feedstocks such as waste cooking oils, animal fats or non-edible oils like: jathropa, castor oil and tall oil. When produced from vegetable oils, like whole crops, then it is a first generation biofuel.[8] The HVO-diesel follows the diesel specifications in all aspects except for density, which means that it can be considered as a drop-in fuel and be used in an ICE without needs of modifying the engine or the fuel systems of the vehicle.[12] Volvo and OKQ8 are currently testing 100 % HVO-diesel as fuel in a test programme to be finished in 2015, which so far has shown no adverse affects. The HVO is produced from slaughter residues by Neste.[13]

DME

Dimethylether (DME) is a nontoxic and clean, colorless liquefied gas that can be produced in two ways: either by letting synthesis gas (hydrogen, carbon monoxide, and carbon dioxide mainly) react to methanol over a copper catalyst, then dehydrating the methanol in the presence of another catalyst to form DME or by direct gasification of the synthesis gas. [12] The advantages of DME compared to diesel include the high cetane number, the good mixing together with air within the engine as well as the high oxygen content resulting in no emissions of smoke after the combustion. [14]

The DME-engine works according to the diesel-principle. The density and heating value of DME is quite low, which means a higher volume of DME needs to be injected into the engine, compared with conventional diesel. The poor lubricity of the fuel also means that additives that increase the lubricity needs to be added for the fuel to work within the engine (similar to low sulphur diesel). DME is more corrosive than conventional petroleum diesel, which means that certain anti-corrosive sealing materials will need to be installed within the engine to make sure that no leakage occurs. [14]

Synthetic diesel

Synthetic diesel, also called Fischer-Tropsch diesel (FT-diesel) or BtL (Biomass to Liquid)-diesel, is a type of diesel that is produced using the Fischer-Tropsch synthesis process. FT-diesel is produced from synthesis gas at very high temperatures and pressures in the presence of a catalyst. BtL-diesel is produced from gasification of biomass to produce synthesis gas and thereafter following the FT-process. [15]

The basic reaction mechanism when producing FT-diesel is as follows:

$$2nH_2 + nCO \leftrightarrow n(-CH_2-) + nH_2O \tag{2.1}$$

FT-diesel has a higher cetane number than conventional diesel, which leads to shorter ignition delays. The shorter ignition delay means higher thermal efficiencies and lower specific fuel consumptions [14]. FT-diesel can be considered a drop-in fuel as long as it meets the standards for EN590 diesel oil. [12]

Biomethanol

Methanol is a biodegradable, toxic and corrosive alcohol that burns with an invisible flame. It is a high octane fuel and therefore requires an Otto engine. Methanol is currently made from natural gas but can be derived from biomass by partial oxidation reactions. Biomethanol can be derived from catalytic synthesis using CO and H_2, from distillation of liquids from wood pyrolysis, from the gaseous products of biomass gasification or from synthetic gas made from biomass and coal. [8]

Bio-SNG

Bio-Synthetic Natural Gas (Bio-SNG) is produced through a thermal gasification process from wood or woody biomass. The end product is considered to be the same as biogas (methane) but as the feedstock is different, it is given a different name. [16] In Gothenburg, Göteborg Energi owns a plant called GoBiGas that produces methane from gasification from forest residual products, such as branches, woodchips and tree tops. Through indirect gasification methods, a biogas is produced and then distributed to Gothenburg city through the existing gas grid. [17]

Biogas/Biomethane

Biogas mainly consists of methane and carbon dioxide, and is produced through the biological degradation of organic materials. In the absence of oxygen, micro organisms degrade organisms forming biogas in a combustion chamber. Biomethane refers to the upgraded version of biogas. The biogas feedstock consists of agricultural waste, manures, landfill, energy crops, catch crops, sewage sludge, landscape management, municipal solid waste (MSW), grass, food waste and other by- and waste products. [16]

2.1.3 Third and Fourth generation biofuels

The third generation biofuels mostly discussed today is biodiesel produced from algae, and that is derived from aquatic cultivation and converted to triglycerides. Other third generation biofuels include the alcoholic-based products biopropanol and biobutanol. The fourth generation biofuels will contain genetically modified feedstocks or the use of targeted synthetic microbes to produce synthetic or carbon-negative biofuels. [4]

2.2 Conversion steps

The conversion steps for biofuel production are many and their functions vary significantly. The three main conversion categories are:

1. Chemical conversion
2. Biological conversion
3. Thermochemical conversion

Figure 2.1 shows various conversion steps for the conversion of biomass to biofuel:

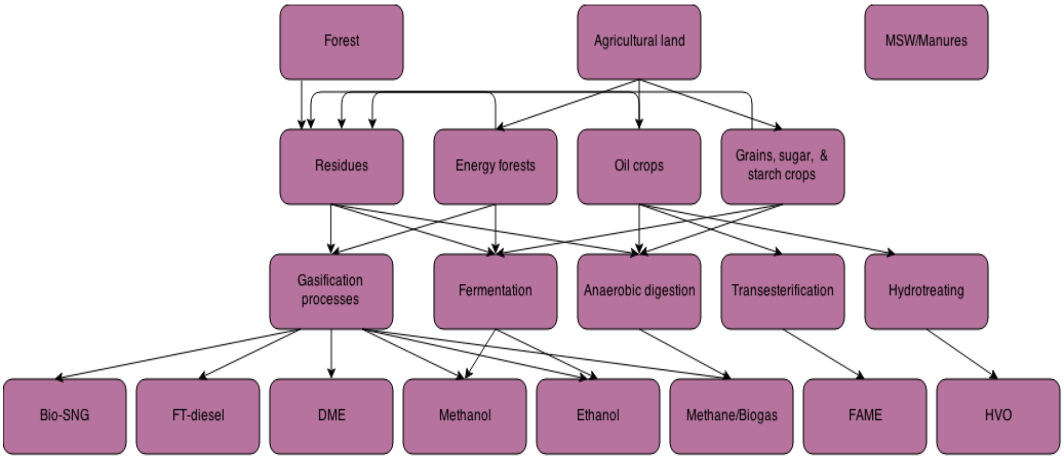

Figure 2.1: Feedstock to biofuel flowchart

The MSW/manures feedstock is a very broad feedstock and the conversion paths of this will be discussed more in detail in the result part of the thesis as some assumptions need to be made for the scenario calculations.

2.2.1 Chemical conversion

In the chemical manufacturing process, chemical transformation takes place, and the end product receives a different chemical composition compared to the starting material. The chemical manufacturing processes usually consists of a sequence of conversion steps that will make a change in one or more of the following states [18]:

- chemical composition
- concentration
- energy level
- phase state

Transesterification

Transesterification refers to a reaction between an ester of one alcohol and a second alcohol to form an ester of the second alcohol and an alcohol from the original ester[19]. Rapeseed oil, palm oil and waste oil are converted using transesterification to produce either FAME or HVO-diesel. [20]

Figure 2.2 shows the transesterification reaction.

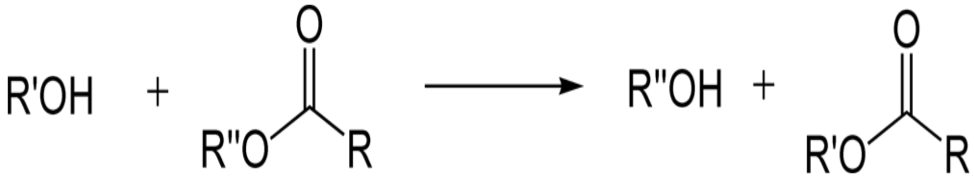

Figure 2.2: Transesterification reaction

Hydrotreating/Hydrogenation

A catalytic process used in the petroleum industry in which hydrogen is put in contact with the product stream to remove impurities such as nitrogen, sulfur, oxygen or unsaturated hydrocarbons. [21]

2.2.2 Biological conversion

Biological conversion is the change of organic substances, such as plants or waste materials, by using biological processes like fermentation to form products like methane by the process of fermentation. [22]

Fermentation

Alcoholic fermentation is a chemical reaction where a ferment cause the organic molecules to split into simpler substances. For example the anaerobic conversion of sugar to ethyl alcohol using yeast, is an alcohol fermentation process. [23] When producing second generation biofuels from lignocellulosic feedstocks further mechanical and physical actions to size up and clean the biomass are needed. The cell structure is destroyed and further chemical/biological treatments can be performed. The lignin part of the biomass also needs to be removed and the hemicellulose hydrolysed to monomeric and oligomeric sugars. These sugars are then fermented to ethanol, then purified and dehydrated. The cellulose is hydrolysed to glucose. [24]

Anaerobic digestion

The use of microorganisms in an anaerobic environment to break down organic materials is called anaerobic digestion. This method is also used for treating wastewater and reducing emissions from landfills. It is also the method of for producing biogas and bio-SNG from manure and crop residues.[25]

2.2.3 Thermochemical conversion

Thermochemical conversion applies heat to chemical processes when producing energy products from biomass feedstocks. This process is performed in multiple stages:

1. converting the solid biomass to gases
2. condensing of the gases into oils
3. conditioning and synthesizing of the oils to produce synthesis gas.

The synthesis gas can then be used as a feedstock for producing BtL-fuels. [25]

Pyrolysis

Pyrolysis utilizes very high temperatures and pressures together with low oxygen levels to start to decomposing the biomass. The end product consists of a liquid fuel and char residues. [25]

Gasification

The process of gasification uses high temperatures (about 800 ° C) under controlled environments to convert biomass into synthesis gas. The process is done in two stages[25]:

1. partial combustion of the biomass to form gas and charcoal
2. chemical reduction with the formation of synthesis gas

2.3 Internal Combustion Engine theory

Internal Combustion Engines (ICEs) are devices that mix fuel and air, which subsequently is burned within a volume constricted by a cylinder and the piston walls. The combustion generates a high pressure inside the volume which forces the piston downwards creating a force to a rotating crankshaft. The rotating of the crankshaft can then be used to produce electricity or foe the propulsion of vehicle, for instance. [26]

When discussing ICEs, one can use many different classifications to describe the engines referred to:

- applications (car, truck, power generation...)
- fuel (gasoline, diesel...)
- working cycle (two-stroke, four-stroke)
- mixture preparation method (direct injection, port injection)
- ignition method (spark ignition, compression ignition)
- thermodynamic cycles (Otto, Diesel)

For this thesis, the cycles discussed will be either Otto or Diesel, perhaps with a few modifications.

2.3.1 Otto engine

The Otto Engine is so called Spark Ignition (SI) engine, as a high-energy spark is needed to ignite the fuel-air mixture. The Otto cycle works under constant volume leading to instantaneous combustion.

There are certain restrictions for heavy-duty vehicular uses of an Otto-engine as they are limited in efficiency by: the octane number of the fuels used, the ability of lean mixtures to propagate the flame, the variability of cycle-to-cycle and that fuel sometimes get trapped in crevices.[26]

2.3.2 Diesel engine

The diesel engine is a Compression Ignition (CI) engine as the air-fuel mixture ignites on its own as it is compressed. The combustion takes place under constant pressure. The Diesel engine is the dominant type of engine used for heavy-duty vehicles both on road and off-road, for marine engines and for industrial applications.[26]

2.4 Well-to-Wheel methodology

The Well-to-Wheel methodology describes the production and use of a fuel. It differs from Life Cycle Assessment (LCA) by not taking into account the vehicle or plant production or the energy needed for end-of-life. One unit of fuel is followed (e.g 1 MJ of fuel) through its production and use. The source used for WTW-calculations comes from the technical report put together by the European Commissions Joint Research Centre, Eucar and Concawe (JEC).

The WTW-methodology consists of two parts called Well-to-Tank (WTT) and Tank-to-Wheel (TTW). The WTT part used by the JEC takes into account the energy use expended and the associated greenhouse gas emissions (GHG) for all production steps of a fuel, from the moment it is extracted from the original source, until it reaches the fuel pump.

The JEC use the following five generic steps for their method of calculating the GHG-emissions for the European Market:

- production and improving at the source
- transformation at source
- transportation to the EU
- transformation at the EU
- conditioning and distribution

The TTW part takes into account the energy expended by the vehicle/fuel combinations as well as the GHG emissions associated with these. This includes the engine efficiency of converting the fuel energy to moving the vehicle. Tail pipe emissions of GHG gases, N_2 and CH_4 are also included.[27]

Figure 2.3 shows the different steps that are taken into account for the WTT and TTW-methods.

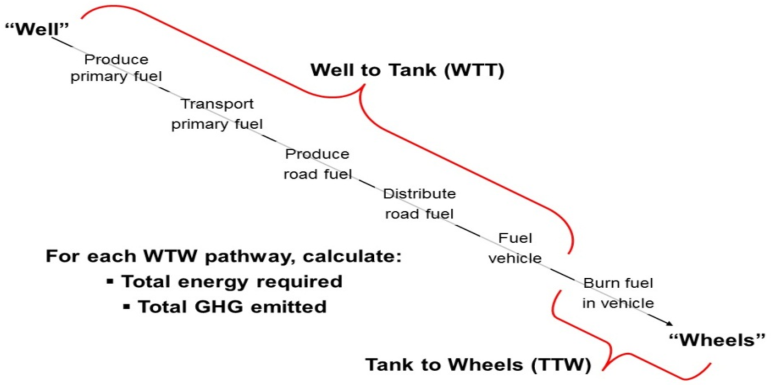

Figure 2.3: The Well-to-Wheel Method. [27]

3

Methodology

The purpose of this thesis is to study biofuels used for heavy-duty, long-haul vehicles at Volvo GTT. The European Commision has set targets for improving environmental issues for the year 2030 and this will therefore be the time frame used.

3.1 Research approach

This thesis follows a literature review with a two-step approach with an internal and external report review. This is followed by a literature study for the focus categories chosen. Interviews are done to complement the literature studies when necessary.

3.2 Literature review

The literature reviews performed are divided into two phases: studying of internal and external reports with the same background premises as this thesis, and reviews of biofuel-based articles and technical reports.

3.2.1 Internal/External background review

The first phase of the literature study was done as a background research for the start up of the project. Eight different reports were provided by Volvo GTT with many different approaches to investigate biofuel use for the future. Approaches like cost focus, GHG-emission savings, technology and pathways for road mobility and energy efficiency are a few of the focus points of these reports.

The reports provided by Volvo GTT were:

1. A harmonised Auto-Fuel biofuel roadmap for the EU to 2030. E4tech (2013). [28]
2. Energy Carriers for Powertrains for a clean and efficient mobility. ERTRAC (2014). [29]
3. Dagens och framtidens hållbara biodrivmedel. Börjesson et al (2013). [30]
4. Zukünftige Kraftstoffe für Verbrennungsmotoren und Gasturbinen Report. FVV (2013).[31]
5. Sustainable Mobility: Using a Global Energy Model to Inform Vehicle Technology Choices in a Decarbonized Economy. Grahn et al (2013). [32]
6. Well-to-Wheels analysis of Future Automotive Fuels and Powertrains in the European Context. Edwards et al (2013). [27]
7. Alternative fuels for VCE. Magnusson and Salomonsson (2011).[33]
8. Climate issues in focus. AB Volvo (2008). [34]

Thorough read through of each report gave an idea of which method would be the best fit for the remainder of the thesis work. It also gave great suggestions to which categories should be the focus points of the second phase of literature reviews.

The categories chosen for further investigations were:

- Biomass Feedstock Potential
- Cost
- GHG-emissions
- Vehicle properties

3.2.2 Article/Technical report literature review

Phase two of the literature review gave a more detailed view of each chosen category. Most of the time spent on literature studies during the thesis was spent studying articles and technical reports about the biomass potential around the world.

The literature study was done for the categories Potential and Cost analysis until the information found was deemed satisfactory. The GHG-emissions and Vehicle Properties categories will be using facts from previously recommended reports and methods, but adopted to the fuels and applications in the report.

Literature review of Biomass Feedstock Potential

Many of the articles focusing on potential were found through backtracking of the references from the most cited articles. Some of the articles and reports that have been studied for this thesis include references [11, 24, 30, 35, 36, 37, 38, 39, 40, 41, 42].

Cost analysis literature review

For the cost analysis part of the literature study, an interview was held with Karin Pettersson, Assistant Professor at the Energy and Environment department at Chalmers University of Technology, to gain more knowledge about what prospects of cost analysis could be interesting to look at. The technical reports from Börjesson et al (2013) and Ekblom et al (2012) were recommended by Karin Pettersson for BtL-fuels and these were deemed very useful for further studies.

The articles and reports studied for the cost analysis can be found in references [10, 24, 30, 43, 44, 45, 46, 47].

3.3 Data collection

The data collecting part for the result was done with different approaches for each category as will be discussed below.

Biomass Feedstock Potential

The article "The global technical potential of bio-energy in 2050 considering sustainability constraints. Helmut Haberl et al (2010)" was used as the source for calculating a biomass potential scenario for the Global, European, North American and Chinese markets. The data in this report was in accordance with other articles and reports considerering the more sustainabile outlook on potential but gives a more detailed outlook on the underlying data.

The scenario used assumptions and preexisting factors to calculate a biofuel potential from the numbers provided by Haberl et al (2010). The preexisting factor for the calculations were the conversion factor from feedstock to fuel[1]. The assumtions made for the calculations were:

1. Splitting up of the Bioenergy crops category into three subset feedstock categories:
    - Bioenergy forests
    - Sugar and starch crops

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[1] The amount of feedstock energy converted to fuel energy

    - Oil crops

2. Subset amount to use for biofuel production from the total potential
3. Dedication of feedstock to each respective fuel

These assumptions were based on the precautionary principle when finding a possible biofuel potential. Meetings were held with Patrik Klintbom and Cecilia Gunnarsson at Volvo AB together with Per Hanarp at Volvo GTT to discuss the plausibility of the assumptions for each fuel individually. The result is presented in this thesis.

Cost analysis

The data collection for the cost analysis was fulfilled by using the three ([30] [43] [44] sources deemed most favorable and credible from a cost analysis perspective. Changing of the ground data to the same unit (€/100 km) for comparison was necessary for all the data chosen. Most of the initial cost data only represented the production cost for a commercially produced fuel (the nth factory) and did not include costs such as start-up of projects or investments made. A distribution cost was also added to the fuels where it was not included in the original data.

The final production- and distribution cost was then translated to €/MWh and then further more to €/100 km for comparison amongst each other.

GHG-emissions

For the GHG-emissions, the report made by JRC, Eucar and Concawe (this will henceforth be called the JEC) called "Well-to-Wheels analysis of Future Automotive Fuels and Powertrains in the European Context." (2013) was used. The JEC calculates the CO_2, N_2O and CH_4 emissions for the European market. The time span for the JEC is 2020-2025, which was considered to be relevant for the thesis time frame (i.e 2030-2050).

The JEC assumes a state-of-the-art technology for the fuel production, which will deliver the best technically feasibile efficiency. The WTW methodology makes the implicit assumption that energy use and GHG emissions have the same impact wherever in the surveyed area they occur.

For calculations where the efficiency greatly varies, a best and worse case scenario are presented to give a more fair result.

JEC WTW study limitations
The JEC study disregards the energy and GHG emissions associated with constructing and the end of life disposal of a vehicle or plant. For biomass originated fuels the emissions caused by direct or indirect land change uses (iLuC) is not included in the calculations either.

The JEC-model only takes into account the cultivatable land-use for biofuels and can therefore not be compared with the potentials part of the result. Emissions from nitrous oxide originated from agriculture is deemed to much of an uncertain GHG emission balance to study and has therefore been excluded from the JEC WTW study as well.

As the JEC only studies the European market, it is assumed that the GHG-emissions represent the other investigated markets as well.

Vehicle properties

The vehicle properties data collection used the VCE Internal Report and the Climate issues in focus from Volvo as sources to decide whether large/complex modifications are needed or if very small or no modifications will be necessary.

3.4 Fuel assessment

The fuel assessment of the result lists the advantages and disadvantages of all the biofuels and compare them with each other to see which fuels are worth looking into further and which can be discredited from further investigation.

4

Evaluation of methods

The eight reports, articles and studies provided by Volvo GTT were evaluated and the advantages and disadvantages of each are listed below:

A harmonised Auto-Fuel biofuel roadmap for the EU to 2030 by E4tech

The E4tech network investigates biofuel contributions to GHG-emission savings for the year 2030 as well as for a longer perspective within the EU. It also looks at how to meet the needs of the fuel and automotive industries in addition to their customers. The method uses different scenarios in which the calculation of available biofuel supplies is varied depending on the following criteria: potential, blend wall, infrastructure and added vehicle cost.

Energy Carriers for Powertrains for a clean and efficient mobility by ERTRAC

The Ertrac-report is a roadmap that describes different technologies and pathways to achieve the set goals for road mobility. It provides an overview of energy carriers and production routes which can contribute to the decarbonization of the transport system's energy supplies. The main output of the Ertrac roadmap is a description of research needs within biofuels, hydrogen gas and electricity.

Dagens och framtidens hållbara biodrivmedel by f3

The report is a background report from the f3 organization to the Swedish governmental investigation about fossil-free vehicles[1] that analyzes the energy efficiency, climate performance and production costs of alternative fuels from a WTT-perspective. Every single production chain is evaluated with factors like availability of raw material and growth areas for crops, logistics, integration with other industries and the removal of external heat and byproducts.

Zukünftige Kraftstoffe für Verbrennungsmotoren und Gasturbinen Report by the FVV

The FVV report is based on a German study that focuses on screening, characterization and selection of 10 different alternative fuels. A detailed analysis of the selected fuels from a number of different perspectives such as cost, environment, availability and infrastructure was then performed.

Sustainable Mobility: Using a Global Energy Model to Inform Vehicle Technology Choices in a Decarbonized Economy by Grahn et al

The article by Grahn et al looks at a Global Energy Model (GET) that takes into account the interactions between different energy sectors and assesses the uncertainties in future vehicle technology costs for example light-duty vehicles. It also assesses the progress of other energy sectors and how this progress affects cost-effective fuel and technology choices.

Well-to-Wheels analysis of Future Automotive Fuels and Powertrains in the European Context by the JEC

The JEC uses a WTW-methodology that only looks at the GHG-emissions on a European basis. The methodology of WTW is explained more in detail in the theory.

Alternative fuels for VCE by VCE

The VCE-report uses a Pugh Matrix to evaluate different alternatives of fuels as systematically and objective as possible. The Pugh Matrix consists of a set of criteria for each fuel or technology alternative which is then divided into sub-criteria that are weighed against each other and then summed up for a final score. The weighed sum of all criteria

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[1] Fossilfri Fordonstrafik

is then used to rank the different options. The report takes eight different initial inputs into account and evaluates these.

Climate issues in focus by AB Volvo

The climate issues in focus is a study by Volvo Group where seven categories are evaluated for seven different fuel/fuel mixtures. The categories investigated were: climate impact, energy efficiency, land use efficiency, fuel potential, vehicle adaptation, fuel cost and fuel infrastructure for a North American and European perspective. The fuels examined were: biodiesel, synthetic diesel, DME, Methanol/ethanol, biogas, biogas+biodiesel and hydrogen+biogas. Each criteria is then rated on a descending scale from five (best) to one (worst) for each fuel.

Choice of method

All the methods have different perspectives on what the main focus points are, the setting of the system boundries, the use applications and criteria and what the set time perspective is. The different perspectives make it difficult to compare the results from one another. There are similarities between the methods as they all investigate the attributes of cost, environmental issues (most commonly GHG emissions), resources and infrastructure. These parameters are used to a higher and lower extent, depending on evaluation method, but can be seen as key parameters overall when making further evaluations.

Another category mentioned in the two Volvo-based reports is the vehicular adaptations needed when transferring from diesel or gasoline to biofuels. This category may influence the cost of the truck quite significantly if a lot of modifications are needed. All together the two Volvo reports are the most useful to use as inspiration for what categories are the most important to research further. The VCE-report is done with construction equipment in mind and some of the categories could be grouped together to give a better result. The same goes for the Climate issues in focus report, that also have some categories that could be overlapped for this thesis result.

Modifications of the categories mentioned above gave the following definitions to be used for the remainder of the thesis:

1. ***Potential***
   Available biomass feedstock for dedication to the production of biofuels.
2. ***GHG-emissions***
   GHG-emissions calculated through the WTW-methodology.
3. ***Cost***
   Fuel cost at pump assuming a commercial market production without investment costs and taxes.

4. ***Vehicle Properties***
   Added vehicle complexity that impacts the cost of the vehicle.

5

Criteria results

This chapter shows and describes the results given for each of the criteria, previously decided on in the Evaluation of methods chapter.

5.1 Biomass Feedstock Potential

A very important criteria when discussing biofuels is the availability of each feedstock, which will henceforth be referred to as potential. The term potential refers to the energy content of the biomass and does not take into account the amount of energy needed for production, transportation or conversion into fuel.[36]

An important aspect to remember is that biomass has many uses that compete for the same feedstock. These uses provided around 10 % of the global primary energy supply in 2008, both on a low- and high efficiency basis. Low efficiency traditional biomass is used for cooking, heating and lighting in the developing part of the world. Highly efficient bioenergy uses include solids, liquids and gases as secondary energy carriers to produce heat, electricity and transportation fuels.[48] It is also important to remember that a crop that is used to make a biofuel may also be used as fodder for the meat market and as a oleochemical feedstock.

The amount of carbon dioxide converted into carbohydrates during photosynthesis is called Net Primary Production (NPP)[36] and it accounts for about 2280 EJ/yr. When only taking into account the above ground carbohydrates, this value becomes approximately 1240 EJ/yr. The amount of carbohydrates destroyed in some way (for instance by burning or harvesting for food production) accounts for about 370 EJ/yr. [37]

When discussing biofuel potential, a varity of institutions, companies and research groups have immensely different opinions depending on which definition of potential they use. There are five general definitions of potential that can be used to differentiate between how much of the biomass can be used for production of fuels, energy, food and fodder.[36]:

1. *Theoretical potential:* The upper limit of bioenergy production that is limited by fundamental physical and biological barriers. The production from lands, rivers, oceans and seas is included in this potential.
2. *Geographical potential:* The theoretical potentials fraction that is limited by the land areas.
3. *Technical potential:* The fraction of the geographical potential that is not used for the production of food and fodder, infrastructural projects, and the conservation of forests and lands. This is based on an assumed level of advancement in agricultural technology levels.
4. *Economic potential:* Looks at the fractions of the technical potential that can be produced at economically profitable levels.
5. *Implementation potential:* Takes the economic potential and uses the fraction that can be implemented within a certain time frame, with the account to institutional and social constraints as well as policy incentives.

None of the definitions above suits my need to keep a sustainable approach to creating a biofuel potential scenario. A sustainable approach to potential will also try to keep biodiversity, soil quality and water use and quality in mind as well [49]. A sustainably constraining technical potential would fit the best making it a point 3.5 in the list above. According to Intergovernmental Panel on Climate Change (2012), an upper bound of the technical potential in the year 2050, could be about 500 EJ/yr [48]. This number was used as a upper-level of biomass potential when making assumptions about the biomass feedstock further on in the thesis.

Many of the reports and articles mentioned in the methodology all point in the same direction when discussing technical potential, but the one found that best sums up the technical potential from a sustainable criteria stand-point on both a global and a market basis was the article ”The global technical potential of bio-energy in 2050 considering sustainability constraints” by Helmut Haberl et al (2010).

5.1.1 Scenario assumptions

For the scenario part of the result, assumptions were made for each feedstock, based on conversion efficiency, how much feedstock can be used to make fuel without compromising with sustainability criteria and plausibility of the fuel in question actually being produced.

Figure 5.1 shows a flowchart for the conversion of the Haberl et al (2010) biomass potential to biofuels.

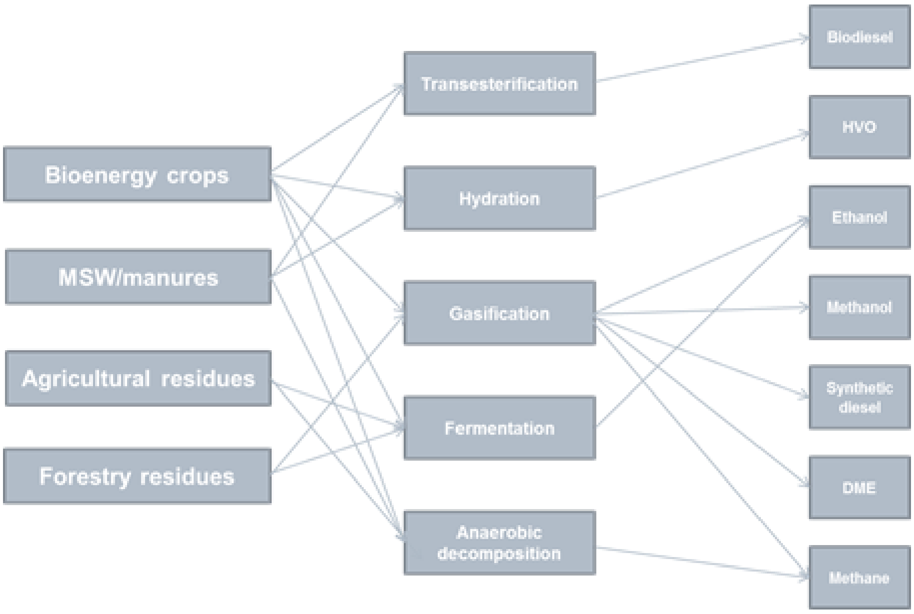

Figure 5.1: Biomass to biofuel flowsheet

Table 5.1 show the assumptions made for the biomass to biofuel conversion and how much of the chosen biomass is converted into what fuel. For instance, if the MSW/Manures column is studied, it can be noted that 50 % of the feedstock can be dedicated to the production of biofuels without compromising any sustainability constraints. Out of this biomass, 5 % will become either FAME or HVO, and the remaining 95 % will be turned into biogas. When a X is located in the table, it means that this path was not deemed a plausible/efficient conversion from biomass to fuel and therefore excluded as a pathway for production of biofuels.

Table 5.1: Use and dedication of biomass feedstock to biofuels

	Bioenergy crops	**MSW/Manures**	**Agricultural residues**	**Forestry residues**
Use	30 %	50 %	30 %	30 %
FAME/HVO	25 %	5%	X	X
Ethanol (1st gen)	25 %	X	X	X
Ethanol (2nd gen)	5 %	X	50 %	X
Methanol	X	X	X	X
Synthetic Diesel	23 %	X	X	50 %
DME	23 %	X	X	50 %
Biogas	X	95 %	50 %	X
Bio-SNG	X	X	X	X

The sections below will discuss how and why the assumptions for the scenarios were made for each category of feedstock. All biofuel feedstock calculations are based on the tables in Appendix 2. The calculations done below is for the global market but will be the same for the European (Europe Total), North American and Chinese (Centrally planned Asia, China) markets.

Bioenergy crops

Haberl et al. (2010) make the distinction of putting the first generation biofuel feedstocks as well as trees and grasses together into a category called bioenergy crops. This bioenergy crops part of the biomass feedstock focuses on the biomass used for energy purposes. These energy purposes also include, besides the use for biofuel production, stationary applications such as production of heat/electricity from pellets, heating of houses, and cooking. We are trying to keep a cautious approach when calculating the biofuel potential scenarios and to keep a sustainable point of view, which correlates to an assumption of 30 % for biofuel use from the bioenergy crops feedstock.

Haberl et al. (2010) calculate the arithmetic mean of minimum, maximum and intermediate estimates of the global potential to grow dedicated bio-energy crops (table A.4 in the appendix). Using the mean of intermediate estimates for the global total of 81 EJ/yr [37] and multiplying this with the assumed 30 % biofuel use gives us the following equation, which calculates the global biomass potential used for biofuel production in this scenario:

$$\text{Mean of intermediate estimates} \times 0{,}30 = 81 \times 0{,}30 = 24{,}3\text{EJ/yr} \tag{5.1}$$

Haberl et al. (2010) speak of potential as NPP and does not specify how much of the bioenergy crops feedstock is bioenergy forests, oil crops or sugar crops. Hence another assumption was made that the bioenergy crop feedstock consisted of 50 % bioenergy forest, 25 % sugar and starch crops, and 25 % oil crops.

This assumption doesn't account for land use efficiencies which can change the outcome of how much fuel is finally produced in correlation to the amount of land needed for growing the biomass feedstock. This is something that could be useful to look at for the future.

Of the 24,3 EJ/yr calculated for biofuel use, the following amount will consist of bioenergy forest feedstock:

$$24{,}3\text{EJ/yr} \times 0{,}50 = 12{,}15\text{EJ/yr} \tag{5.2}$$

Of the 24,3 EJ/yr calculated for biofuel use, the following amount will consist of sugar crop and oil crop feedstock:

$$24{,}3\text{EJ/yr} \times 0{,}25 = 6{,}08\text{EJ/yr} \tag{5.3}$$

MSW/Manures

Municipal Solid Waste (MSW) and manures are very under-appreciated sources for the production of biofuels today. MSW is mainly used as an energy source (particularly in Sweden and Europe) for the heat and power networks. As for manure, it is used for fertilizers in the agricultural industry.[19]

The technical primary energy potential of crop residues, MSW and animal manures in 2050 (table A.3 in Appendix 2) from Haberl et al. (2010) was used for the MSW/Manures scenario. The assumption for the use of MSW/manure feedstock conversion to biofuel was 50 %.

$$(\text{MSW} + \text{Animal Manures}) \times 0{,}50 = (11 + 39) \times 0{,}50 = 25\text{EJ/yr} \tag{5.4}$$

Agricultural residues

The agricultural residue potential is taken from the Crop residues category in table A.3 in Appendix 2.The assumption for the use for biofuel feedstock is 30 % because of the sustainability criteria previously mentioned.

$$\text{Crop residues} \times 0{,}30 = 49 \times 0{,}50 = 24{,}5\text{EJ/yr} \tag{5.5}$$

Forestry residues

The forestry residues are calculated from the table Forestry residue potential for 2050 for a high, low and arithmetic case (table A.5 in Appendix 2). The arithmetic mean category is used as the potential. The forestry residues have the same assumption of 30 % as agricultural residues.

$$\text{Arithmetic mean} \times 0{,}30 = 81 \times 0{,}50 = 24{,}3\text{EJ/yr} \tag{5.6}$$

Conversion efficiency

Considering the conversion efficiency for each fuel discussed, it varies depending on the fuel produced and from which feedstock it is converted. Table 5.2 shows the conversion efficiencies for Bioenergy crops, MSW/Manures, Agricultural residues and Forestry residues for the given biofuel products. Some production paths are deemed not plausible and are therefore not taken into account in this thesis. The conversion efficiencies are assumed to be the same for all markets discussed.

Table 5.2: Conversion efficiency for biofuels and feedstock

	Bioenergy crops	**MSW/Manures**	**Agricultural residues**	**Forestry residues**
FAME/HVO	60 %	60 %	X	X
Ethanol (1st gen)	55 %	X	X	X
Ethanol (2nd gen)	40 %	X	50 %	40 %
Methanol	60 %	X	X	60 %
Synthetic Diesel	44 %	X	X	44 %
DME	65 %	X	X	44 %
Biogas	60 %	40 %	60 %	X
Bio-SNG	70 %	X	X	X

5.1.2 Global Scenario results

Figure 5.2 shows the scenario on a global market basis with the discussed BtL-fuels put together in the same category. The scenario is compared to the biofuel situation today and a predicted 2020 level. The total fuel and diesel demand is also included in the graph for comparative reasons.

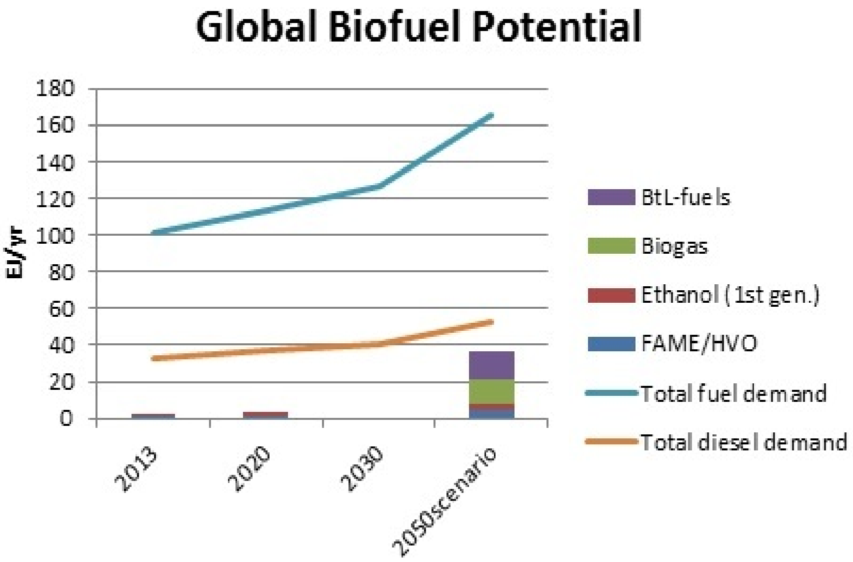

Figure 5.2: Global Biofuel Potential Scenario

Calculation of the 2030-2050 scenario gives a total biofuel potential of 36 EJ/yr on the global market. This corresponds to 69 % of the total diesel demand of the world in the year 2050 and 22 % of the total fuel demand.

When dedicating all of the available biomass feedstocks into one particular fuel, a maximum potential per fuel is calculated. This gives an indication of how significant each fuel is compared to the feedstock availability. A fuel such as biogas have many different biomass feedstocks that can be dedicated to its production, whereas FAME/HVO have fewer feedstock options as can be seen in figure 5.3 below.

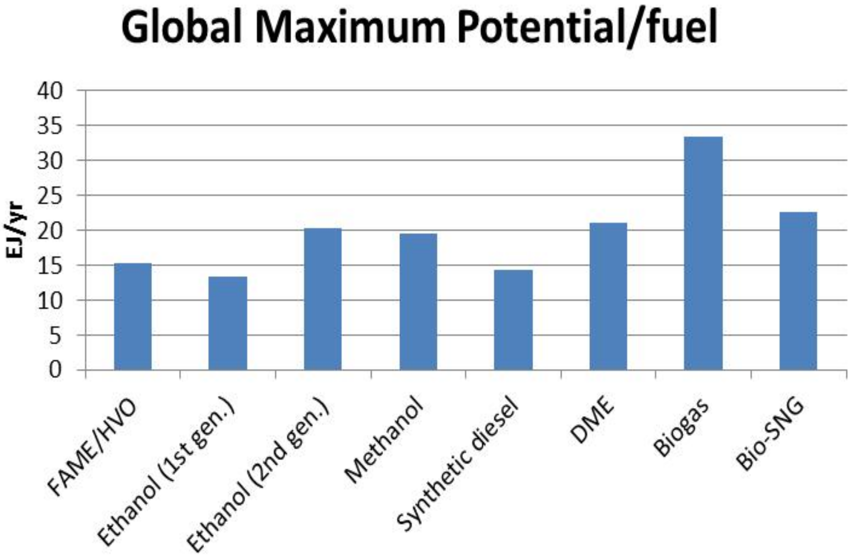

Figure 5.3: Global Maximum Potential per Fuel

5.1.3 European Scenario Result

Figure 5.4 shows the biofuel scenario for the European market.

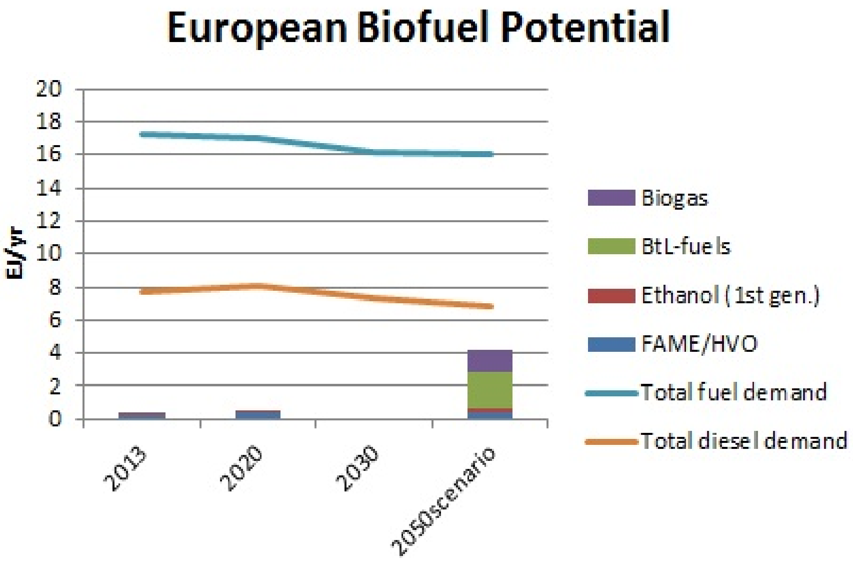

Figure 5.4: European Biofuel Potential Scenario

The European scenario potential gives a total biofuel potential of 4,15 EJ/yr. This means that 60 % of Europes total diesel demand in 2050 can be met with biofuels.

The maximum fuel potential scenario for Europe is shown in figure 5.5:

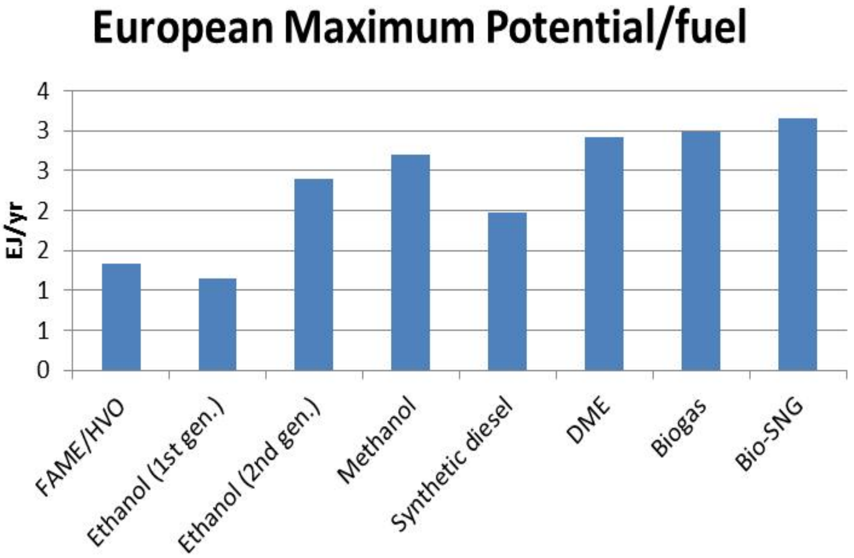

Figure 5.5: European Maximum Potential per fuel

5.1.4 North American Scenario Results

Figure 5.6 shows the scenario on the North American market.

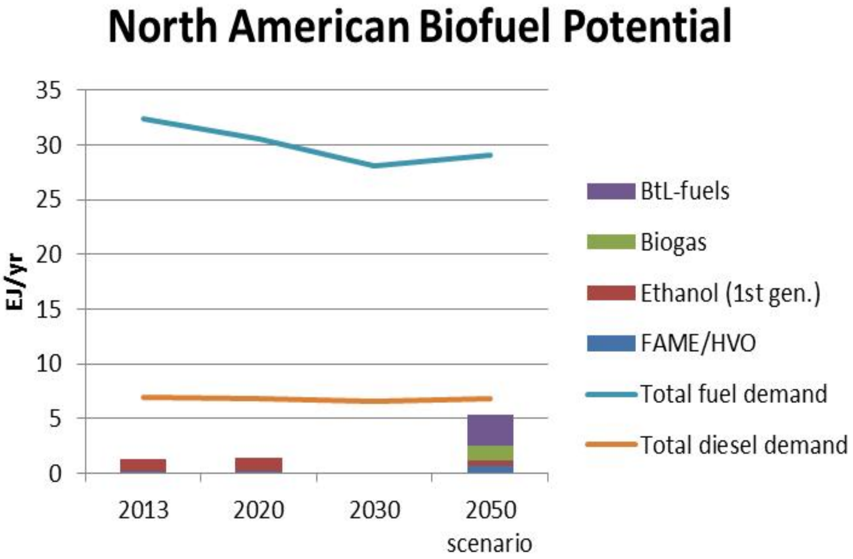

Figure 5.6: North American Biofuel Potential Scenario

The total biofuel potential for the North American market was 5,31 EJ/yr. This correlates to 79 % of the total diesel demand for the North American market in the year 2050.

The North American maximum potential is illustrated in figure 5.7 below:

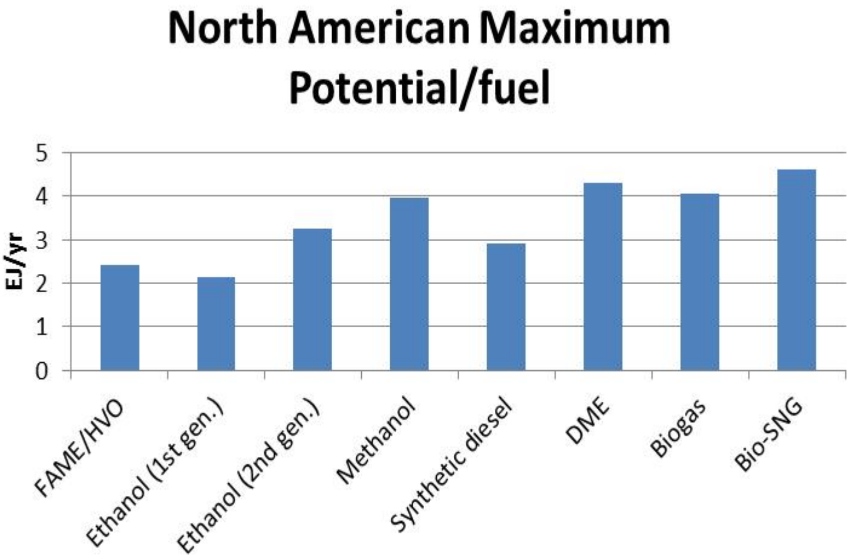

Figure 5.7: North American Maximum Potential per fuel

5.1.5 Chinese Scenario Results

Figure 5.8 shows the scenario for the Chinese market:

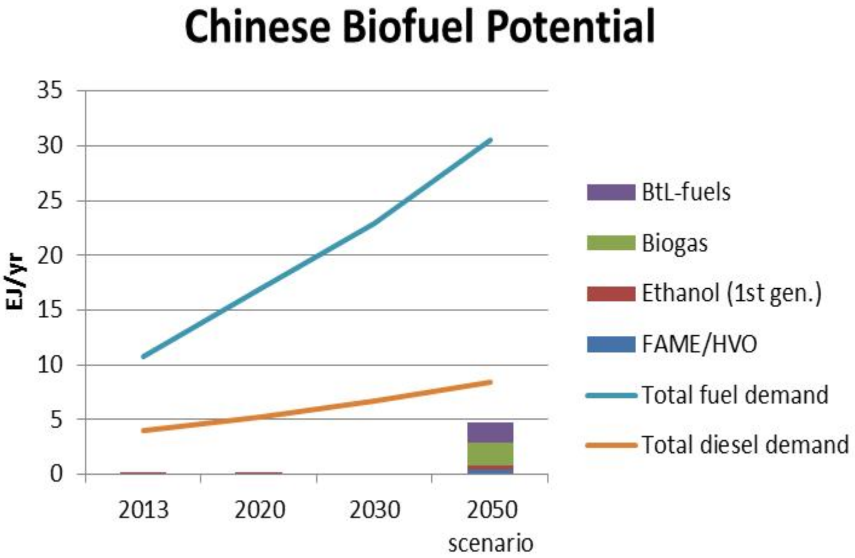

Figure 5.8: Chinese Biofuel Potential Scenario

The total Chinese potential from the calculated scenario correlated to 4,74 EJ/yr. This translates to 56 % of the total diesel demand in China in 2050.

A scenario where the maximum potential for each fuel was calculated is shown below:

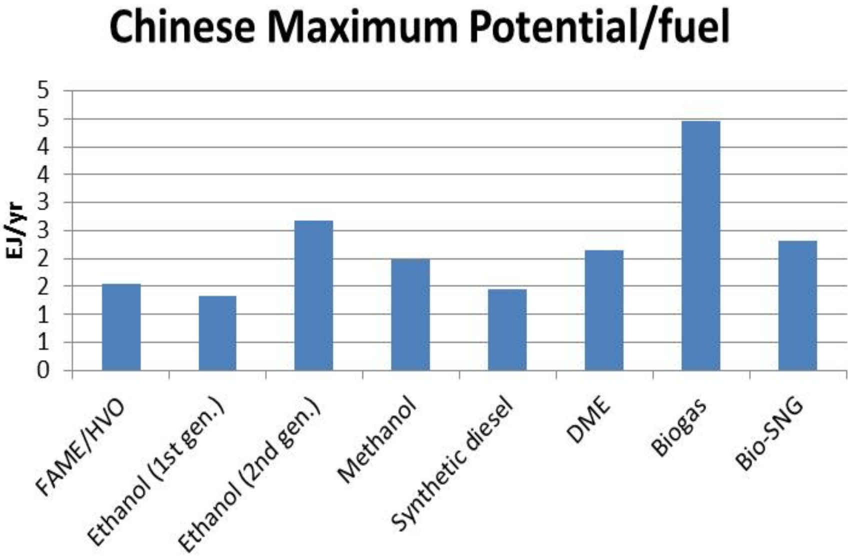

Figure 5.9: Chinese Market Maximum Potential per fuel

5.1.6 Summary Biofuel Potential

The calculated scenarios for the four markets all show that at least 50 % of the total diesel demand in the year 2050 can be met through biofuel production. This result would be different if the assumptions and allocations from the different feedstocks to the biofuels had been done differently.

All the markets show big promises for all biofuels investigated in the area of maximum potential, meaning that no fuel can be disregarded as a fuel worth investigating further from a potential point of view. A distinction of this kind will not be relevant until it is clear which technologies that have been invested in a more commercial basis. The technology choices can vary greatly with each market, hence giving advantages to some fuels more than others.

We can however see a larger potential in the biogas/bio-SNG and BtL-fuels than the first generation fuels. The upgraded version of biogas (biomethane) could also be used as a feedstock for DME, synthetic diesel and methanol which would make the maximum potential of these fuels even more significant.

A comparison of the results in this thesis with scenarios from the internationally renown source of the International Energy Agency shows that these results are a good estimation that can be used for further research. The IEA has concluded that around 27 % of the total transport fuel demand will be biofuel-based by the year 2050. The biomass feedstock needed for meeting this demand would be around 65 EJ when taking the IEA BLUE Map scenario into account [49]. According to Haberl et al, the global biomass potential in the year 2050, excluding food and fodder, will be 217 EJ [37].

The scenarios given above can be compared with the IEA numbers based on the ETP 2010 BLUE Map scenario which has a set target of reducing the energy-related CO_2 emissions with 50 % by the year 2050. In order to meet this target, a set of visions has been used.

The BLUE Map Scenario envisions installations of commercial-scale, advanced biofuel plants within the next decade, which will greatly contribute to a rapid growth of second generation biofuels. Third generation biofuels have also been taken into account in the beyond 2020-2030 timespan. Expansion of the energy crop production, mainly lignocellulosic biomass production, is also assumed to meet the targets set. 50 % of the total feedstock to be used for advanced biofuel and the bio-SNG production is assumed to come from wastes and residues.[49]

Table 5.3: IEA Blue Map scenario[49]

Biofuel	***2050 (EJ/yr)***	***2030 (EJ/yr)***
Biomethane (Bio-SNG)	5,83	0,69
Biojet (excluded from our results)	6,86	1,37
Biodiesel advanced (FT-diesel/HVO)	10,64	1,72
Biodiesel conventional	0	0,69
Ethanol (cellulosic)	4,80	1,72
Ethanol (cane)	3,43	2,06
Ethanol (conventional)	0	1,03
Total	**31,57**	**9,26**

The IEA Blue Map scenario has estimated a biofuel potential in the year 2050 of around 32 EJ/yr to be compared to my results of 36 EJ/yr. This shows that the calculated scenarios are quite similar to one made by the IEA on a global basis and therefore can be taken as a plausible result to be used for further research.

The Blue Map Scenario also estimates that the use of conventional ethanol and biodiesel (FAME) will increase until 2030 and then slowly be phased out for more second generation fuel uses instead in the 2050 time span.

5.2 GHG-emissions

For the GHG-emissions, the methodology set by the JEC for the European Union was used. The calculations performed followed the Well-to-Tank data for all processes from the extraction of the raw feedstock material, until the processing and distributing of the final fuel. The data collected is based on the JEC WTW studies using the Renewable Energy Directive (RED) methodology approach.

The fuel productions often bring the formation of different by-products (e.g glycerine from FAME production, digestate from biogas production). The RED methodology allocates the CO_2 produced between the by-products based on energy content (LHV). When waste products from agriculture or forestry applications are used as biofuel feedstock, the CO_2 emissions from the production of the primary biomass are not included.

This way of allocating gives an averaged out picture for the production and use of a chosen unit of fuel. The other approach to calculating the production and use of the same chosen unit of fuel is the system expansion route, which uses the LCA ISO standard of looking at the alternative uses of the by-products and feedstock and evaluating each individually. This allocation method is more useful when following a specific production path for one chosen fuel.

Figure 5.10 shows the GHG-emissions on a WTW-basis with a comparison between the averages of the fossil fuels and first/second generation biofuels.

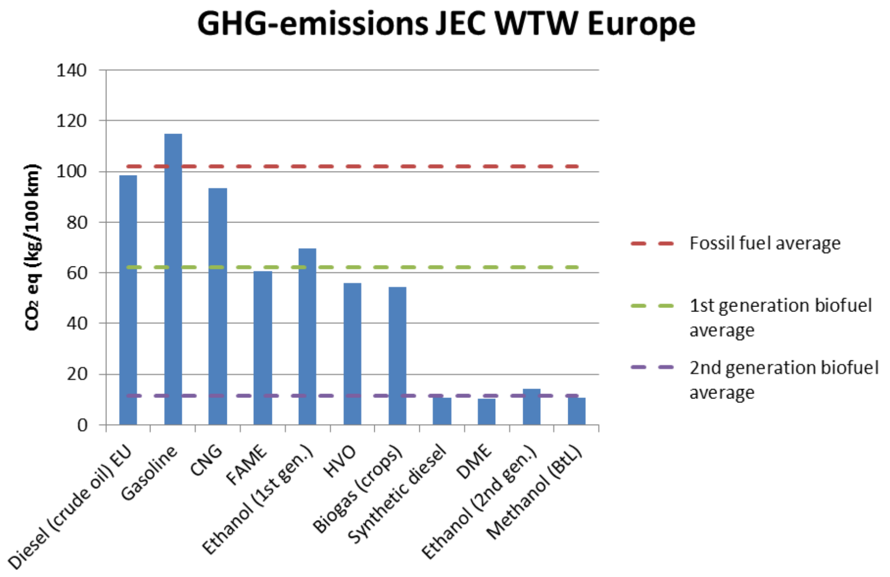

Figure 5.10: WTW result Europe

Bio-SNG is not included in the JEC WTW calculations and are therefore not part of the result calculations as can be seen in figure 5.10. It is assumed that the CO_2 equivalents/100 km for bio-SNG is in the level of the other second generation BtL-fuels as the production process is the same as for the BtL-fuels.

The value calculated for HVO is based on production from rapeseed, hence giving a first generation GHG-emission value. The second genereration levels for HVO can be seen in Appendix A.5.

Studying of the graph above shows that the liquid-based second generation fuels clearly are more environmentally friendly than the first generation and gaseous fuels in terms of kg CO_2-equivalents/100 km. However as the first generation fuels also show good levels of GHG-emissions it shows that no fuels can be discarded from further investigations when compared to fossils fuels based on the GHG-emissions factor.

5.3 Cost aspects

The cost aspect section will compare the fuel production- and distribution cost in €/100 km for the fossil fuels: diesel, gasoline and CNG and the biobased fuels: DME, FT-diesel, HVO-diesel, FAME, methanol from a lignocellulosic feedstock, ethanol, Bio-SNG, and CBG from crops.

The first step of calculating the cost of the fuel was to translate the initial ground prices into the same unit of measurement. These conversions can be seen in Appendix A.4 Cost Calculations where all the initial data can be seen as well.

Figure 5.11 displays the calculated cost in €/100 km for comparison with diesel with tax included in the price.

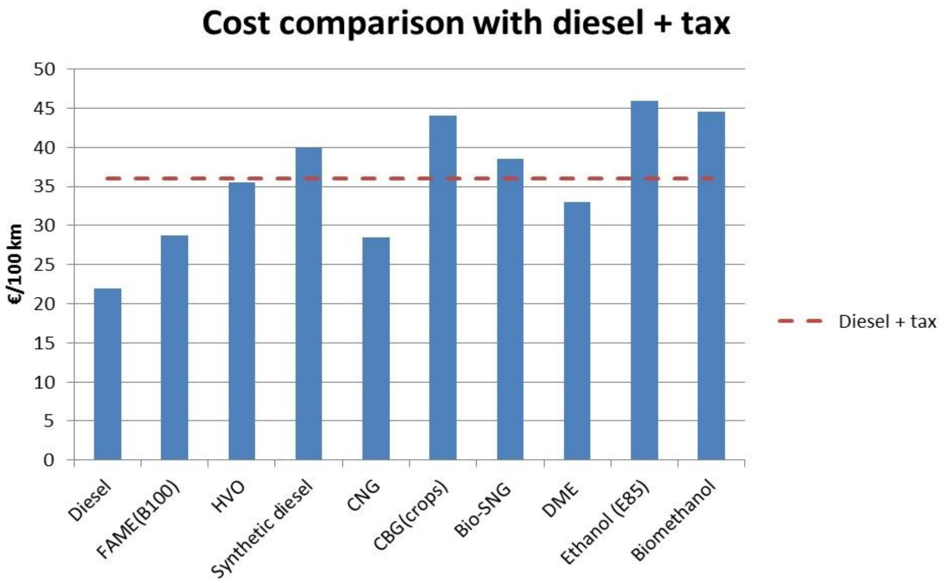

Figure 5.11: Cost comparison of biofuels with diesel+tax

When disregarding fossil diesel (without tax) and CNG the following conclusions can be drawn from figure 5.11 above. Ethanol, methanol and CBG produced from crops all reach a cost higher than 40 €/100 km and coming close to the current[1] Swedish diesel with tax price for diesel. FAME is the cheapest fuel at pump with a price under 30 €/100 km. DME is the second cheapest fuel at 33 €/100 km. HVO, synthetic diesel and bio-SNG all cost less between 35-40 €/100 km.

The result gives an indication that the diesel-equivalent fuels will have a greater chance of becoming the biofuels worth investing in in the future. As the sources used focuses on the Swedish and European market however, these result can also be misguiding for the North American and Chinese markets.

There are some insecurities in the costs for the fuels that aren't commercially available on the market today (Ethanol, FAME and HVO). For the BtL-fuels, this is because of the assumptions made about the investment costs for the production of the fuels. For CBG, it is because of the uncertainties in the price of the feedstock (CBG from manures instead of crops for instance). When comparing the calculated cost for synthetic diesel and CBG with other sources[44, 45] an insecurity of 20-30 % can be seen.

It is clear however that all fuels show capacity of being cost-effective when being compared to a high European level of taxes on fossil fuels.

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[1] IEA:Energypricesandtaxes

5.4 Vehicle properties and adaptations

Vehicle adaptations may be needed when replacing diesel with biobased fuels. Some fuels such as biodiesel and synthetic diesel are suitable for long-haul, heavy-duty applications and require no or very small adaptations for the truck. Other fuels may have more complex fuel storage, need modifcations on the engine or may get a lower performance that will influence the cost of the truck.[34]

5.4.1 Modifications per fuel

The modifications I have chosen to look at are the ones that will impact the cost of purchasing and using the truck (excluding fuel cost). Table 5.1 describes the factors that affect the cost for all biofuels previously discussed in the theory. The source used for these correlations is the VCE Internal report (2011).

An evaluation factor correlating to a NO means that no or small/few modifications are needed to the truck. A factor YES correlates to large/complex modifications that will greatly influence the cost of the truck. The factors will then be summarized and evaluated to give a final score used to classify the adaptations needed. A score of 5 means no/very small cost increasing alterations needed. A 1 means a lot of modifications are necessary, making the final truck less cost efficient.

The factors evaluated for the vehicle properties when comparing to conventional diesel are:

1. Engine: Are any modifications to the engine necessary (compared to current available technologies on the market)?
2. Fuel storage: Does the fuel storage tank require more complex storage than the one for diesel?
3. Performance: Is there lower performance expected for a long-haul application?
4. Service demand: How often will the truck have to be serviced as a consequence of the fuel used?
5. Range (fuel density): Driving range compared to diesel based on energy onboard.

Table 5.4: Vehicle Properties

	Engine	**Fuel storage**	**Range (fuel density)**	**Performance**	**Service interval**	**Score**
Diesel	NO	NO	NO	NO	NO	5
Biodiesel	NO	NO	NO	NO	YES	4
HVO	NO	NO	NO	NO	NO	5
Methane CNG (otto)	NO	YES	YES	YES	YES	1
Ethanol (otto)	NO	NO	YES	YES	YES	2
Methanol (otto)	NO	NO	YES	YES	YES	2
DME	YES	YES	NO	NO	NO	3
Synthetic diesel	NO	NO	NO	NO	NO	5

As can be seen in table 5.4 above, the diesel-equivalent fuels HVO and synthetic diesel get a total score of 5. FAME gets a total score of 4, meaning a quite small overall cost increase for the truck needed. Methane (CNG) and methanol both get a score of 1, meaning that neither is to recommend when looking at the Vehicle Properties category.

DME gets a score of 3, which indicates that quite a few modifications are needed for the trucks to work when using diesel as a fuel.

HDPI engines have not been studied as a substitute to the otto engine based fuels, which could affect the score of the vehicle properties for these fuels.

6

Fuel Assessment

This chapter discusses the advantages and disadvantages for each of the biofuels for the set time perspective.

FAME(B100/Biodiesel)

FAME is the cheapest biofuel in €/100 km when considering the cost analysis results and with a score of 4 in the vehicle properties section, it also proves that it is good for the cost of truck.

Studying the first generation biofuels feedstocks in the given time perspective shows that there is a potential for FAME but not as great as for the second generation biofuel and biogas(biomethane) potentials. The GHG-emission levels for kg CO_2 equivalents/100 km show that it is right in line with the first generation biofuel emissions and cannot therefore be discredited as a fuel because of this reason either.

Ethanol

The evaluation of ethanol will be two-fold as the results depend on whether the feedstock comes from whole crops (first generation ethanol) or from residual feedstocks (second generation ethanol).

Ethanol shouldn't be disregarded as a fuel as it shows average results in all categories except vehicle properties. The vehicle properties for ethanol resulted in a score of 2 which is quite poor, considering a Volvo perspective set today. A lot of large and expensive modifications would be needed for ethanol to be used as a fuel by Volvo when compared to today's technology.

Methanol

The results for methanol are quite similar to those for second generation ethanol. Methanol should not be disregarded either, for the same reasons.

HVO-diesel

HVO-diesel got a score of 5 in the vehicle properties category, making it a great fuel from this point of view. When evaluating the GHG-emissions it is wise to compare the rapeseed HVO-diesel levels of 49,1 kg CO_2 equivalents/100 km to the ones made from waste cooking oil of 8,1 kg CO_2 equivalents/100 km. The HVO made from waste cooking oils gives the best GHG-emissions of all fuels, and the rapeseed HVO levels are below average for first generation biofuels as well.

The potential for HVO also indicates an adequate result as it can be produced both as a first and second generation biofuel. The cost of HVO is right below the European tax level which can also be considered a satisfactory result for a biofuel that is commercially available on the markets today.

Synthetic diesel

Synthetic diesel is the outstanding fuel from a vehicle adaptations stand-point as absolutely no modifications are needed on the truck. Another advantage of synthetic diesel is the low levels of GHG-emissions.

The price is above the European tax level but not high enough to disregard synthetic diesel because of this factor. The maximum potential of synthetic diesel is quite high as well.

DME

For the biomass feedstock potential, DME shows that it is a great contender to being a large biofuel competitor on the future markets. The GHG-emission levels for DME is also the lowest of all the biofuels studied, which shows that it is a great contestant for biofuel market share from this stand-point. The cost analysis results show a cost lower than the European tax level which is also an advantage for further studying DME as a biofuel worth investing in.

The only category where DME does not shine is the vehicle properties as some modifications are needed for it to work within a Volvo truck. However as Volvo already has their DME demo project these increases in cost for the vehicle are currently being investigated.

Biogas (Biomethane)

Biogas is the fuel that conclusively shows the greatest maximum scenario potential on a global basis. As the MSW/Manure feedstock doesn't have the same restrictions and competition of uses as the other feedstocks, the potential from this feedstock is more significant than the others. Hence making biogas a large biofuel competitor from a potential point of view. A great advantage of biogas is that after it is upgraded to biomethane, it can be used as a feedstock for many of the other biofuels mentioned in the thesis, making their maximum potential even greater.

For the other researched categories biogas came on the same level as the first generation biofuels for GHG-emissions, a cost level around that of ethanol and methanol (when being produced from crops) and a vehicle properties score of 1, which can be considered as less satisfying results in these three categories.

Bio-SNG

Bio-SNG has the advantage, when being compared to biogas, of being a cheaper fuel per 100 km, as well as showing that it too has significant possibilities of being a great biofuel when looking at biomass feedstock potential. The same advantage as for biogas of bio-SNG being converted into other biofuels makes this potential even greater as well.

The JEC WTW data does not take bio-SNG into account, which means that this does not have a GHG-emission level to compare to the other biofuels. However, this can be assumed to be around the same level as the other BtL-fuels as they compete for the same feedstocks and use similar conversion techniques.

The vehicle properties are taken from methane CNG giving it too a score of 1, making it a very expensive truck to produce.

7

Discussion & Conclusion

The resuls shows that no biofuel can be completely discredited from future investigations for the time perspective of 2030-2050 when looking at the four criteria of potential, cost, GHG emissions and vehicle properties. Some fuels show great strengths in some categories but lack in others, but none of the fuels can be discluded in it's entirety.

Some recommendations for further investigative work within the same area of work from Volvo GTT:s point of view are listed below:

The factor of land use has not been included when discussing the biomass feedstock potential of biofuels. This is something that should be looked at for further investigations, regarding which biofuels that will be most plausible as a substitute to fossil fuels in the 2030-2050 time span. It is an important aspect to look at when discussing biofuels as the first generation biofuels need significant amounts of land to grow, whereas waste and residues does not need agricultural land and therefore can be considered to be better from a land use efficiency standpoint.

The categories that discuss markets in any way (potential, GHG emissions and cost to a small extent) have assumptions that are worth looking into even further. The potential scenarios assume that the dedication of biomass to biofuel is the same on a global basis and does not take into account what the market looks like today. The North American market has a large ethanol focus whereas Europe has a much larger biodiesel based market. This could be done if a more true overview of the markets should ever be interesting to look at.

The cost analysis results show costs mostly based from a Swedish and European point of view as the sources used only look at these markets. A wider research for the North American and Chinese markets could give other price indications as their feedstocks vary from the ones used in Europe. The BtL-fuels aren't produced on a commercial scale at present, which means that no taxes or investment costs are included in the price resulting in a somewhat unrealistic cost scenario when comparing to the diesel cost with tax. It is however a good indication of what the fuel cost trend for all the fuels may be in the upcoming future.

When discussing the WTW-data, this also just relates to an European perspective. There are similar methodologies for the North American market (e.g GHGenius and GREET) worth looking at to see whether the calculations made for Europe are comparable with North America. For this thesis however, the JEC WTW data was deemed good enough to give an overview for the biofuels discussed.

In conclusion, the fuels FAME, HVO-diesel, Synthetic Diesel, DME, Ethanol, Methanol, Bio-SNG and Biogas, all are important for the transport industry of the future.

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A

Appendix

A.1 Appendix 1: Conversion factors

For all calculations throughout the thesis the following conversion factors have been used:

Table A1 below show the factors used when converting the cost factors and when performing the WTW-allocations.

Table A.1: Conversion factors

Fuel	**Density** [**kg/m^3**]	**LHV** [**MJ/kg**]	**Fuel consumption relative to diesel in L/100 km**
Diesel	832	43,1	1
Gasoline	745	43,2	1,2
Methanol	793	19,9	1,2
HVO	780	44	1
FAME	890	37,2	1
FT-diesel	780	44	1
DME	670	28,4	1
Ethanol	786	29,2	1,2
CNG/CBG	0,79	45,1	1,2

Table A.2 shows the emission factors used for the GHG-emission factors on a TTW-basis. For the FAME a factor of 4,0 g/MJ is the emission factor.

Table A.2: Emission factors

Fuel	**Emission factor** N_2O **[kg/MJ]**	**Emission factor** CH_4 **[kg/MJ]**
Diesel	0,0061111	0,0019556
Gasoline	0,0055556	0,0019556
Methanol	0,0055556	0,0019556
HVO	0,0061111	0,0019556
FAME	0,0061111	0,0019556
Synthetic diesel	0,0061111	0,0019556
DME	0,0061111	0,0019556
Ethanol	0,0055556	0,0019556
CNG/CBG	0,055556	0,0019556

A.2 Appendix 2: Biofuel feedstock tables

The technical primary energy potential of crop residues, MSW and animal manures in 2050 according to Haberl et al[37]:

Table A.3: Technical primary energy potential of crop residues, MSW and animal manures in 2050.

Market	**Crop residues (EJ/yr)**	**MSW (EJ/yr)**	**Animal Manures (EJ/yr)**	**Total (EJ/yr)**
Western Europe	3	1	3	7
Central and Eastern Europe	1	0	1	1
Europe Total	4	1	4	8
North America	4	1	4	9
Centrally planned Asia, China	9	2	5	16
Global total	49	11	39	100

The global potential to grow dedicated bio-energy crops[37]:

Table A.4: Arithmetic mean of minimum, maximum and intermediate estimates of the global potential to grow dedicated bio-energy crops.

Market	**Mean of minimum estimates [EJ/yr]**	**Mean of maximum estimates [EJ/yr]**	**Mean of intermediate estimates [EJ/yr]**
Western Europe	2	8	5
Central and Eastern Europe	1	3	2
Europe Total	3	11	7
North America	6	21	13
Centrally planned Asia, China	5	15	8
Global Total	44	133	81

The forestry residue potential in the year 2050[37]:

Table A.5: Forestry residue potential for 2050 for a high, low and arithmetic case.[37]

Market	Low estimate [EJ/yr]	High estimate [EJ/yr]	Arithmetic mean [EJ/yr]
Western Europe	4	7	6
Central and Eastern Europe	1	2	2
Europe Total	5	9	8
North America	6	12	9
Centrally planned Asia, China	2	3	3
Global Total	19	35	81

A.3 Appendix 3: Potential calculations

For conversion from Mtoe to EJ:

$$1Mtoe = 4{,}1868 \times 10^{16} J \tag{A.1}$$

Table A.6: Global 2030-2050 scenario

Fuel (EJ/yr)				
	2013	*2020*	*2050 scenario*	*2050 max potential*
FAME/HVO	0,88	1,16	4,40	15,33
Ethanol (1st gen.)	1,91	2,21	3,34	13,37
Ethanol (2nd gen.)			4,16	20,31
Methanol			0	19,44
Synthetic diesel			4,19	14,26
DME			6,19	21,06
Biogas			13,91	33,40
Bio-SNG				22,68
Summary Bt_-fuels				
			14,54	
Total potential				
	2,79	3,38	36,18	

Table A.7: European 2030-2050 scenario

Fuel (EJ/yr)				
	2013	*2020*	*2050 scenario*	*2050 max potential*
FAME/HVO	0,34	0,43	0,39	1,34
Ethanol (1st gen.)	0,09	0,14	0,29	1,16
Ethanol (2nd gen.)			0,34	2,40
Methanol			0,00	2,70
Synthetic diesel			0,74	1,98
DME			1,09	2,93
Biogas	503 TJ		1,31	2,98
Bio-SNG			0,00	3,15
Summary Bt_-fuels				
			2,17	
Total potential				
	0,42	0,56	4,15	

Table A.8: North American 2030-2050 scenario

Fuel (EJ/yr)				
	2013	*2020*	*2050 scenario*	*2050 max potential*
FAME/HVO	0,18	0,17	0,66	2,42
Ethanol (1st gen.)	1,11	1,18	0,54	2,15
Ethanol (2nd gen.)			0,38	3,24
Methanol			0,00	3,96
Synthetic diesel			0,98	2,90
DME			1,45	4,29
Biogas			1,31	4,06
Bio-SNG			0,00	4,62
Summary Bt_-fuels				
			2,81	
Total potential				
	1,28	1,34	5,31	

Table A.9: Chinese 2030-2050 scenario

Fuel (EJ/yr)				
	2013	*2020*	*2050 scenario*	*2050 max potential*
FAME/HVO	0,01	0,02	0,47	1,55
Ethanol (1st gen.)	0,04	0,06	0,33	1,32
Ethanol (2nd gen.)			0,72	2,67
Methanol			0,00	1,98
Synthetic diesel			0,44	1,45
DME			0,64	2,15
Biogas			2,14	4,46
Bio-SNG			0,00	2,31
Summary Bt_-fuels				
			1,80	
Total potential				
	0,05	0,08	4,74	

Figure A.1 below shows the potential from the IEA BLUE Map Scenario in table 5.3 in the Criteria results part of the thesis.

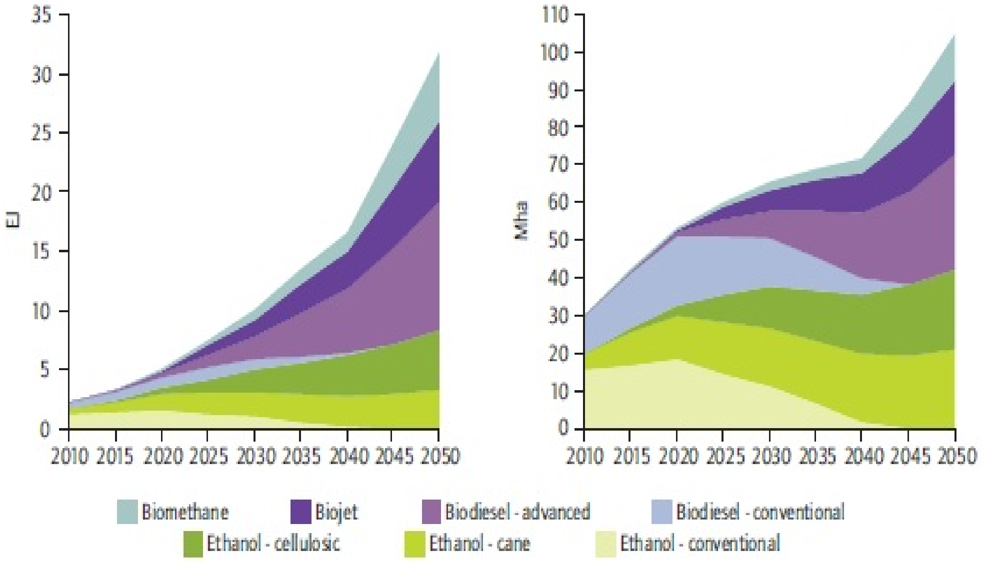

Figure A.1: Demand for biofuels and resulting land demand. IEA Blue Map Scenario. [49]

A.4 Appendix 4. Cost calculations

The initial data for the cost calculations were taken from the figures and tables seen below and summarized in table A.11.

The estimated production costs of different biofuels according to Börjesson et al (2013):

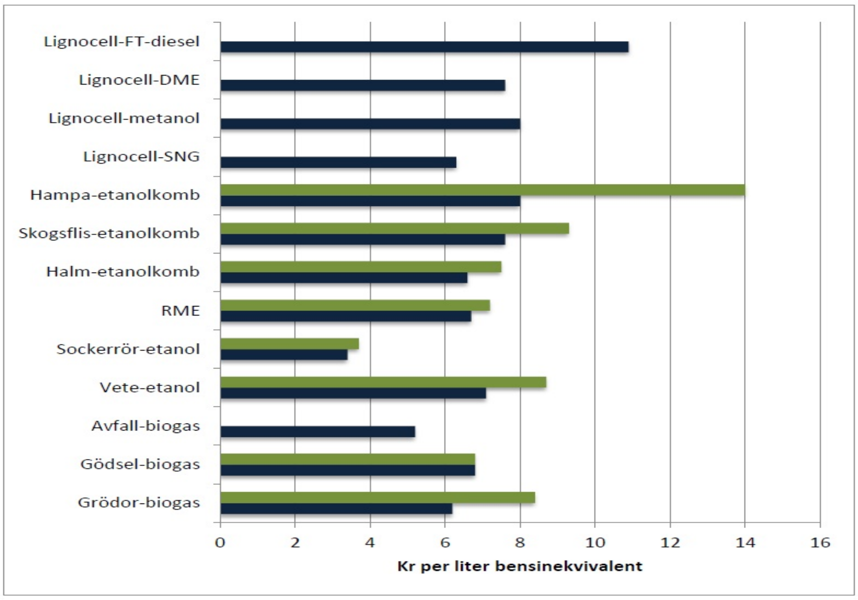

Figure A.2: Estimated production costs in SEK/l gasoline equivalents.[30]

Table A.10 shows the estimated production cost for methanol, DME, Synthetic Diesel and Bio-SNG in MSEK as calculated by Ekblom et al (2012):

Table A.10: Uppskattade produktionskostnader för respektive fall, MKR per år om ej annat anges[43]

Produktionskostnad	**Metanol**	**DME**	**FTD**	**SNG**
Driftskostnader (MSEK)	814	766	845	796
Kapitalkostnad (MSEK)	505	478	641	420
Totala kostnader (MSEK)	1319	1244	1486	1216
Produktionskostnad (SEK/MWh)	900	802	1149	662
Produktionskostnad (SEK/tonne)	4979	6416	14061	6,3 (SEK/Nm^3)
Ekvivalentliter (SEK/L)	8,0	7,1	10,2	6,3

Figure A.3 shows the ethanol price trend for 2011-2013 in SEK/L estimated by Energimyndigheten (2014). The price level used for the cost analysis is the 2013-11-04 trendline price.

Figure A.3: Prisutveckling för etanol på den Europeiska marknaden under 2011-2013, löpande priser respektive genomsnitt för helår kr/l. [44]

The distribution costs were taken from Ekblom et al (2012). They estimate the distribution cost for diesel to be 1-1,5 SEK/L which in average becomes 1,25 SEK/L. This is considered to be the same for Synthetic diesel, HVO-diesel and FAME as well. [43]

AS for Ethanol and Methanol, the distribution cost is said to be 20-30 % higher than for fossil fuels, hence 1,56 SEK/L. DME is said to be around 80 % higher in the distribution cost than the fossil fuels making this 2,25 SEK/L. Bio-SNG has a distribution cost of 2 SEK/L, which is considered to be the same for all of the biogas-type fuels.[43]

The final cost in €/100 km was calculated in four steps:

1. Production cost (SEK/L gasoline or diesel equivalents) + Distribution cost (SEK/L)= Fuel cost (SEK/L gasoline or diesel equivalents)
2. Fuel cost (SEK/L diesel or gasoline equivalents) /Exchange rate from SEK to €= Fuel cost (€/L diesel or gasoline equivalents)
3. Fuel cost (€/L diesel or gasoline equivalents) / MWh/L = Fuel cost (€/MWh)
4. Fuel cost (€/MWh) x Fuel consumption (MWh/100 km) = Fuel cost (€/100 km)

For the cost converting factors from SEK to €, the ECB-average for the year 2013 has been used.

This is given as 1 SEK = €8,6515 [50]

For the factor MWh/L, this is individual for each fuel and is calculated by using factors from table A.1 in Appendix A.1.

$$\rho([kg/m^3] \div 1000) \times LHV[MJ/kg] \div 3600MJ) = MWh/L \tag{A.2}$$

The fuel consumption relative to diesel can also be found in Table A.1 in Appendix A.1, which gives the calculation from Fuel cost (€/MWh) into fuel cost (€/100 km).

Table A.11 shows a conclusions of all ground data and the convertions for all the cost comparisons. Some categories have been excluded from figure 5.11 in the result.

Table A.11: Cost comparison table

Biofuel costs				
Fuel	**SEK/l (diesel eq.)**	**Distribution cost (SEK/l diesel eq.)**	**€/MWh**	**€/100 km**
DME	7,1 [43] 7,45[30]	2,25[43]	108,5 112,56	33,03
FT-diesel	10,3[43] 10,2[30]	1,25[43]	134,03 132,37	39,88
HVO	9[44]	1,25[43]	118,94	35,54
FAME (B100)	6,9[44] 7,2[30]	1,25[43]	94,57 98,05	28,78
Fuel	**SEK/l (gasoline eq.)**	**Distribution cost (SEK/l gasoline eq.)**	**€/MWh**	**€/100 km**
Bio-SNG (ligno.)	6,3[43] 6,25[30]	2[43]	107,31 106,67	35,02
CBG (crops)	7,50[30]	2[43]	122,83	40,08
CBG (manures)	7,47[30]	2[43]	122,44	39,95
CBG (MSW)	4,3[30]	2[43]	81,45	26,85
Methanol	8[43] 8,1[30]	1,56[43]	123,64 124,93	40,56
Fuel	**SEK/l ethanol**	**Distribution cost (SEK/l ethanol)**	**€/MWh**	**€/100 km**
Ethanol (E85)	5,20[44]	1,56[43]	128,27	41,86

The diesel plus tax cost (13,20 SEK including VAT) comes from the Energimyndigheten report. [44]

Some of the categories stated above were disregarded from the result.

A.5 Appendix 5. WTW allocations

The JEC WTW Version 4a[27]:

Pathway COD1: Crude oil from typical EU supply, transport by sea, refining in EU (marginal production), typical EU distribution and retail.

Pathway COG1: Crude oil from typical EU supply, transport by sea, refining in EU (marginal production), typical EU distribution and retail.

Pathway ROFA1: Rapeseed to biodiesel. Glycerine export to chemical.

Pathway WOFA3: Waste cooking oil to biodiesel. Glycerine to internal biogas.

Pathway POFA3a: Palm oil to biodiesel. No CH_4 emissions recovery, heat credit (oil mill), glycerine to internal biogas.

Pathway ROHY1a: Rapeseed, meal export to animal feed, NexBTL

Pathway WOHY1a: Waste cooking oil

Pathway POHY1: Palm oil, no CH_4 recovery, heat credit, NexBTL

Pathway WFSD1: Farmed wood to syndiesel via conventional gasification/synthesis plant.

Pathway WFME1: Famed wood to methanol.Conventional gasification /synthesis plant.

Pathway WTWT1: EU wheat to ethanol. Production energy provided by as heat from NG-fired boiler and grid electicity.

Pathway SCET: Brazilian sugar cane to ethanol. Excess bagasse used for electricity production.

Pathway WTET3: EU wheat to ethanol. Production energy provided by lignite-fired CHP-plant. DDGS to animal feed or electicity production.

Pathway STET1: EU wheat straw to ethanol.

Pathway FMG2C: Upgraded biogas from maize (wole plant) as CBG closed digestate storage.

Pathway WMG2C: Upgraded biogas from wet manure as CBG. Digestate storage closed or open.

Pathway FMG2C: Upgraded biogas from maize (wole plant) as CBG closed digestate storage.

Pathway WMG2C: Upgraded biogas from wet manure as CBG. Digestate storage closed or open.

Pathway FMG2C: Upgraded biogas from maize (whole plant) as CBG closed digestate storage.

Pathway WMG2C: Upgraded biogas from wet manure as CBG. Digestate storage closed or open.

Special pathway: DME produced from biogas. An approximation done by Per Hanarp as the JEC does not calculate the WTW data for DME produced from biogas feedstock.

Calculations

The results for the following calculations can be seen in tables A.12-A.14. A generic example for each calculation will be shown to display how the result has been brought forward. The $\rho(kg/m^3)$ and LHV (MJ/kg) for each fuel as well as the Fuel consumption constants can be found in Appendix A.1, table A.1.

Base data First calculate the base data to be used throughout the WTT and TTW calculations. The calculations shown below will be for gasoline:

1. Calculate the Fuel consumption for each fuel:

Fuel consumption (MJ/100 km diesel equivalents (for diesel)) x Fuel consumption constant (per fuel) = Fuel consumption (L/100 km diesel eq. (for the fuel))

$$30 \times 1{,}2 = 36\text{MJ/100 km diesel eq.} \tag{A.3}$$

2. Calculate the efficiency for the fuel:

Efficiency (diesel) x Fuel consumption constant (per fuel) = Efficiency (per fuel)

$$0{,}42 \times 1{,}2 = 0{,}35 \tag{A.4}$$

3. The fuel consumption (MJ/100 km per fuel) is then calculated to remove the diesel equivalent factor:

(Fuel consumption (L/100 km diesel eq. (per fuel) x ($\rho(kg/m^3)$/1000)) x LHV diesel(MJ/kg) = Fuel consumption (MJ/100 km)

$$(36 \times (832 \div 1000)) \times 43{,}1 = 1291\text{MJ/100 km} \tag{A.5}$$

WTT calculations

For the natural gas fuels, fossil diesel and biobased diesel fuels, Adblue is added in the WTT-calculations. For the WTT calculations DME will be used as an example:

1.Fuel consumption (L/100 km diesel eq.) x Adblue consumption (%) x Ecoinvent factor amount of CO_2 used to produce Adblue (kg/CO_2/L)[51] = Adblue CO_2 eq. (kg/100 km)

$$30 \times 7{,}5 \times 0{,}563 = 1{,}3\mathrm{CO_2}\ \text{eq. kg/100 km} \tag{A.6}$$

2. Fuel consumption (MJ/100 km) x (WTW GHG emitted (g CO_2 eq/MJ final fuel)/1000) + Adblue CO_2 eq. = CO_2 eq. (kg/100 km)

$$1076 \times (6{,}6 \div 1000) + 1{,}3 = 8\mathrm{CO_2}\ \text{eq. kg/100 km} \tag{A.7}$$

TTW calculations

For the TTW calculations, fossil fuels have a contribution of emission factors that contribute to the total CO_2 emissions. These fuels are diesel, gasoline, CNG, DME (natural gas), methanol (natural gas) and FAME.

The calculations below are shown for gasoline. GWP (100 years) refers to the Global Warming Potential for the last 100 years. This factor is a relative measure of how much heat a particular GHG has trapped in the atmossphere for the last 100 years.

1. Fuel consumption (MJ/100 km) x Emission factor (kg/MJ) = CO_2 emissions (kg/100 km)

$$1291 \times 73{,}4 = 95\text{kg/100 km} \tag{A.8}$$

2. Fuel consumption (MJ/100 km) x CH_4 emissions (kg/MJ) x GWP CH_4 (100 years)[52] = CH_4 CO_2 equivalents (kg/100 km)

$$1291 \times 0{,}0019556 \times (25 \div 1000) = 0{,}06 kg/m^3 \tag{A.9}$$

3. Fuel consumption (MJ/100 km) x N_2O emissions (kg/MJ) x GWP N_2O (100 years)[52] = N_2O CO_2 equivalents (kg/100 km)

$$1291 \times 0{,}0061111 \times (298 \div 1000) = 2{,}14 kg/100km \tag{A.10}$$

4. CO_2 emissions + CH_4 CO_2 equivalents + N_2O CO_2 equivalents = CO_2 equivalents 100 years (kg/100 km)

$$95 + 0{,}06 + 2{,}14 = 97{,}2\text{kg/100 km} \tag{A.11}$$

Table A.12: WTT data

Fuel	**Fuel consumption**	**Conversion technology**	**Efficiency**	**Fuel consumption (L/100 km diesel eq.)**	**Fuel consumption (MJ/100 km)**	**Pathway**	**WTT GHG emitted (g CO_2/MJ final fuel) (excl.Adblue)**	**Adblue consumption (added volume %)**	**Adblue CO_2 eq.**	**CO_2 eq. (kg/100 km)**
Fossil Fuels										
Diesel (crude oil) EU	1	DI	0,42	30,0	1076	COD1	15,4	7,5%	1,3	18
Gasoline	1,20	Otto	0,35	36,0	1291	COG1	13,8		0,0	18
CNG SI (natural gas)	1,20	Otto	0,35	36,0	1291	GMCG1	13		0,0	17
DME (natural gas)	1,00	DI	0,42	30,0	1076	GRDE1	22	7,5%	1,3	25
Methanol SI (natural gas)	1,20	Otto	0,35	36,0	1291	GRME1	24,9		0,0	32
First Generation Biofuels										
FAME	1,00	DI	0,42	30,0	1076	ROFA1	49,3	7,5%	1,3	54
FAME (best case)	1,00	DI	0,42	30,0	1076	WOWA3	13,8	7,5%	1,3	16
FAME (worst case)	1,00	DI	0,42	30,0	1076	POFA3a	54,3	7,5%	1,3	60
HVO	1,00	DI	0,42	30,0	1076	ROHY1a	49,1	7,5%	1,3	54
HVO (best case)	1,00	DI	0,42	30,0	1076	WOHY1a	8,1	7,5%	1,3	10
HVO (worst case)	1,00	DI	0,42	30,0	1076	POHY1	59,6	7,5%	1,3	65
Ethanol SI	1,20	Otto	0,35	36,0	1291	WTET1	52,3		0,0	68
Ethanol SI (best case)	1,20	Otto	0,35	36,0	1291	SCET	27,5		0,0	36
Ethanol SI (worst case)	1,20	Otto	0,35	36,0	1291	WTET3	61,1		0,0	79
CBG SI (crops)	1,20	Otto	0,35	36,0	1291	FMG2C	39		0,0	50
Second Generation Biofuels										
Synthetic diesel	1,00	DI	0,42	30,0	1076	WFSD1	7	7,5%	1,3	9
DME	1,00	DI	0,42	30,0	1076	WFDE1	6,6	7,5%	1,3	8
Ethanol SI 2nd gen	1,20	Otto	0,35	36,0	1291	STET1	9,2		0,0	12
Methanol SI (wood)	1,20	Otto	0,35	36,0	1291	WFME1	6,6		0,0	9
CBG SI (manure) best	1,20	Otto	0,35	36,0	1291	WMG2C	13		0,0	17

Table A.13: TTW data

Fuel	***CH_4 emissions (g/MJ)***	***N_2O emissions (g/MJ)***	***CO_2 emissions (kg/100km)***	***CH_4 CO_2eq (kg/100km)***	***N_2O CO_2eq (kg/100km)***	***CO_2eq (kg/100km)***
Fossil Fuels						
Diesel (crude oil)	0,002	0,006	79	0,05	1,96	81
Gasoline	0,002	0,006	95	0,06	2,14	97
CNG SI (natural gas)	0,056	0,006	73	1,79	2,14	76
DME (natural gas)	0,002	0,006	74	0,05	2,00	76
Methanol SI (natural gas)	0,002	0,006	89	0,06	2,14	91
First Generation Biofuels						
FAME	0,002	0,006	4	0,05	1,96	6
FAME (best case)	0,002	0,006	5	0,06	2,06	7
FAME (worst case)	0,002	0,006	5	0,06	2,06	7
HVO	0,002	0,006	0	0,05	1,96	2
HVO (best case)	0,002	0,006	0	0,05	1,96	2
HVO (worst case)	0,002	0,006	0	0,05	1,96	2
Ethanol SI	0,002	0,006	0	0,06	2,14	2
Ethanol SI (best case)	0,002	0,006	0	0,06	2,14	2
Ethanol SI (worst case)	0,002	0,006	0	0,06	2,14	2
CBG SI (crops)	0,056	0,006	0	1,79	2,14	4
Second Generation Biofuels						
Synthetic diesel	0,002	0,006	0	0,05	1,96	2
DME	0,002	0,006	0	0,05	1,96	2
Ethanol SI 2nd gen	0,002	0,006	0	0,06	2,14	2
Methanol SI (wood)	0,002	0,006	0	0,06	2,14	2
CBG SI (manure) best	0,056	0,006	0	1,79	2,14	4

Table A.14: WTW data including averages

Fuel	***CO_2eq (kg/100km)***	***CO_2eq (kg/100km) (best)***	***CO_2eq (kg/100km) (worst)***	***Fossil fuel average***	***First generation biofuel average***	***Second generation biofuel average***
Fossil Fuels						
Diesel (crude oil) EU	99			102	62	11
Gasoline	115			102	62	11
CNG	93			102	62	11
First Generation Biofuels						
FAME	61	37	9	102	62	11
Ethanol	70	32	11	102	62	11
HVO	56	44	11	102	62	11
Biogas (crops)	54	34		102	62	11
Second Generation Biofuels						
Synthetic diesel	11			102	62	11
DME	10			102	62	11
Ethanol (2nd gen.)	14			102	62	11
Methanol (BtL)	11			102	62	11