Gasoline-Ethanol-Methanol (GEM) Ternary Fuel Blend as an Alternative Passenger Car Fuel in Sweden

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Abstract

This paper discusses the potential of gasoline, ethanol and methanol ternary blend as an alternative passenger car fuel in Sweden. Sweden has set various targets aimed to reduce its GHG emissions and to increase the share of renewables in the transportation sector. Nevertheless, the majority of the energy consumed in the road transportation sector still comes from fossil fuels. In order to replace the energy supply of fossil fuels by more renewable fuels, the potential of alternative renewable fuels needs to be explored. Therefore, the potential of a domestically produced ternary blend of Gasoline-Ethanol-Methanol (GEM) fuel blend is analysed in this report. In order to test whether it has the potential to become a successful alternative fuel, an analysis is performed on the: methanol and ethanol production potential from domestic second-generation feedstocks, the selection of the most suitable production pathways of the biofuels, the potential for a Swedish GEM fuel distribution infrastructure, the economic competitiveness of GEM fuel, and lastly on the environmental impact of the shift from cars running on neat gasoline to GEM fuel. In order to perform the analysis, two scenarios are developed for projecting the share of the GEM cars(cars running on GEM fuel) in the Swedish passenger car fleet, considering a time horizon from 2017 to 2030. In Scenario 1, a high share of passenger cars running on GEM fuel is obtained with 22 percent by 2030. In Scenario 2, a low share of cars running on GEM fuel is obtained with 17 percent by 2030. In both scenarios, the passenger cars running on GEM fuel take over the share of cars running on gasoline. The scenarios serve to project the energy demand for GEM fuels. By 2030, the projected energy demand for GEM fuels is 9.7 and 7.5 TWh for Scenario 1 and Scenario 2, respectively.

From the biofuel potential studies, it can be concluded that the production potential of the alcohol fuels, derived from currently untapped domestic secondary resources, exceeds the projected energy demand of 9.7 and 7.5 TWh in 2030. According to this thesis, the production potential of 2nd generation ethanol and methanol are 36 and 61.1 TWh, respectively, by 2030. Moreover, the study shows that the majority of the existing fuel distribution network of E85 and gasoline, which is forecasted to have a significant overcapacity in the same time-span as the scenarios, can be utilized in a GEM fuel distribution network. As a consequence, no major investments are required to develop a Swedish GEM fuel distribution network. Regarding the selection of the biofuel production pathways, this study indicates the most suitable way of producing methanol is by black-liquor gasification. Regarding second-generation ethanol, this thesis indicates that the fermentation forestry residues is the most beneficial production pathway. The biofuel production pathways are selected based on the energy yield ratios, the biofuel production cost and biomass feedstock cost. Moreover, this study demonstrates that under the current Swedish policies, GEM fuels blends are economic competitive with gasoline and E85. In order to test the economic competitiveness, a pay-off curve was developed based on the pump price of gasoline and fuel economy of GEM fuel blends. This study shows the pump prices of GEM fuel blends pay-off in comparison to gasoline. This analysis indicates that the pump prices of GEM fuel blends lays between 0.87 and 0.92 euro per liter. Regarding the environmental impact, this study indicates that the amount of GHG emissions avoided varies between 10.1 and 13.3 million metric tons $CO2_{eq}$ in Scenario 1. In Scenario 2, the amount of GHG emissions that can be avoided varies between 8.6 and 11.3 million metric tons $CO2_{eq}$. Moreover, this study indicates that high methanol containing GEM fuel blend are more favourable in terms of biomass utilization, and high ethanol containing GEM fuel blends are more favourable in terms of economy and GHG savings.

Keywords: *GEM fuel, Biofuels, Sweden, Bioenergy, Methanol, 2nd generation Ethanol, Black Liquor Gasification, Gasoline-Ethanol-Methanol (GEM) ternary blend, Distribution Network Biofuels, E85 Flexible Fuel Vehicles, Forestry Residue Fermentation*

Executive Summary

The country of Sweden has recognized the dangers of climate change and has therefore developed various targets in order to reduce its GHG emissions. One of these targets is to reduce the GHG emissions of the transportation sector by 70 percent between 2010 and 2030. Moreover, the country attempts to have fully renewable energy sector by the year of 2045. Despite the various targets, the country is still heavily dependent on the import of crude oil, which is mainly used in the road transportation sector. Hence, the transportation sector contributes significantly to the countries emissions. In order to decrease these emissions alternative fuels, which have the potential to replace the long-term energy demand of fossil fuels, need to be explored. In this thesis, a potential alternative fuel is analysed, which is a ternary fuel blend constituting of gasoline, ethanol and methanol, also known as GEM fuel. This report primarily analyses the theoretical production potential of GEM fuel using secondary domestic biomass feedstocks. Biofuel production pathways (i.e. conversion technologies), GEM fuel distribution network, economic competitiveness of the alternative fuel, and associated environmental impact of the shift from cars running on neat gasoline to GEM fuel are investigated in the thesis. In order to perform the analysis, two scenarios are developed for projecting the share of the GEM cars in the Swedish passenger car fleet, in the time span from 2017 to 2030. In both scenarios, the passenger cars running on GEM fuel blends take over the share of cars running on gasoline. In Scenario 1, a high share of passenger cars running on GEM fuel is obtained with 22 percent by 2030. In Scenario 2, a low share of cars running on GEM fuel is obtained with 17 percent by 2030. The scenarios serve to project the energy demand for GEM fuels, when passenger cars running on GEM fuel obtain different shares in the Swedish passenger car fleet. By 2030, the projected energy demand for GEM fuels is 9.7 and 7.5 TWh for Scenario 1 and Scenario 2, respectively.

Recent studies indicate that GEM ternary fuel blend is a fuel that can be successfully utilized as a transportation fuel for E85 flex-fuel vehicles, GEM fuel is a collective name for fuel blends consisting of gasoline, ethanol and methanol, with an air to fuel ratio similar as E85.The varying compositions of the ternary fuel can successfully be implemented in E85 flexible fuel vehicles. The main research question treated in this report reads:

> *What is the potential of GEM fuel blends as alternative transportation fuels in the Swedish passenger car fleet?*

In the first step of the thesis, the biofuel production potentials of methanol and ethanol from domestic second-generation feedstocks are assessed. Only second-generation feedstocks are analysed due to the limited potential of first-generation ethanol. The limited potential of first-generation biofuels is the result of the cap of 7 percent by 2021, on the usage of first-generation biofuels in the transportation sector of EU member states, stated in the revised Renewable Energy Directive. [6] The cap is going down progressively to 3.8 percent by the year of 2030. Moreover, the production of first-generation ethanol is globally well-established. For these reasons, only alcohol fuel production from second-generation feedstocks is considered in this thesis. The assessment of the biofuel production potential is based on the potential of untapped second-generation Swedish biomass feedstocks, as well as the energy yield ratios from feedstock to biofuel of key methanol and ethanol production technologies. For the different secondary biomass feedstocks, it is analysed whether it can be implemented as feedstock for methanol and/or ethanol production. Regarding the potential of biomass feedstocks, multiple studies indicate that there are large amounts of

biomass feedstocks that can become available and which can be utilized for the production of ethanol and methanol.[7-9] Feedstocks such as forestry residues, industrial wood waste, black liquor and straw. In addition, both ethanol and methanol can be produced from secondary energy crops such as cultivated energy forest. Most of the biomass feedstocks can be used for the production of both alcohols. Regarding methanol production, black liquor is a feedstock that is currently not untapped, since the substance is combusted for the production of power and heat in pulp and paper plants. [10] However, if other solid biomass feedstocks are combusted instead of the black liquor, the black liquor can be utilized as a feedstock for the methanol production.

This thesis estimates that the untapped potential of secondary biomass feedstocks, that is suitable for ethanol production, is around 90 TWh annually by 2030. Moreover, it estimates, that the corresponding annual production potential of second-generation ethanol is 25.9 TWh. Regarding methanol production, this study estimates that the annual potential of biomass feedstocks, that could become available for methanol production, is 106 TWh by 2030. This study estimates that the total annual production potential of methanol is 56.5 TWh by 2030. Due to the fact that most of the biomass feedstocks can be utilized for the production of both bioalcohols, the estimated production potentials of the individual biofuels can only be achieved if only one of the biofuels is produced. Therefore, the estimated production potentials of both ethanol and methanol cannot be added up in order to determine the GEM fuels potential. Nevertheless, the biofuel potential study identifies that there is a large theoretical production potential for both bioalcohols.

After the biofuel potentials are verified, the most beneficial production pathways of both the alcohol fuels (ethanol and methanol) are selected. In the purpose of this thesis, 'production pathway' is described as the feedstock and the conversion technology implemented to produce a biofuel. The selection is based on three criteria: (1) the energy yield ratio of the conversion technology, (2) the biofuel production costs, (3) the biomass feedstock costs. Regarding methanol production, the study indicates that the gasification of black liquor is the most suitable pathway for producing the fuel. According to Andersson et al, black liquor is currently inefficiently combusted by chemical pulp and paper plants.[10] However, as mentioned previously, the substance is perfectly suitable as a feedstock for methanol production. When biomass is combusted instead of black liquor, the black liquor can be used as a feedstock for methanol production. The energy yield ratio from the additional biomass feedstocks to methanol is 78 percent. The production costs of the methanol via black liquor gasification lays between the 77 and 87 euro per MWh, depending on the size of the pulp and paper plant. Instead black liquor, all the previously mentioned types of solid biomass could be combusted. As a consequence, methanol production via black liquor gasification, has a high availability and flexibility of biomass feedstocks. Regarding 2nd generation ethanol production, this study shows that the fermentation of industrial wood waste, such as sawdust and shavings, is the production pathway most suitable in Sweden. The conversion costs of the production process are 97 euro per MWh and the energy yield ratio from industrial wood waste to ethanol is 34 percent. [11, 12]

Since a variety of GEM fuel blends can be implemented in E85 flex-fuel vehicles, in this study, three different GEM fuel blends are considered in combination with the two scenarios. In Blend HM, one GEM fuel blend with a high methanol content is analysed, consisting of 36.5, 23.5 and 40 volume percent of respectively gasoline, ethanol and methanol. In Blend ME, one GEM fuel blend with a medium content of methanol and ethanol is considered, consisting of 29.5, 42.5 and 28 volume percent of respectively gasoline, ethanol and methanol. In Blend HE, one GEM fuel blend with a high ethanol content is considered, consisting of 19.5, 71 and 9.5 volume percent of respectively gasoline, ethanol and methanol. The selected GEM fuel blends, in combination with the Scenarios, serve to identify the economic, environmental and biomass utilization impacts of the implementation of a high methanol, a high ethanol and a medium methanol/ethanol GEM fuel blend. Since the varying contents of the alcohol fuels in GEM fuel blends, results in different environmental, economic and biomass utilization impacts. For policy makers, these impacts can be from varying importance. Therefore, the analysis on the GEM fuel blends, in combination with the Scenarios, provide insights on which of these GEM fuel blends is the most beneficial in terms of the individual impacts. Moreover, the GEM fuel blends are selected to derive which blend would be the most favorable GEM fuel blend and to verify whether one the biofuels is more favorable as part of the blend. Hence, based on the results of this study, policy makers can decide whether to direct policy support into the production of advanced ethanol and/or methanol.

The developed scenarios are based on a business as usual forecast of the shares of different car types in the Swedish passenger car fleet, developed by the Swedish Transport Analysis Agency. The business as usual forecast, projects the share of gasoline cars to be 20 percent by 2030, in the Swedish passenger car fleet. Moreover, the forecast projects the share of E85 flex-fuel vehicles to decrease to 2 percent by 2030. In the purpose of this thesis, 'GEM cars' are described as E85 flex-fuel vehicles running on GEM fuel blends. As mentioned previously, in Scenario 1, it is considered that GEM cars take over the entire share of gasoline cars and E85 flex-fuel vehicles. In Scenario 2, it is considered that cars running on GEM fuel take over 75 percent of the gasoline cars. In addition, it is considered that GEM cars take over the 2 percent of E85 flex-fuel vehicles, resulting in a share of 17 percent by 2030. It is assumed that GEM cars take over the share of gasoline cars, since both cars are powered by spark ignition engines and can be readily be converted from one to another. Scenario 1 and 2 are developed, in combination with the selected GEM fuel blends, to project the energy demand of GEM fuel blends, which is created by the shift from cars running on neat gasoline to GEM fuels blends. The projected energy demand of GEM fuels, that is created by the shift and needs to be satisfied by GEM fuel blends, is 9.7 TWh in Scenario 1 and 7.5 TWh in 2030, respectively. This study indicates that the highest energy demand for alcohol fuels is created by Scenario 1 in combination with the high ethanol containing GEM fuel blend.(blend HE) Moreover, this study shows that the biomass utilization in the GEM fuel blends with high ethanol contents, in combination with the scenarios, are significantly higher than high methanol containing GEM fuel blends. In order to satisfy the GEM fuel demand in Scenario 1 and Blend HE, a biomass utilization of 19.6 TWh is required. In comparison, in order to satisfy the energy demand in Scenario 1 in combination with Blend HM, a biomass utilization of 9.6 TWh is necessary.

In this thesis, the considered distribution network constitutes of the activities related to the transport, blending, storage and retailing of GEM fuel and its components. In the Swedish GEM fuel distribution network analyses, first, it is analysed what parts of the existing fuel distribution network of E85 and gasoline can be implemented in a GEM fuel distribution network. Sweden has a well-established existing distribution network for E85 and gasoline, constituting of i.e. storage terminals, tanker trucks, blending stations and retail fuelling pumps, which are developed for both fossil fuels and biofuels. Due to the countries' many efforts to promote biofuels in the transportation sector, around two thirds of the countries' retail stations supply currently E85 fuel. Nevertheless, in 2016, the consumption of E85 fuel was extremely low, with less than half a percent consumed of the total road transportation fuel consumption. The consumption of E85 has decreased with 80 percent, between 2011 and 2016.[13] As a consequence, an over-capacity of the E85 distribution network has appeared. Moreover, multiple studies forecast that the consumption of petroleum fuels to decrease in the coming decades, with the consequence that an overcapacity in the entire vehicle fuel distribution network will appear. [14-16] From this study, it can be concluded that the majority of the existing distribution network of transportation fuels can be utilized for the distribution of GEM fuel and therefore offers an alternative use. This study indicates that the capacity of the existing fuel distribution network for E85 and gasoline is sufficient to supply the projected energy demand of GEM fuel blends. As a consequence, major investments in a GEM fuel distribution infrastructure are not required, resulting in low distribution costs in comparison to other renewable alternatives for passenger car fuels. The E85 fuelling pumps can, after minor adaptions on the gaskets, be converted to GEM fuel pumps. Nevertheless, this study indicates that in-line fuel blending systems need to be newly-established in order to blend the gasoline, ethanol and methanol into GEM fuel blends. This study indicates that the most suitable locations for the blending systems are at the storage terminals. This study determines the total blending cost to be lower than 0.01 euro per MWh. The total costs of all the distributing activities, including transport, storage and blending, of GEM fuel are estimated to be 3.2 euro per MWh.

From the economic competitiveness studies, it can be concluded GEM fuel blends are economic-competitive with gasoline and E85. In order to investigate the economic competitiveness of the GEM fuel blends, a pump price of the fuel blends is estimated. The pump price is based on the cost of production(including biomass feedstock costs), distribution, blending, retailing and the VAT. In addition, on the gasoline part of the GEM fuel blends, the energy and carbon dioxide tax are considered. In Sweden, under the current policies, biofuel components in fuels are exempted from the energy and carbon taxes. Therefore, it is considered that the biofuel fractions of the GEM fuel are also made exempt from the energy and carbon dioxide tax. In order to test the economic competitiveness of the estimated pump prices of the GEM fuel blends, a pay-off limit curve is developed based on the gasoline price and the fuel economy of GEM fuels in comparison to gasoline. The determined pump prices for GEM fuel blend HM, ME and HE are 145.2, 142.6 and 138.8 euro per MWh(0.92, 0.90 and 0.87 euro per liter), respectively. This study shows that for the last 8 years, the pump prices of all the selected GEM fuel blends are economic competitive. The economic competitiveness analysis shows that when the current policy instruments are implemented, GEM fuel blends can become economically competitive in the passenger car fuel market. However, this report shows additionally that the production costs of 2nd generation ethanol and methanol, are still higher than the production costs of gasoline. Therefore, policy instruments, such as the current energy and carbon dioxide tax, are necessary in order to make the GEM fuel economic-competitive with gasoline. As indicated from the results of the economic competitiveness analysis, the higher the ethanol content in GEM fuel blends, the more favourable blends become in terms of economy. This is a result of the lower gasoline content in high ethanol containing GEM fuel blends.

In this study, the environmental impact is based on the GHG emissions avoided by the shift from cars running on neat gasoline to GEM fuel(with both high methanol and high ethanol content options). The scenarios, in combination with the selected GEM fuel blends, show that significant amounts of GHG emissions are avoided with the implementation of GEM fuel instead of gasoline. Since both ethanol and methanol in the GEM fuel are produced from second-generation feedstocks, the GHG savings are high, in comparison to other alternative fuels. [6] The well to wheel GHG savings of ethanol produced from forestry residues and methanol produced from black liquor are respectively 78 and 97.[17] This study indicates that the GHG savings per individual blend are 44, 50, 57 percent for Blend HM, Blend ME and Blend HE, respectively. The larger amount of GHG emissions avoided in the GEM fuel blends with a higher ethanol content, is due to the higher biofuel content in the GEM fuel blends. This study indicates that the GHG savings for Scenario 1, when the selected GEM fuel blends are implemented, are 10.1, 11.4 and 13.3 million metric tons $CO2_{eq}$ for blend HM, blend ME and Blend HE, respectively. For Scenario 2, this study shows that 8.6, 9.7 and 11.3 $CO2_{eq}$ million metric tons CO2eq are avoided if respectively Blend HM, Blend ME and Blend HE are implemented. Hence, this study shows that high ethanol containing GEM fuels are favourable in terms of GHG emissions avoided, due to the lower gasoline content. Moreover, this study shows that by implementation of the Scenarios in combination with the selected GEM fuel blends, the total GHG emissions of the Swedish transportation sector can be decreased with a value of 9 to 5 percent by 2030.

In conclusion, from the thesis, it can be indicated that GEM fuel has the potential to become a successful alternative passenger car fuel in Sweden. The biofuel production potential assessment proves that the projected energy demands for GEM fuel blends, created by the shift with a time horizon to 2030, can be met from Swedish second-generation biomass feedstocks. Moreover, it can be concluded, that with minor investments, the existing fuel distribution network of gasoline and E85 can be implemented for the distribution of GEM fuel and that the capacity is sufficient. Blend HM, is the most beneficial in terms of bioenergy utilization, implying that less biomass feedstocks are necessary in order to meet the future energy demand of GEM fuel. Furthermore, it can be concluded that, with the current policy instruments, GEM fuel can be supplied for an economic-competitive pump price. Blend HE, has a slightly lower pump price in comparison to Blend HM and Blend ME, and is therefore more favorable in terms of economic competitiveness. Regarding the environmental impact, this thesis indicates that the implementation of GEM fuel blends in the scenarios can save up to 13.3 and 8.6 million metric tons CO2eq. The higher the ethanol content in the GEM fuel blends the more GHG emissions are saved. Hence, this report indicates that there are no obstacles for GEM fuel to become a successful alternative fuel. However, political support is needed in order to make the economic-competitive. Therefore, it is recommended that policy instruments will be implemented that make the GEM fuel economic-competitive. Hence, it is recommended that political support is created in order to promote GEM fuel blends and the E85/GEM flex-fuel vehicles. Regarding economy and GHG savings, high ethanol GEM fuel blends are favorable. This is due to the lower gasoline content in comparison to high methanol containing GEM fuels. Regarding the biomass utilization, this study indicates that high methanol containing GEM fuel blends are favorable.

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List of Acronyms

GEM Fuel	Gasoline-Ethanol-Methanol ternary blend
SI	Spark Ignition
CI	Compression Ignition
FFV	Flexible Fuel Vehicle
E85	Fuel consisting of 85 % Ethanol and 15 % Gasoline
ICE	Internal Combustion Engine
MJ	Mega Joule
L	Liter
BM	Biomass feedstocks
EL	Electricity
DH	District heating
RVP	Reid Vapour Pressure
$CO2_{eq}$	Carbon dioxide equivalent
Mt	Million Metric Tonnes

List of Conversion Factors

1 Euro	1.161 Dollar
1 Euro	9.75 SEK
1 m^3 Gasoline	9.1 MWh
1 m^2 Ethanol	5.88 MWh
1 Barrel	0.159 m^3
1 kg Straw	18.7 MJ (89 % DM)
1 L Diesel	39 MJ

Definitions

Energy Yield Ratio	Is the energy yield ratio from biomass feedstock to biofuel
E85 Flex-fuel vehicle	A flex-fuel vehicle, is a passenger car that can run on E85, gasoline and GEM fuel
Gx Ey Mz	The G, E and M stand for gasoline, ethanol and methanol. The x, y, y stand for the volume fractions in the blend.
Pump Price	The pump price is the price that costumers pay for the fuel at the retail stations
Distribution network	A distribution network is the supply chain that distributes transportation fuels constituting of transport, storage, blending and retailing.
Lump Sum	One-time payment for the total or partial value of an asset.
2^{nd} -generation feedstocks	Biomass feedstocks that can be implemented for biofuel production and that are inedible
GEM Cars	E85 flex-fuel vehicles that are fuelled with GEM fuel blends
Biofuel Production Pathway	describes the feedstock and conversion technology implemented to produce a certain biofuel

1 Introduction

Climate change is non-arguably one of the biggest problems that the world is facing at present. It is a complex process which is in part a result of the tremendous amounts of global emissions of anthropogenic greenhouse gases. Globally, the transportation sector is responsible for a significant part of the greenhouse gas emissions. In order to mitigate climate change, all over the world targets are being set in order to reduce the amount of carbon emissions into the atmosphere. One objective that the European Union seeks to establish and which is stated in the Renewable Energy Directive, is that 10 percent of the transportation fuels is derived from renewable resources by the year of 2020[18]. Furthermore, EU legislation requires in the same year a decrease of 6 percent in GHG emissions of transportation fuels in comparison to the year 2010[19]. As result of such targets, a growing demand is created for renewable alternatives of the currently dominating conventional fossil fuels.

Sweden is globally one of the frontrunners when it comes to sustainability. The country has set a goal to eliminate non-renewable energy conversion by the year of 2045.[20] In 2015, more than half of the final energy consumed was derived from a renewable energy source[4]. Nevertheless, the country still consumes large amounts of fossil fuels, mainly in the road transportation sector. [4] In order to decrease emissions of the transportation sector, the country has set the ambitious target to have, in the year 2030, a 70 percent decrease in GHG emissions in comparison to the year of 2010. [20] Sweden has set such an ambitious targets, because in 2016, the transportation sector was responsible for 41 percent of the total domestic GHG emissions, while the energy consumption in the transportation sector accounted for only 26 percent of the final energy consumption. [21] [4] To achieve the target, a significant shift in the current fuel usage in the passenger car fleet needs to occur. According to the Swedish Energy Agency, in the year 2016, approximately 81 percent of the passenger cars was fuelled with a conventional fossil fuel. [1]

Biofuels are the renewable alternatives with a large potential to displace the energy demand from conventional fuels in the road transportation sector. Biofuels can, similarly as fossil fuels, be used in internal combustion engines. In 2016, approximately 92 percent of the passenger cars in use were powered by an internal combustion engine. [1] There are mainly two different types of internal combustion engines used, respectively the spark ignition and the compression ignition engine. The engine used in gasoline- and flexible fuel vehicles is a spark ignition engine and the engine used in diesel vehicles is a compression ignition engine. In 2016, approximately 65 percent of the Swedish passenger cars was powered by a spark ignition engine, constituting of gasoline and E85 cars.[22] In order to increase the amount of renewable fuels and to decrease the GHG emissions in the Swedish passenger vehicle fleet, a major shift in fuel usage for spark ignition engine vehicles has to be made in addition to the ongoing shift towards electric propulsion. The SI engines used in gasoline vehicles and E85 flexible fuels vehicles are profoundly similar and can easily be converted from one to the other. [3]

In 2016, there were 220 thousand E85 flexible fuel vehicles in the Swedish passenger car fleet, accounting for 5 percent of the total. [23] The large amount of FFV's is because Sweden has put a lot of effort into promoting biofuels during the last decades. The Swedish government have offered many financial incentives in order to promote bioethanol and E85 flexible fuel vehicles. A policy instrument implemented to promote biofuels is the law(2005:1248), the so called Pump Law, which states that every pump station, with annual sales of fuels above 1000 cubic meters, is obliged to supply an alternative renewable fuel. [20] Moreover, the Swedish government offered financial support in terms of the exemption of the energy and carbon dioxide tax, and a lump sum credit of around 1000 euro to subsidize the purchase of a E85 FFV's.[24] The political support has resulted in well-established E85 distribution network and a significant an amount of around E85 FFV's on the road. According to Pacini et al., after Brazil, Sweden has the largest distribution network. [24] At present, around two thirds of the Swedish retail stations, supplies E85 fuel at its specialized E85 fuelling pumps. [25] Despite the large number of E85 FFV's in the Swedish passenger car fleet and the well-established distribution network, the amount of E85 consumed by the E85 FFV's is extremely low. In 2016, less than half a percent of the total road transportation fuel consumption was E85 fuel.[25] [13] The consumption of E85 has decreased with 80 percent, between 2011 and 2016.[13] This is because the majority of the E85 FFV owners fuel their cars with gasoline instead of E85.[25] According to F. Sprei, the decrease of E85 consumption is a result of E85 losing its economic benefit in comparison to gasoline, the loss of the exemption of the congestion charge in Stockholm and the negative media attention regarding first generation bioethanol. [26] Due to the decrease of E85 consumption, a significant overcapacity in the distribution network of the E85 has appeared.

As previously mentioned, Sweden's aims to reduce the GHG emissions of the transportation sector and to decrease the amount of fossil fuels consumed in the passenger car fleet. An alternative fuel, that has possibly the potential to become a successful alternative fuel for SI cars, is GEM fuel. GEM fuel is a ternary blend constituting of gasoline, ethanol and methanol. Various recent studies have indicated that high alcohol containing GEM fuel blends can be successfully utilized in the spark ignition engines of E85 FFV's.[27] [3] [28] The applicability of GEM fuels in SI engines makes it an attractive alternative for gasoline and E85. GEM fuel can be utilized in E85 FFV's without any modifications and according to L. Bromberg et al. a gasoline vehicle engine can be transformed to GEM FFV vehicle with minor adaptions. [29] GEM fuel is commercially not yet implemented as a passenger car fuel, however the fuel is currently successfully used in the auto race industry. [30] In comparison to gasoline, GEM fuels have the advantage that the energy utilization of the fuel is improved. Hence, in order to cover a certain amount of distance, 5 percent less energy input of GEM fuel is required.[31] Moreover, due to the similar characteristics of GEM fuels and E85, GEM fuel can potentially be distributed in the current well-developed E85 distribution network.

Beside the improved engine performances, GEM fuel blends have the advantage that, in comparison to the E85 that has been supplied in Sweden, the variety, flexibility and availability of biomass feedstocks is increased. The E85 that has been supplied in Sweden, consisted mainly of first-generation ethanol derived from energy crops such as sugarcane and corn. [13] Methanol is a biofuel that can be produced from what currently is and ever was a plant.[30] The biofuel can be produced from lignocellulosic feedstocks, such as forestry residues, industrial wood waste and black liquor.[10] Hence, by adding methanol to the binary mixture, the biomass limit and variety of the fuel are enlarged[30]. Moreover, many steps forward are being made in the process of producing of 2nd generation ethanol from lignocellulosic feedstocks.[11] Introducing methanol to the binary mixture, in combination with the developments being made in the production of 2nd generation ethanol, can possibly create a significant boost to the utilization of alcohol fuels in the Swedish passenger car fleet. Furthermore, the energy diversification of sources in the transportation sector would increase significantly by the implementation of the advanced bioalcohols.

Beside minimizing the GHG emissions in the transportation sector, the European Union attempts to limit the usage of biofuels derived from food crops, in the Renewable Energy Directive, it is stated that there is a cap of 7 percent on the usage of first-generation biofuels in the transportation sector. [6] The European Commission has even proposed to lower the cap to 3.8 percent by the year of 2030.[18] As mention previously, GEM fuel has the advantage that both of the alcohols can be produced from second-generation feedstocks. The majority of Sweden's surface area is covered by forest and the pulp and timber are large industries in the country.[4, 8] As a consequence, the country has tremendous amounts of untapped lignocellulosic feedstocks, such as forestry residues, industrial wood waste and black liquor, that could be implemented for the production of the bioethanol and methanol. [7] Resulting in potentially a large biofuel production potential of the biofuels.

1.1 Background

- **Ethanol**

Sweden has a long history with the use of alcohols as transportation fuels. In 1986, SEKAB, a leading European ethanol supplier, was the first in Europe to produce ethanol fuel, used to fuel three buses. The fuel that was introduced is called ED95 and contains an ethanol volume of 95 percent. Three years later the company started to produce ethanol fuel in order to fuel 30 buses in the city centre of Stockholm. In the year 1994, around 50 flexible fuel vehicles model Ford Taurus were imported to the municipality Örnsköldsvik. The Ford Taurus was originally a methanol flexible vehicle, which was capable of running on M85, a mixture of 85 percent methanol and 15 percent gasoline. SEKAB started to produce E85 and subsequently delivered the fuel to local retail fuelling stations. Within a few years, the amount of imported flexible fuel vehicles would increase to 350 and the first public retail fuel stations with E85 pumps become available. In 1998, 2000 new flexible fuel vehicles model Ford Focus were ordered by the city of Stockholm. From then on, the amount of flexible fuel cars in the Swedish vehicle fleet increased to what is today. Due to the rise of the usage of ethanol, Sweden has a large E85 distribution network, consisting of 1745 E85 dispensing pumps.[25] As mentioned previously, despite the well-established distribution infrastructure of E85, the use of ethanol after 2008 has decreased significantly. [4]

For decades, the production and distribution of first generation ethanol is widely practiced and is therefore well-established. At present, the Swedish company AgroEthanol produces annually around 1.5 TWh of ethanol from first-generation feedstocks.[32] As mentioned previously, the emphasis in this report lays on the production of second-generation ethanol production, which is analyzed in the continuation of the report. In Sweden, second-generation ethanol is produced by facilities of ST1 in Gothenburg and in Örnsköldsvik with a capacity of respectively 34 and 64 GWh annually. The ethanol produced by ST1 is produced by the patented Etanolix technology. However, the production potential for the technology is relatively limited, since mainly bakery residues are used as the feedstock for the process. In Örnsköldsvik, ethanol is a by-product of the production process in which lignocellulosic feedstocks are used to produce cellulose and lignin. [33] The ethanol is blended into low ethanol blends and therefore not in E85.

- **Methanol**

Methanol is an alcohol that is derived by the catalytic conversion of syngas. Syngas is a mixture of hydrogen and carbon-monoxide gases. The gas is most commonly produced by the following thermochemical processes, i.e. steam reforming of natural gas/upgraded biogas, gasification of hydrocarbons and coal. The diversity and availability in feedstock for methanol results in a security of supply, which is an important factor for fuels. Regarding methanol production in Sweden, Södra, Sweden's largest forest-owner association, announced recently that it will start to build a biomethanol production plant with an output 5000 tonnes of biomethanol annually, starting to deliver by 2019.[34]

In the past, methanol has been successfully implemented as a transportation fuel in Sweden. The interest in the fuel aroused due to oil crises between 1970 and 1980. Methanol was mixed in a 15 percent low-blend with gasoline and was called M15. [35] The low blend was successfully tested in approximately 1000 gasoline cars and a total of 3000 cubic meters was consumed. However, when the oil crisis disappeared and the price of petroleum products decreased, it turned out that the industry was not on such a scale that the methanol could compete with conventional fossil fuels. The methanol was produced by the gasification of the fossil fuel natural gas and coal.

Globally methanol has also been implemented as a transportation fuel. Between the 1980s and 1990s in the USA, the high blend M85 constituting of 85 percent methanol and 15 percent additives was experimentally tested. The blend operated in original gasoline cars which were converted to dedicated methanol vehicles. [29] Following the experiment, Ford introduced two flexible fuel vehicles models which could run on M85 and gasoline. As of 1997, around 21000 M85 FFV were on the road with about 100 public and private M85 fuelling stations. Even though, the start seemed to be successful, ethanol eventually took over the methanol demand. In 2005, the methanol blend was not available in the USA anymore, after 25 years and 320 million km the operation was over. [29] According to Bromberg et al. the failure of methanol was caused by no strong advocacy of the fuel and the rapidly dropping oil price during the period of time. Methanol as a transportation fuel has been consumed in the largest quantities in China. [29] Methanol blends are commercially available with a methanol content varying from 5 to 100 percent. The low blend M15 has the largest methanol share. In 2015, the transportation sector in China consumed an amount of around 5 – 6.5 million tonnes of methanol. The methanol blends are implemented in special dedicated methanol vehicles, M85 FFV's and gasoline vehicles. Beside light-duty fuel, M100 is also implemented as the fuel for busses. [29]

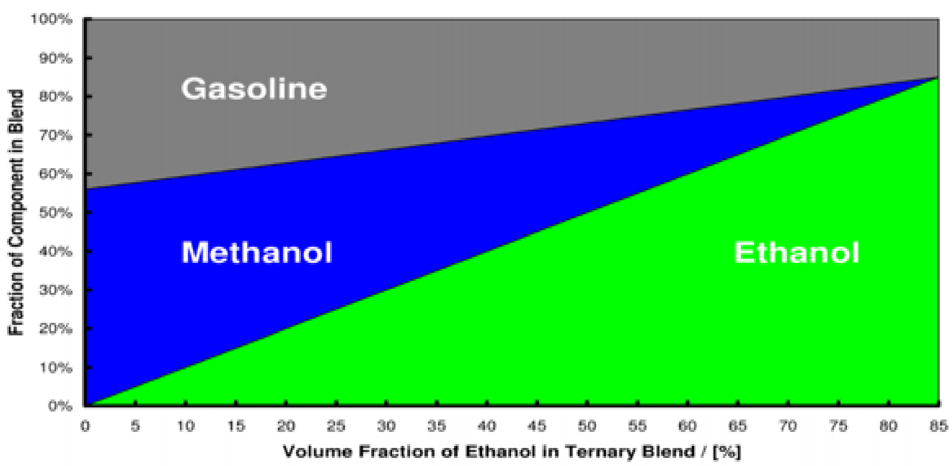


Figure 1-1: Different fuel compositions of that are successfully implementable in a flexible fuel vehicle[3]

- **GEM fuel**

As mentioned previously, GEM fuel can be implemented without any modifications in an E85 flexible fuel vehicle. In figure 1-1, different compositions of GEM fuels are depicted that can be successfully utilized. As can be seen in Figure 1.1, the blends in the left side of the figure contain higher amounts of methanol and the blends in the right side of the graph contain higher ethanol contents. The different blends have the same stoichiometric conditions as E85, namely an air to fuel ratio of 9.7, and can therefore be implemented in the same engine. As can be seen in the graph, the methanol content can vary from 0 to 56 percent. The energy content of different fuel compositions varies from 29.09 MJ per kg for E85G15(Ethanol 85% and Gasoline 15%) up to 29.66 MJ per kg for M56 G44(Methanol 56% and Gasoline 44%).[3]

1.3 Motivation of the study

To tackle climate change, Sweden aims to decrease the GHG emissions of the Swedish vehicle fleet significantly by the year of 2030. The country aims to decrease the GHG emissions in the transportation sector with 70 percent between 2010 and 2030. However, between 2010 and 2015 the GHG emissions has decreased by only 11 percent [21] Therefore, in order to achieve the target, steps towards cleaner alternatives road transportation fuels are required.

In 2016, 36 percent of the total energy consumption in the entire Swedish transportation sector, was derived from gasoline and consumed by the spark-ignition engines of passenger cars.[23] GEM fuel is a fuel that has possibly has the potential to become a successful alternative fuel for the SI fuels: gasoline and E85. In 2016, the consumption of E85 fuel was extremely low, with less than half a percent consumed of the total road transportation fuel consumption. The consumption of E85 has decreased with 80 percent, between 2011 and 2016.[13] Despite the many efforts that Sweden has put into the promotion of E85 fuel and E85 flex-fuel vehicles, the conventional E85 has not succeeded in Sweden. As mentioned previously, the E85 flexible fuel vehicles hold a share of 5 percent in the current Swedish passenger car fleet.[4] The vehicles have the potential to run on renewable fuels, however the cars are currently fueled with fossil fuels and therefore not contributing to the decrease of GHG emissions in Sweden. [4] GEM fuel is a blend of mostly renewable fuels which can be used in today's E85 FFV's. In addition, the majority of the Swedish cars have gasoline SI engines which can be transformed to E85 FFV's by minor adaptions. Showing that there is a large potential market of GEM fuel. Furthermore, Södra has planned to start the large-scale production of biomethanol starting from the year 2019. The methanol could be utilized in SI engines of passenger cars in part of the GEM fuel. Hence, by introducing the GEM fuel to the market, in a relatively short period of time, the GHG emissions of these vehicles can be reduced significantly and the share of renewable fuels in the transportation sector be increased. However, before the fuel can be introduced to the passenger car fuel market, the potential of the fuel has to be comprehensively analyzed. There is thus a need for potential studies on the implementation of GEM ternary fuel blends as alternative fuels in Sweden.

Beside the current over-capacity in the E85 distribution network, it is expected that as well an over-capacity is going to appear in the distribution network of fossil fuels. Recent studies have forecasted that the consumption of petroleum fuels is going to decrease with a value in the order of 40 to 70 percent between 2015 and 2030(see Appendix 12.6). [14-16] Major investments have been made in order to establish the distribution infrastructures of fossil fuels and E85. Due to GEM fuels' comparable physicochemical characteristics to gasoline and E85, the fuel offers a potential alternative use of the valuable assets and therefore loss of capital can be prevented.[36] This favors GEM fuel in comparison to other alternative fuels such as hydrogen and biogas, which demand tremendous investments in distribution infrastructures and currently have an extremely low share in the Swedish passenger car fleet.[22, 37] A lacking distribution network has been proven to be a major obstacle for various alternative fuels.[38] In comparison to the biofuel HVO, GEM fuel has the environmental benefit that the advanced methanol and ethanol have significantly higher GHG savings. HVO has well to wheel GHG savings between 40 to 68 in comparison to fossil fuels. [6] In comparison, the advanced alcohols have both significantly higher GHG savings with respectively more than 80 and 90 percent for ethanol and methanol. [6] Therefore, the implementation of the advanced alcohols is more favorable in terms of the environmental impact.

In comparison to renewable alternatives which involve electric engines, GEM fuel has the advantage that is does not heavily rely on power of the Swedish power network. The electric alternatives for ICE cars increase the pressure on the Swedish power industry and the Swedish electrical grid. [39] Moreover, it is decided that four of Sweden's eight nuclear plants will be decommissioned by the year of 2020. [40]The eight Sweden's nuclear power plants provide the country with approximately a third of its electricity.[22] Thus, the decommissioning of the nuclear plants and the rise of electric vehicles would result in a tremendous amount of electrical power which is needs to be produced by renewable energy technologies. In addition, increased capacity from the grid is necessary when implementing electric vehicles as alternatives for ICE cars due to the increased power consumption, which requires large financial investments.[39]

Moreover, multiple studies have concluded that GEM fuel can be successfully utilized as a transportation fuel in flexible fuel vehicles without negatively influencing the vehicle performances and with decreasing the vehicle emissions.[5, 30] The EU aims to enhance the usage of advanced biofuels in the transportation sector and to enlarge the energy diversification. [18] The two alcohols in the blend can be produced from a variety of secondary resources, such as forestry residues, industrial waste residues and wood waste. Various recent studies indicate that there is a large potential of these untapped feedstocks in Sweden, resulting in possibly a large production potential of both advanced biofuels.[7, 8] In addition, the implementation of GEM fuel enlarges the diversification of energy sources in the transportation sector and since there is currently no advanced alternative which has the potential to overtake all the fossil fuel energy demand in the Swedish passenger car fleet, for a cost-competitive price, all renewable alternatives need to be explored to their full potential.

As mentioned previously, multiple studies have successfully tested GEM fuel ternary blends as passenger car fuels in flex-fuel vehicles. However, no studies are performed on the potential of GEM fuel in terms of GHG mitigation, economic and biofuel production potential. At present, there are no studies performed on the production potential of GEM fuel constituting of methanol and ethanol from Swedish second-generation feedstocks. Moreover, no studies are conducted on the economic competitiveness and the environmental impact of GEM fuel in comparison to fossil fuels. In addition, no studies are performed of the implementation of GEM fuel in the existing Swedish fuel distribution network for gasoline and E85. Therefore, this thesis is important since it aims to contribute to a better understanding by policy makers, industrial actors and all other stakeholders of the conditions for implementation of domestically produced GEM fuel. This thesis develops an insight whether GEM fuel has the potential to become a successful alternative fuel for gasoline and E85. Furthermore, the thesis provides information on the potential of untapped domestic biomass feedstocks, the production potential of second-generation ethanol and methanol, the environmental impact of the implementation of GEM fuels, the economic competitiveness of GEM fuels, a GEM fuel blending infrastructure and a Swedish GEM fuel distribution network. Moreover, this study provides energy demand projections of GEM fuel blends, when passenger cars, running on GEM fuel obtain a share on the Swedish passenger car fleet.

1.3 Objective and Research Questions

The general objective of this research is to analyze and present the potential of domestically produced GEM fuel as an alternative passenger car fuel in Sweden. This thesis aims to identify the potential in terms of biofuel production, implementation, economic, and GHG savings potential. Moreover, this study attempts to project and analyze a shift from passenger cars running on neat gasoline to GEM fuel blends in the Swedish passenger car fleet, in a time span of 2017 to 2030. To obtain the main objective of this study, the following sub-objectives are:

I. To assess the biofuel production potential of the both methanol and ethanol from Swedish 2nd generation feedstocks and to select the most suitable production pathway for both fuels
II. To analyze a Swedish GEM fuel distribution and blending infrastructure
III. To estimate the pump prices of GEM fuel blends and to test the economic competitiveness in comparison to gasoline and E85 fuel.
IV. To assess the associated environmental impact of the shift from cars running on neat gasoline to GEM fuel

The main research question that will be addressed in this research: What is the potential of GEM fuel blends as alternative transportation fuel in the Swedish passenger car fleet? By answering the research question, it aimed to achieve the previously mentioned research objective. In order to answer the main research question, the following sub-questions are developed.

1. What is the production potential of the alcohol fuels from domestic second-generation feedstocks until 2030 and what is the most suitable production pathway?
2. How is the outlook of a Swedish GEM fuel distribution network and what blending system is the most suitable for blending the GEM fuel blends?
3. What are the pump prices of GEM fuel blends and are the pump prices economic competitive in comparison to gasoline and E85 fuel?
4. What are the GHG emission avoided by the shift from Swedish passenger cars running on neat gasoline to GEM fuel blends?

1.4 Scope of the thesis and limitations

This report primarily analyses the theoretical production potential of GEM fuel using secondary domestic biomass feedstocks, biofuel production pathways (i.e. conversion technologies), GEM fuel distribution network, economic competitiveness of the alternative fuel, and associated environmental impact of the shift from neat gasoline to GEM fuel are investigated in the thesis. In figure 1.2, the research system of this study is presented. This thesis focuses on the supply chain activities involved with the implementation of GEM fuel blends in Sweden, as depicted in figure 1.2. Moreover, this research aims to investigate the shift from gasoline to GEM fuel, as an alternative renewable fuel, and the system is limited to the identification of the environmental, biomass utilization and economic impacts. In this thesis, 'biomass utilization impact' is described as the amount of biomass feedstocks necessary in order to produce the energy demand of the GEM fuel blends.

In order to perform the analysis, two scenarios are developed for projecting the share of the GEM cars in the Swedish passenger car fleet, considering a time horizon from 2017 to 2030. In Scenario 1, a high share of passenger cars running on GEM fuel is obtained with 22 percent by 2030. In Scenario

1, GEM cars take over the entire share of gasoline cars by 2030. In Scenario 2, a low share of cars running on GEM fuel is obtained with 17 percent by 2030. In Scenario 2, GEM cars take over 75 percent of the gasoline cars by 2030. The scenarios serve to project the energy demand for GEM fuels and its components in a time span of 2017 and 2030. In this thesis, the projected energy demand of ethanol and methanol is tested with the outcome of the biofuel production potential assessment on ethanol and methanol.

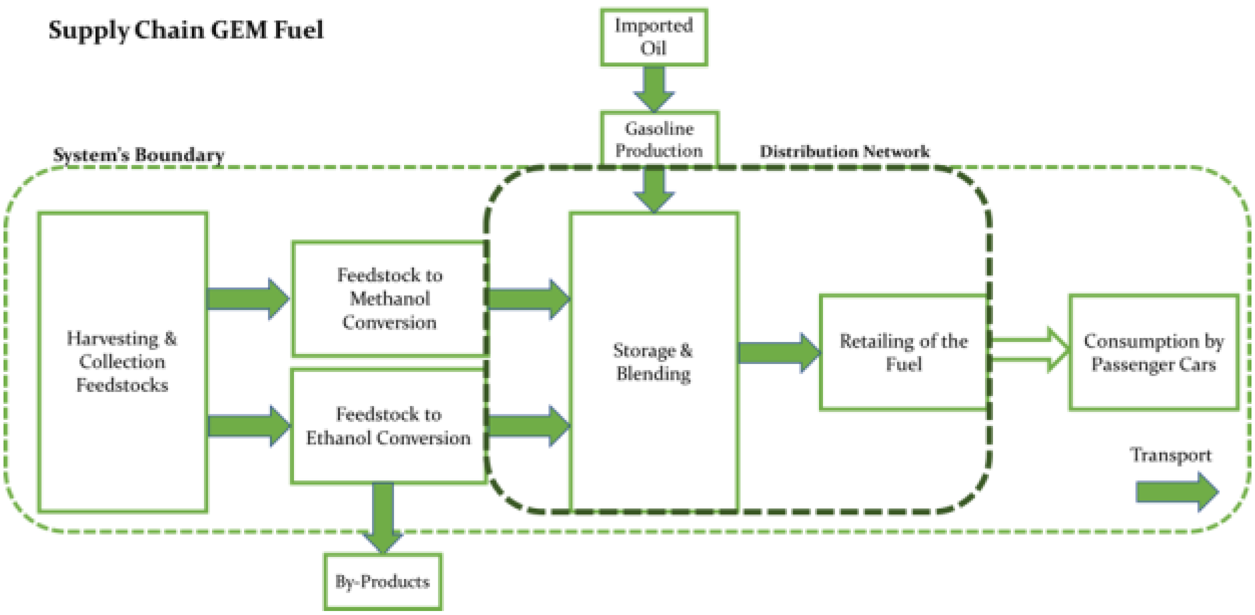


Figure 1-2: Research system and boundaries

Since a variety of GEM fuel blends can be implemented in flex-fuel vehicles, in this study, three different GEM fuel blends are selected and analysed in combination with the two scenarios. In Blend HM, a GEM fuel blend with a high methanol content is selected. In Blend ME, a medium ethanol and methanol containing GEM fuel is selected. In Blend HE, a high ethanol containing GEM fuel blend is selected. The selected GEM fuel blends, in combination with the Scenarios, serve to identify the economic, environmental and biomass utilization impacts of the implementation of a high methanol, a high ethanol and a medium methanol/ethanol GEM fuel blend. Since the varying contents of the alcohol fuels in GEM fuel blends, results in different environmental, economic and biomass utilization impacts. For policy makers, these impacts can be from varying importance. Therefore, the analysis on the GEM fuel blends, in combination with the Scenarios, provide insights on which of these GEM fuel blends is the most beneficial in terms of the individual impacts. Moreover, the GEM fuel blends are selected to derive which blend would be the most favorable GEM fuel blend and to verify whether one the biofuels is more favorable as part of the blend. Hence, based on the results of this study, policy makers can decide whether to direct policy support into the production of advanced ethanol and/or methanol.

Regarding the economic competitiveness analysis, the economic competitiveness of GEM fuel blends is tested based on the estimated pump prices of GEM fuel blends, which are subsequently tested in comparison to the pump prices of gasoline and E85. The pump prices of GEM fuel blends are estimated based on the costs of every individual activity in the supply chain of GEM fuels, the energy tax and the carbon dioxide tax on gasoline, and the VAT. Regarding the associated environmental impact of the shift from passenger cars running on neat gasoline to GEM fuel, the environmental impact is determined by assessing the GHG emissions avoided by the shift for the individual scenarios.

In this study, the implementation of GEM fuel is limited to the shift from passenger cars running on neat gasoline to GEM fuel blends in Sweden. This is due to the fact that GEM fuel has not been successfully tested in other vehicle types. Furthermore, as previously mentioned, the implementation of first-generation ethanol in the form of E85 fuel has failed in Sweden. Moreover, second-generation biofuels are strongly advocated by the European Union.[18] For these reasons, only second-generation biofuels are considered in this thesis. In addition, this study only considers secondary Swedish feedstocks, therefore disregarding national and international market for ethanol, methanol and resulting GEM fuel. Lastly, the production cost of 2nd generation ethanol is strongly dependent on revenue created by the sales of the by-products.[11] However, the evaluation whether there is a market for the by-products is too far out of the focus of this research and therefore not taken into account.

1.5 Outline of the Thesis

This report constitutes of twelve chapters in total. It starts with a brief introduction of the topic handled in this report, background information, the importance of the study, the scope, the research objectives and questions. The second chapter represents an overview of the current situation in Sweden regarding energy, transportation sector, GHG emissions, the Swedish fuel distribution network and State-of-the-Art of GEM fuels. The third chapter provides an evaluation of the production pathways of the biofuels, including the harvesting and collection of feedstocks and key production technologies. In the fourth chapter the analytical framework of this thesis is presented together with the implemented data, constituting of the methodology applied and the methods of data collection. In chapters 5 to 8, the results and findings of this study are presented. In the fifth chapter the production potential of both biofuels from Swedish feedstocks is assessed and the biofuel most suitable production pathway for both biofuels is selected. In the sixth chapter, the implemented scenarios are developed and the corresponding energy demand for GEM fuels blends is projected. In chapter 7, a Swedish GEM fuel distribution network is investigated and the GEM fuel blending technology is selected. In chapter eight, the economic competitiveness of GEM fuel blends is investigated together with the associated environmental impact of the shift from passenger cars running on neat gasoline fuel to GEM fuel. The discussion, conclusion, recommendation and future work are discussed in the 9th and 10th chapter. The 11th and 12th chapter of this report constitutes of the bibliography and the appendix, respectively.

1.6 Methodology Applied in the Thesis

In this study, analyses are performed on: the biofuel production potential of ethanol and methanol from Swedish second-generation feedstocks, the most suitable ethanol and methanol production pathway, a Swedish GEM fuel distribution network, the economic competitiveness of GEM fuel blends and the environmental impact of a shift from cars running on neat gasoline to GEM fuel blends. The potential of ethanol and methanol is based on the total untapped potential of second-generation feedstocks that can be used for the production of the biofuels and the energy yield ratios from feedstock to biofuel from key conversion technologies. The data on the potential of the feedstocks and the energy yield ratios is collected by comprehensive literature studies. Once the biofuel production potentials are estimated, the most suitable biofuel production pathway, constituting of the implemented feedstock and conversion technology, is selected. The biofuel production pathway is selected for both alcohol fuels in order to perform the economic competitiveness and environmental impact analysis. The selection of the biofuel production pathway is based on the (1) energy yield ratio of biomass to biofuel (2) the production costs of the biofuel and (3) the biomass feedstock costs.

Two scenarios are developed to project the share of cars running on GEM fuel blends (GEM cars) in the Swedish passenger car fleet, in a timespan of 2017 to 2030. The scenarios are based on a business as usual projection of the share of different car types in the Swedish passenger car fleet, developed by the Swedish Transportation Agency. In both the scenarios, GEM cars replace the share of gasoline and E85 cars in the business as usual projection. In Scenario 1, cars running on GEM fuel blends obtain a high share in the Swedish passenger car fleet and in Scenario 2 cars running on GEM fuel blends obtain a low share. Subsequently, for the two Scenarios the energy demand for GEM fuel is verified based on the share of GEM cars in the Swedish passenger car fleet, a projection of the energy consumption of ICE cars in the Swedish passenger car fleet and the forecasted total distance travelled by the entire Swedish passenger car fleet. In the Scenarios three GEM fuel blends are selected in order to project the energy demand for both ethanol and methanol. A GEM fuel blend with a high methanol, a medium ethanol and methanol, and a high ethanol content are selected. For the Scenarios in combination with the GEM fuel blends, the energy demand for ethanol and methanol is tested in comparison with the outcome of the biofuel production analysis in order to verify if the energy demands can be met from Sweden second-generation feedstocks. The scenarios and the three GEM fuel blends are developed in order to perform the economic competitiveness analysis, the Swedish GEM fuel distribution network analysis and the environmental impact analysis.

In the Swedish GEM fuel distribution network analysis, it is analysed if the GEM fuel blends can be distributed in the existing fuel distribution network of E85 and gasoline. Moreover, it is investigated if the existing distribution activities cannot be implemented for distributing GEM fuel blends, how the equipment can be converted to equipment capable of distributing GEM fuel blends. Furthermore, it is investigated if the capacity of the existing distribution network of gasoline and E85 is sufficient to supply the projected energy demand for GEM fuel blends in the Scenarios. The data that was necessary to perform the analysis is gathered through carefully selected interviews with professionals from the industry. In the economic competitiveness analysis, the pump prices of the three selected GEM fuel blends are estimated by analysing the economic parameters of the pump prices of gasoline, second-generation ethanol and methanol. Subsequently, the pump prices of the GEM fuel blends are verified based on the fuel compositions of the GEM fuel blends and the estimated pump prices of the individual components. In the last part of the economic competitiveness analysis a limit price curve for the GEM fuel blends is developed to test if the pump prices of the GEM fuel blends are economic competitive. The limit GEM fuel pump price curve is based on the historic price development of gasoline for the last decade in Sweden and the ratio between the fuel economy of GEM fuel blends and gasoline in E85 flex-fuel vehicles.

In the environmental impact analysis, the GHG emissions that are avoided with the implementation of cars running on GEM fuel blends instead of neat gasoline are analysed. In order to do so, first, the GHG savings factors of the individual GEM fuel blends are assessed. The values are based on the well-to-wheel saving factors of the second-generation ethanol and methanol produced through the selected biofuel pathways and the energy fractions of ethanol and methanol. Subsequently, the total GHG savings in the scenarios in combination with the GEM fuel blends are estimated based on the total energy replaced by GEM fuel blends and the GHG savings per GEM fuel blend.

2 Energy, Transport, Distribution Network, GEM fuel: A Review

This chapter consists of three paragraphs. The first two paragraphs of this chapter represent a brief review of the Swedish energy situation, the transportation sector and the transportation fuels. The information is mainly gathered through the literature review of secondary resources. The third paragraph of the chapter represents an analysis on the current fuel distribution network. In order to get an overview of the existing distribution network for fuels in Sweden, primary data was gathered from professionals in the transportation fuel field. In addition, several secondary data were collected. The last part of this chapter consists of a brief review on the State-of-the-Art of GEM fuel and its components, mainly collected from secondary data.

2.1 Energy Situation in Sweden

Sweden is one of the front-running countries when it comes to sustainable energy. The country has the lowest share of fossil fuels among all IEA member countries. [2] In 2015, more than half of the energy consumed was originated from a renewable energy source.[4] Figure 2-1 represents the total energy consumption in Sweden, depicted by the original energy carrier. The total domestic energy consumed in 2015 amounted to 370.5 TWh. The largest source of energy consumed in the country is bioenergy. In 2015, 130.4 TWh of the final energy consumption had biomass as its original energy source, contributing to 35.2 percent of the total energy consumption. The second largest renewable energy source was hydropower with 57.6 TWh. The third largest renewable energy source was wind energy with 13 TWh. Moreover, petroleum products were the second largest energy source in the Swedish energy system and were mainly implemented in the transportation sector. The country does not have domestic oil reservoirs and is an importer of crude oil. In 2015, more than 22.5 million cubic meters of crude oil was imported by Sweden.

Figure 2-2 illustrates the final domestic energy consumption by sector. The industrial and residential sectors are the largest consumers of energy with respectively 39 and 38 per cent of the total energy consumed. The pulp and paper industry is an energy intensive industry and accounts for 51 per cent of the total energy consumption in the industry sector. [4] The transportation sector consumed 23 per cent of the total energy consumed in Sweden in 2015.

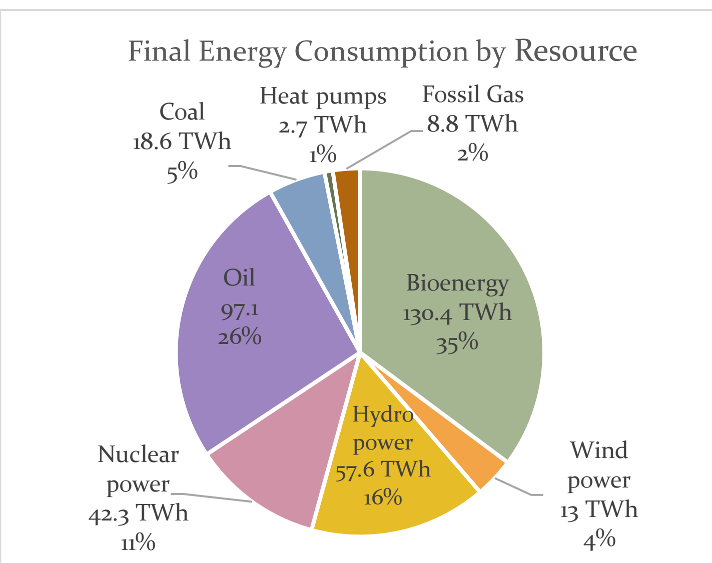


Figure 2-1: Final Energy Consumption by Commodity in 2015 [1]

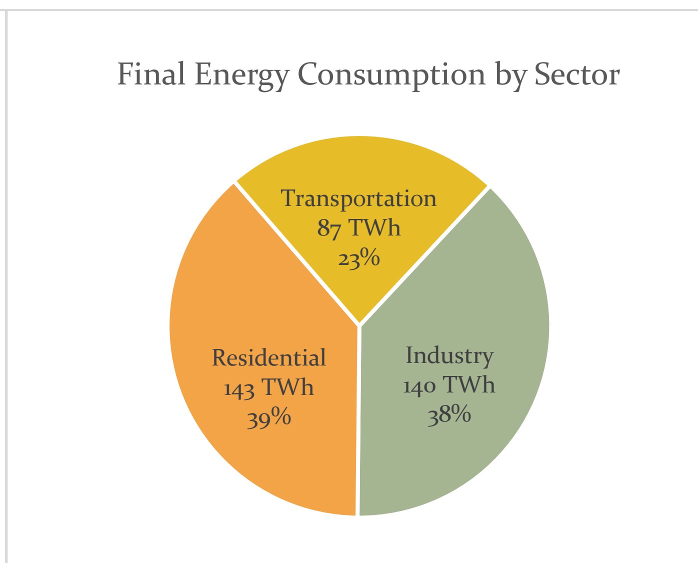


Figure 2-2: Final Energy Consumption by Sector in 2015 [4]

Sweden is a country which is rich in natural resources. the majority of the country is covered by forest area, accounting for 63 percent of the countries' surface. [9] The forest is vitally important for the countries' economy. It is the supplier of large amounts of valuable commodities, used in the domestic timber and pulp & paper industry. Furthermore, is the forest an important provider of biomass feedstocks, used to generate bioenergy.

2.2 Transportation Sector & Fuels in Sweden

As mentioned previously, petroleum products are mainly consumed in the transportation sector. In 2016, 81 percent of the total energy derived from petroleum products was consumed in the transportation sector. Table 2.1 shows an overview of the types of energy consumed in the different sectors of the transportation sector. From table 2-1, it can be denoted that most of the energy was consumed in road transportation, accounting for 95 percent of the total energy consumed in the transportation sector.

Table 2-1: Final Energy Consumption in domestic transportation in Sweden in 2016(TWh) [22]

Transportation sector	**Biofuels**	**Gasoline**	**Diesel**	**Other Oil fuels**	**Electricity**	**Total**
Rail	0	0	0	0	3	**3**
Road	17	29	37	0	0	**83**
In-land Maritime & Aviation	0	0	0	2	0	**2**
Total	17	29	37	2	3	**87**

2.2.1 Road Transportation

Biofuels experienced a significant growth the last years in Sweden. In 2016, the share of biofuels in the Swedish road transportation sector increased to 18.6 percent and grew with 5.1 percent with reference to the year 2015.[23] Biodiesel accounts of the largest share of biofuels with 85 percent, followed by biogas and bioethanol both with 7.5 percent. Of the bioethanol 27 percent was used as a component in E85/ED95 and the other part was blended as a low blend in gasoline.[23] Figure 2-6 represents amount of energy consumed by fuel implemented in the road transportation sector. Half of the energy consumed was generated from diesel fuel, resulting to the largest energy carrier in the road transportation sector. Followed by gasoline as the second largest energy carrier with 32 percent. The amount of electricity consumed by electric vehicles accounted for less than 1 percent of the total energy consumed and is therefore not depicted in the graph.

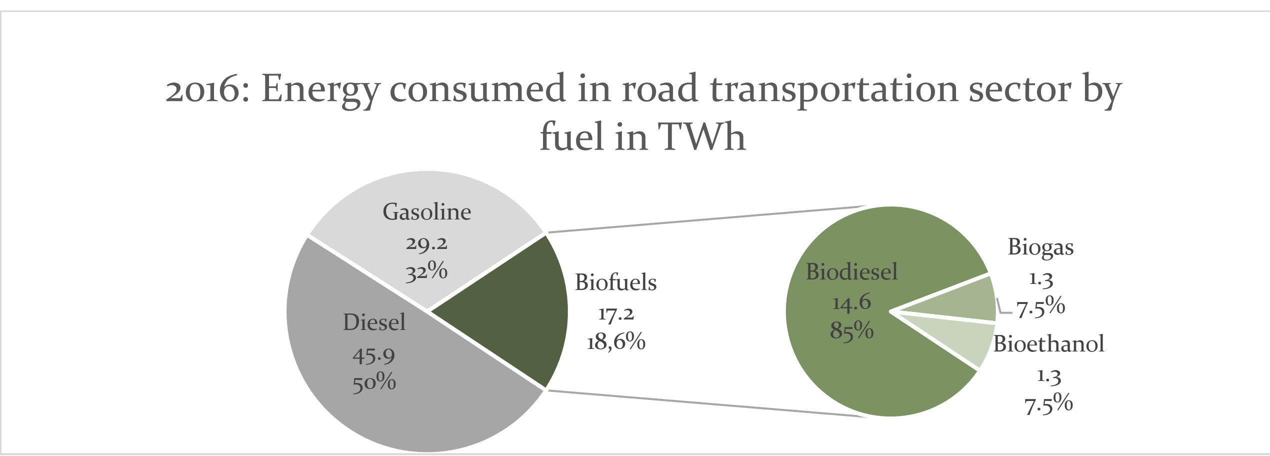


Figure 2-3: Energy consumed in the transportation sector divided by type of fuel[22]

❖ **Swedish vehicle fleet**

In 2016, the Swedish fleet consisted of 4.8 million light duty vehicles, 534 748 light-duty trucks, 81 430 heavy-duty trucks, 13 390 busses. Figure 2-4 represents the Swedish vehicle fleet in the year 2016. Personal cars account for the largest share of the Swedish Vehicle Fleet with 74.9 percent, following are lightweight trucks with a share of 8.4 percent. The number of personal cars increased with 2.1 percent in comparison with the amount of passenger cars in 2015.

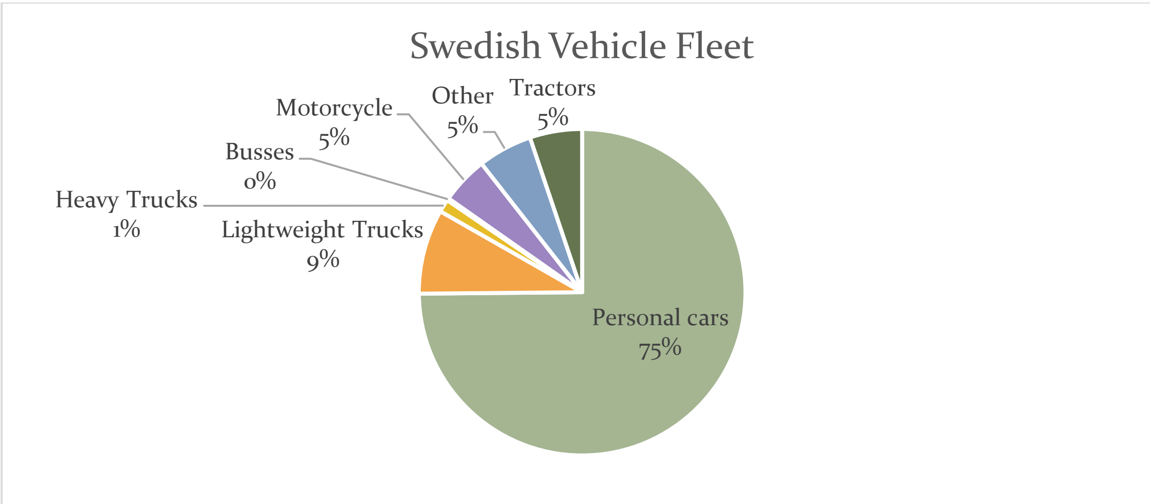


Figure 2-4: Swedish Vehicle Flee 2016, adapted from Swedish Transport Agency[41]

Figure 2.5 depicts the share of cars divided by fuel in the Swedish vehicle fleet. As mentioned in the first chapter, the majority of the Swedish passenger cars are powered by a spark ignition engine, constituting of 60 percent gasoline cars and 5 percent E85 FFV's. Gasoline cars have the largest share of the passenger car fleet with around 2.8 million cars. The second largest share have diesel cars with around 1.5 million cars, followed by around 220 thousand E85 flexible fuel vehicles.

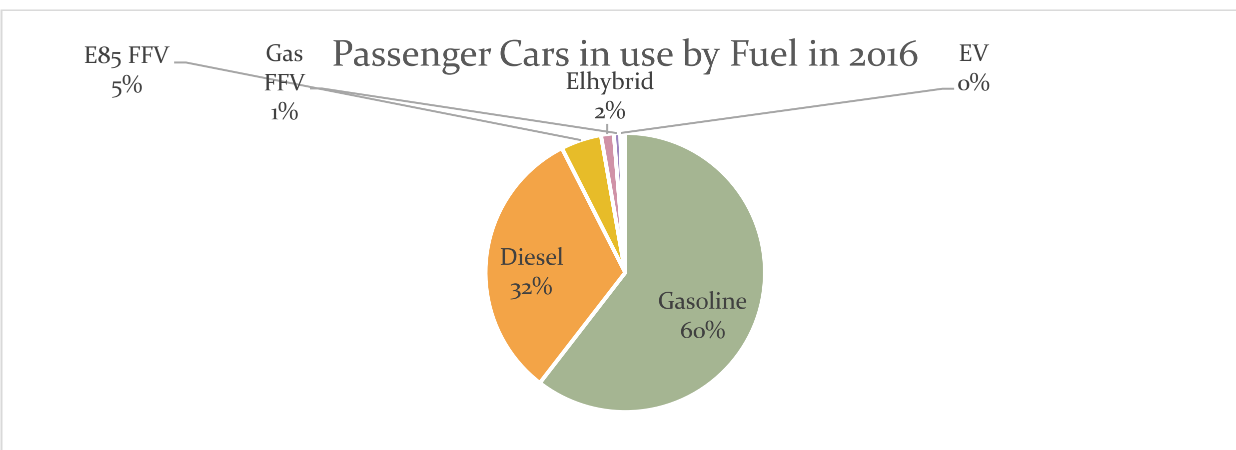


Figure 2-5: Sweden, Passenger Cars in Use by Fuel in 2016[41]

❖ **Domestic fuel consumption**

Figure 2-6 illustrates the domestic fuel consumption of gasoline, diesel and E85 between 2005 and 2016. The consumption of gasoline has decreased with 39.3 percent between 2005 and 2016. The consumption of diesel has increased rapidly between 2005 and 2016, the annual amount consumed of the fuel increased with 37.2 percent. The demand for ethanol peaked in the year 2011, when it surpassed the 220 thousand cubic meters. However, the following years the ethanol demand decreased with 79.54 percent from 2011 to 2016.

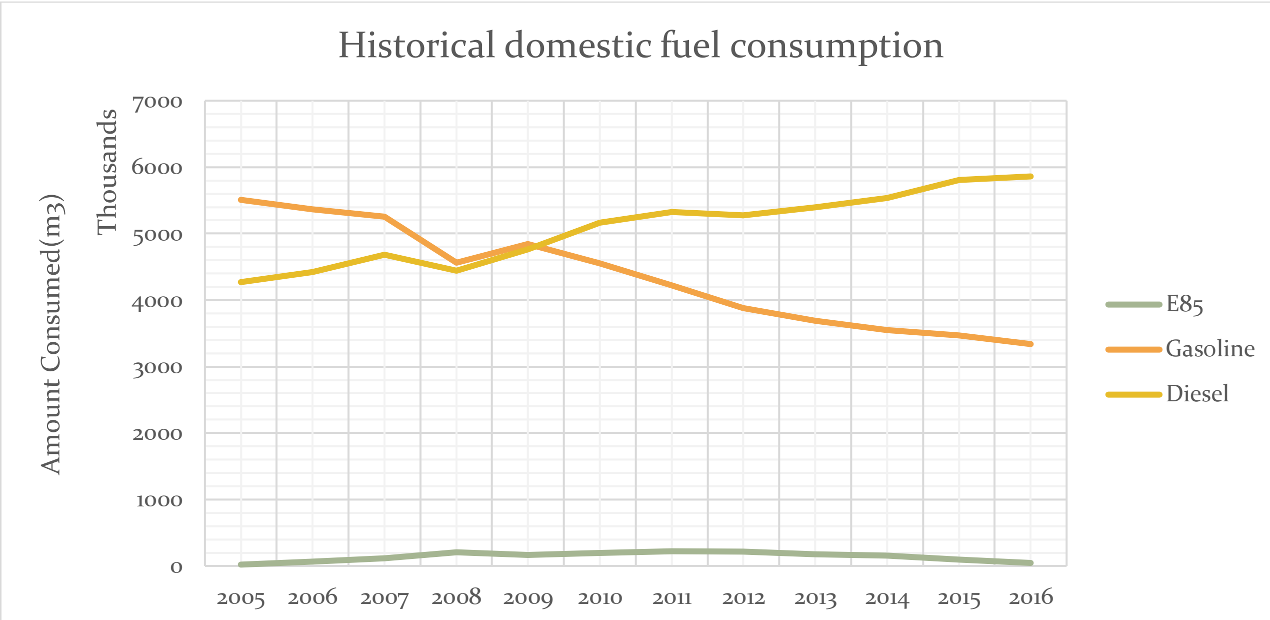


Figure 2-6: Fuel consumption Sweden, adapted from SPBI[25]

❖ **Pump price development**

Figure 2-7 shows the pump price development of gasoline, diesel and E85 for the last decade. In the graph, the prices are depicted in Swedish krona per liter. The price of all fuels increased during the period of time. The price of E85, diesel and gasoline has increased with approximately 32, 24 and 22 percent. The prices include the energy, carbon dioxide and the VAT tax.

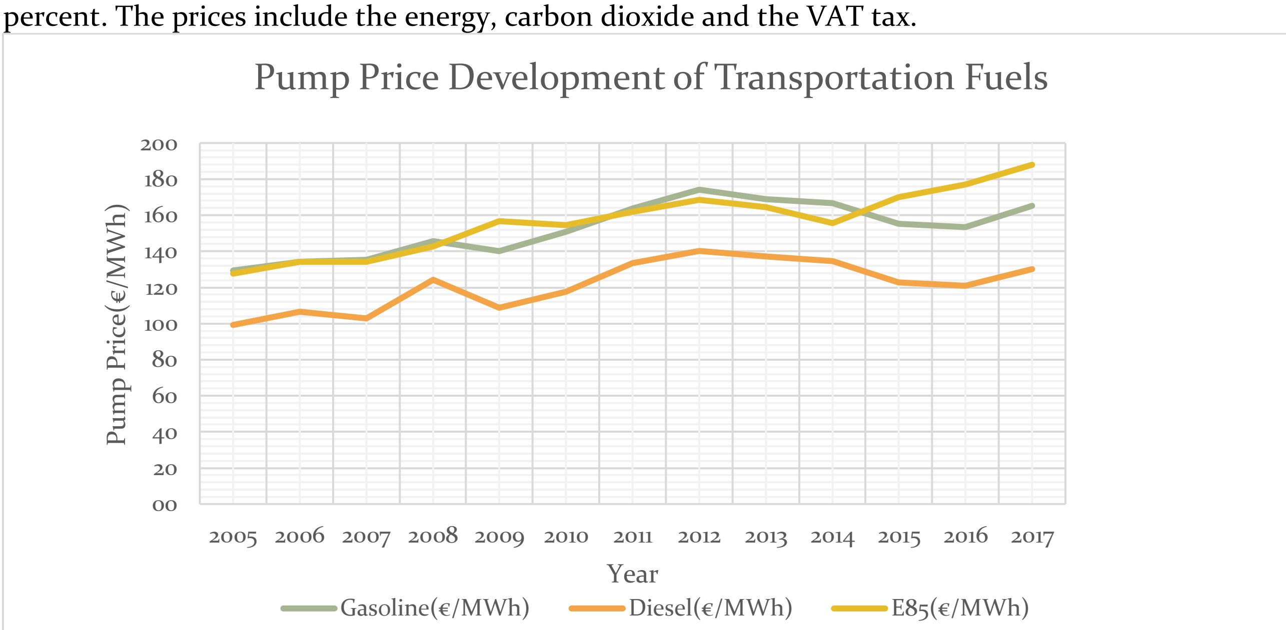


Figure 2-7: Price development fuels in Sweden[25]

Table 2-2 represents a breakdown of fuel price of gasoline in Sweden at the first of January 2017. [23] The information is derived from SPBI, the Swedish Petroleum and Biofuel Institute. The price paid at the retail stations was 169.9 euro per liter. The largest part of the price constitutes of taxes, namely 63 percent.

Table 2-2: Pump Pricing Gasoline in Sweden, 2017[23]

Component	**Cost(€/MWh)**	**(%)**
Production Cost	63,0	37
Energy Tax	43,9	26
CO_2 Tax	29,3	17
VAT(25%)	33,8	20
Total Pump Price	**169,9**	**100**

2.2.2 Policies & Regulations Regarding Transportation Fuels

As mentioned previously, Sweden has an energy tax and a carbon dioxide paid on transportation fossil fuels. Currently, biofuels are exempted from the both taxes. E85 is a combination of a fossil fuel and biofuel and only on the fossil fuel part of the fuel the energy and the carbon dioxide tax are paid. Other policy instruments that have been commonly applied in Sweden to promote biofuels are the Pump law and exemptions from the congestion tax in Stockholm.[26] Moreover, extra policy instruments have been implemented to create and ensure demand for biofuels are mandate systems, investment support, vehicle incentives, emission standards, tax exemptions and subsidies.[38]

Regulations and standards regarding gasoline fuel are stated in the European Standard EN 228.[42] The standards which are involved with the implementation of GEM fuel are the following:

- Fuels which have a low water tolerance an anti-corrosion additive shall be incorporated
- The maximum allowed Reid Vapour Pressure during summer months is 70 kPa

2.3 Existing distribution network for Transportation Fuels

In this paragraph, the current Swedish distribution network for fuels is discussed.

Sweden does not have oil reservoirs, therefore all the petroleum products used in the country are either imported as crude oil and domestically refined or imported as refined fraction. In 2015, more than 22.5 million cubic meters of crude oil was imported by Sweden.[4] The refined petroleum products are either used domestically or exported. Sweden also imports smaller quantities of refined products from neighboring countries. As mentioned previously, the transport sector is dependent on imported petroleum products and therefore the country stores on average 90 days of daily import of crude oil or equivalent, which is a result of the International Energy Program(IEP). [25] The IEP is an agreement between 26 members in order to ensure security of supply.

Figure 2-8: Sweden's fuel distribution network[2]

In Sweden, there are 5 oil refineries which are owned by three different companies and located at three different ports. The total refining capacity of the refineries combined is 435 thousand barrels per day. Preem is the largest oil refiner company in Sweden. It owns two large refineries in the cities Gothenburg and Lysekil, accounting for respectively 48 and 29 percent of the Swedish refinery capacity. [43] Furthermore, there is another oil refinery in Göteburg, owned by St1 and accounting for 18 percent. The other Swedish refinery is only producing non-fuels petroleum products and is located in Nynäshamn and owned by Nynas. [44] The domestic oil infrastructure of Sweden is depicted in figure 2-8, beside the locations of the refineries, the oil products storage terminals and tanker terminals can be seen.

In 2015, 61 TWh of gasoline was produced by the four refineries in Sweden. Furthermore, there was 47 TWh of gasoline exported and 21 TWh imported and the net export of gasoline is 26 TWh. [4] This implies that a significant part of the upstream activities of the supply chain of petroleum fuels, is used for the non-domestic usage of oil, activities such as storing, transporting and refining.

2.3.1 Swedish Supply Chain Petroleum fuels

The Swedish fossil fuel distribution infrastructure is well established. Crude oil is delivered to the refineries by large marine vessels to the ports of the locations where the refineries are located and stored in oil terminals. Subsequently, the crude oil is distillated further treated in order to convert the crude oil into the different fossil fuels. After the refining process, the different fossil fuels are stored in separated terminals located close to the refinery. From the storage terminals close to the refineries, the refined products are distributed over the whole country of Sweden. The supply chain of petroleum products is shown in figure 2-9.

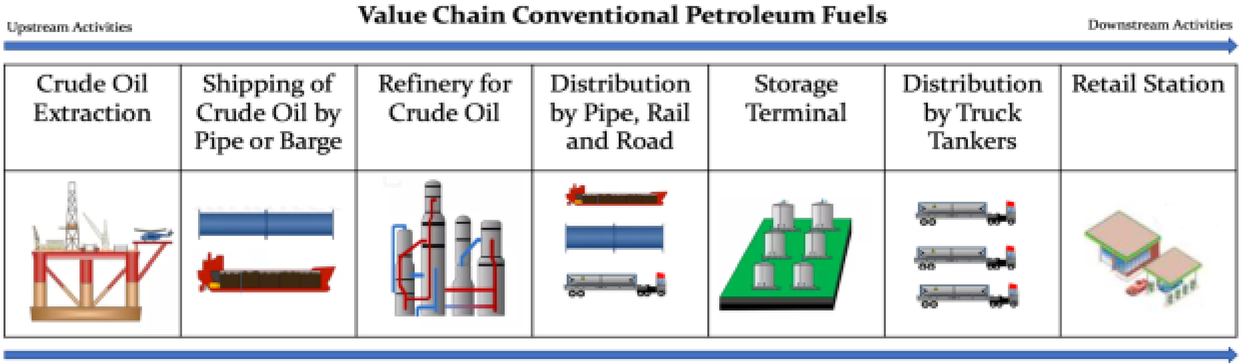


Figure 2-9: Supply chain of fossil fuels in Sweden

The first upstream activity in the supply chain of petroleum products is the extraction of the crude oil, which performed outside the borders of Sweden. Afterwards the oil is transported to the Swedish refineries, located at Swedish ports by barges. Subsequently, the refined petroleum products are distributed throughout the country by pipeline or truck and delivered to storage terminals. At the storage terminal, other activities are applied to the petroleum fuels such as adding additives or blending with biofuels. The finalized fuels are then transported by tanker trucks to the retail fueling station, at which the fuels are delivered to the final costumer.

- **Crude Oil Extraction**

The first step in the supply chain is the crude oil extraction, which occurs in countries where there are oil reservoirs located. The crude oil is typically extracted by drilling in the reserves either located on land or offshore. In 2016, the largest amount of oil purchased was imported from Russia with 42 percent, followed by Norway with 23 percent. [25]

- **Transport**

Transportation of refined products is done by tanker truck, barge and pipe transport. The type of transportation used is dependent on the position in the supply chain. When large volumes of fossil fuels are distributed domestically over large distances, it is preferably done by barge. This is due to the fact that it's the most economical and environmental friendly way of transport. After the refinery, the petroleum products are mainly transported by barge and pipeline to storage terminals. The down-stream transport from the terminals to the retail stations is mainly performed by tanker trucks. This is due to Sweden's relatively small population density and oil market. The country has currently around 800 road tankers which are transporting the refined products from the terminals to the retail stations. [23]

- **Storage Terminals**

The capacity of for crude oil and products in Sweden is determined by the 90 days IEP agreement. The total capacity of oil storage facilities in Sweden is 95.7 million barrels or 15.2 million cubic meters. Throughout Sweden, there are more than 40 storage terminals. [44] The major crude oil storage cities are Göteborg and Lysekil. For gasoline, the most fuel is stored in Gothenburg, followed by Lysekil, Stockholm and Norrköping. The large storage facilities are mostly located at harbor sites, so that large quantities of refined fuels can be supplied by barge. Sweden has thirty different oil terminals with a direct connection to a port.

- **Retail fueling stations**

At present, 2670 retail fuel stations in Sweden supply transportation fuels to the end-consumers throughout the entire country.[13] The well-established distribution network is capable of meeting the current Swedish demand for the fuels. In Sweden, there are four main fuel retailers, namely Cirkle K, Preem, ST1 and OKQ8. [23] Preem and ST1 are companies that also own refineries and are therefore more vertically integrated in the supply chain activities than Circle K and OKQ8. All companies own parts of storage terminals.

2.3.2 E85 Distribution

The ethanol fuel used in Sweden is either domestically produced or imported from other countries. In 2015, around 84 percent of the Sweden's ethanol consumption was imported. [22] Like petroleum products, the ethanol is delivered to Swedish ports by barge transport. Subsequently, the ethanol is blended and distributed to lower parts of the supply chain. The Swedish E85 distribution network is well established and profoundly similar to the gasoline distribution network. When the ethanol is domestically produced, the ethanol is transported straight from the biorefinery to the distribution terminal. Simultaneously, refined gasoline is transported by pipe or barge to the same distribution terminal. In Sweden, ethanol is stored in various terminals. On location, the gasoline, ethanol and additives are blended and distributed to retail stations located through the whole country.

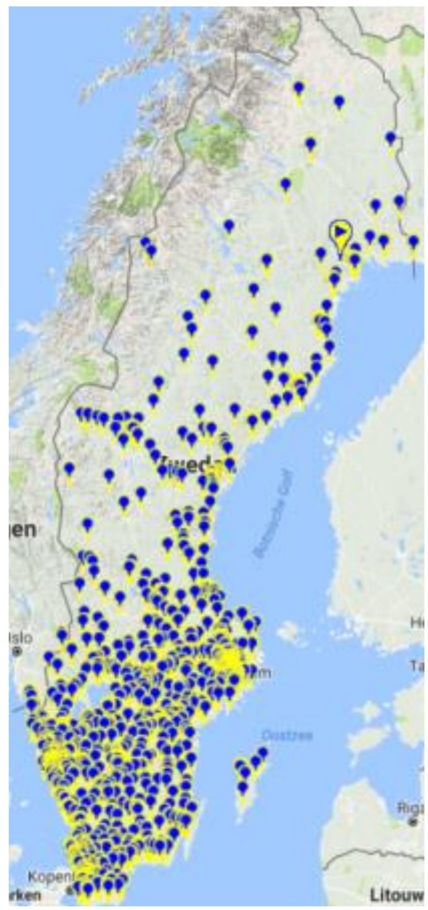


Figure 2-10: E85 Pumps in Sweden, Source: Google maps

At present, Sweden has 1749 E85 pumps. [25] Hence, at around 66 percent of the retail stations in Sweden supplies E85 to customers. [25] The majority of the pumps are specially build for the E85 fuel and is constructed from alcohol resistant materials. An important difference between the E85 pump and the regular gasoline pump is that the nozzle does not contain a latch. Implying that the consumer must hold the nozzle while filling the tank of the vehicle. This is due to regulation by the Swedish Civil Contingencies Agency. As mentioned previously, The E85 pumps are accommodated with vapor recovery systems due to the evaporative emissions of the fuel. This is important, since evaporate emissions could be ignited while filling the car with fuel. The dispensing pump supplies E85 by pumping the fuel out of an underground storage which has an average volume of 10 cubic meters. The pumps are capable of supplying the fuel with a flow of 40 liters per minute. The E85 pumps are specially UL-certified E85 pumps.

The E85 pumps are located throughout the entire country. Figure 2-10 represents an overview of the pumps in Sweden. What can be seen that the majority of the pumps are located in the south of the country. As mentioned in the previously, the demand for E85 has declined significantly since 2011. As a consequence, according SEKAB, the retail stations are not filled up so frequently, only 1 to 3 times a year. Thus, the capacity of the current E85 is tremendously higher than for what it is used for nowadays, simply by filling up more often the storage tanks at the retail stations. The capacity is comparable to the Swedish capacity for diesel and gasoline. In Sweden, the components of E85 are blended before the fuel arrives at the retail station.

There are multiple technologies available on the market to blend alcohols with gasoline. However, in-line truck blending is globally the most commonly used method of blending ethanol/additives with gasoline. [25] The ethanol, gasoline and additives are simultaneously in-line added to the truck. Truck blending is in Sweden the most implemented technology for blending of the E85 fuel. Denaturing additives and corrosion inhibiters are added and blended together with the gasoline and ethanol. A flow control technology is used to ensure the right composition of the fuel. A technology that was used in Sweden to blend ethanol and gasoline was at the retail fueling station site. In the technology, there are two separate storage tanks situated and blended by the fuel dispenser. Sweden has dispensing pumps that are capable of blending gasoline and ethanol. Nevertheless, due to the low demand for E85 the pumps are currently only used for dispensing gasoline.

Though the distribution of ethanol and gasoline is truly similar. Ethanol is an ATEX(atmosphères explosibles) chemical and requires therefore a slightly special and different handling compared to gasoline. Resulting in a distribution costs which is 50 percent higher than gasoline According to SPT, the distribution costs of ethanol are 15 euro per MWh and for gasoline 10 euro per MWh. The distribution costs constitute of storing, blending and transportation costs.

2.4 GEM fuel

This paragraph represents a brief analysis on GEM fuel and its components. The first part of this paragraph, represents a review on the current state-of-the-art of GEM fuel. The studies performed on the fuels are evaluated and the practical implementation of the fuel is described. The second part of this paragraph is an analysis on the properties of the separate components. The third part of this paragraph evaluates the engine performances when GEM fuel is implemented. Lastly, the GHG emissions of the combustion of the advanced bioalcohols are evaluated.

2.4.1 State-of-the-Art GEM fuel

During the last seven years, a growing interest has been developed for the gasoline-ethanol-methanol ternary fuel blend as a transportation fuel. Turner et al. were the first to start studying the implementation of GEM fuels as a fuel for the spark ignition engine vehicles. In the first paper published by Turner et al., four high alcohol content GEM fuels were tested on their emissions and vehicle performance and compared with gasoline fuel.[30] The vehicle used was the Saab 9-3 BioPower from Saab. The study demonstrated that the four different GEM fuels had excellent vehicle performances and could therefore be implemented as flexible vehicle fuel. The following GEM blends were tested in the report: G44 E0 M56, G40 E10 M50, C37 E21 M42 and C15 E85 M0. After the first report, Turner at al. published two more papers with more research performed on the GEM blends and confirmed the suitability as drop-in fuel for E85. [3] [31] In 2015, Pearson et al. published a paper on the stability of four GEM fuels blends in various circumstances. [5] In 2014, Silighem et al. published a study in which four GEM fuel blends were tested on emissions, knock behavior and performance in a single cylinder engine with high compression. [45] The G40 E10 M50 blend, studied in the papers of Turner et al. is replaced by the G29.5 E42.5 M28 blend. Once more, it demonstrated that different compositions of the iso-stoichiometric GEM fuels with AFR of 9.7:1, are excellent substitutes of E85 fuel.

After the first published research findings, motor sports company GUTTS, decided to utilize the fuel as a new racing fuel, mainly due to the high-power output and engine efficiency. The GEM fuel supplied by GUTTS is G37 E21 M42. [13] GEM fuel can be utilized in vehicles with varying fuel compositions and air to fuel ratios. The fuel has been successfully utilized in low and in high alcohol contents. Nevertheless, in this report the iso-stoichiometric GEM fuels that are implementable in flexible fuel vehicles are investigated, implicating that the air to fuel ratio is 9.7:1. [3] The iso-stoichiometric GEM fuels are applicable in the same engine, since the fuels entail the same fuel injection rate. Thus, equal amounts of air and fuel are demanded in the combustion processes.

Globally, the components ethanol and methanol are separately used in blends together with gasoline as commercial fuels. Methanol and ethanol have profoundly similar properties and together with gasoline, are all miscible with each other. Furthermore, the individual components have also been successfully commercially practiced as individual transportation fuels. The concept of methanol as a transportation fuel is not new. The fuel has been successfully utilized in multiple locations/markets in the world, however with fossil energy resource, with coal and natural gas as its main feedstocks. Methanol blends are successfully tested in light-duty vehicles with a varying content from 0 up to 100 percent. High methanol blends can be used in special dedicated methanol vehicles or flexible fuel vehicles. [36]

2.4.2 Properties of the Components

Table 3-1 represents an overview of the different properties of components of the GEM fuel. Ethanol and methanol, as oxygenated molecules, have significant different properties compared to gasoline. When combusted the alcohols have significant lower heating values. Furthermore, the alcohols have lower energy densities. The different energy densities of the components will play a significant part in the development of the distribution network of the GEM fuel. The densities of the different components are relatively similar, the alcohols have slightly higher densities.

Table 2-3: Fuel properties of methanol, ethanol and gasoline [8, 29]

Property	Unit	Methanol	Ethanol	Gasoline
Density	kg/L	0.796	0.794	0.750
Stoichiometric Air/Fuel Ratio	No unit	6.4	9	14.6
Lower Heating Value(LHV)	MJ/L	16	21	32
	MJ/kg	20	27	43
Oxygen content	wt%	49.9	34.7	0
Molecular Weight	g/Mol	32.24	46.07	114.23
Boiling Point	° C	64.6	78.3	125.5
RVP at 38 ° C	kPa	32	15.9	3.54
Solubility in Water		miscible	miscible	hydrophobic
Auto ignition temperature	° C	465	365	246

As can be seen in table 2-3 methanol and ethanol have a relatively low energy content, compared to gasoline. Gasohol blends will therefore contain less energy than gasoline and resulting in higher distribution and storage costs. Hence, as a comparison applying methanol and gasoline as transportation fuels, gasoline has the double amount of energy containing in the same volume than methanol, resulting in storing and distributing the double amount of methanol compared to gasoline. Another property in which alcohols differ from gasoline is that alcohols in hydroscopic, which means that alcohols have the high tendency to absorb water.

Methanol
Methanol is the smallest molecule from the alcohol molecules. It consists of one methyl group connected to an alcohol group. The chemical structure of methanol is depicted below. Due to its small size its more readily to evaporate than for higher alcohols. Methanol is highly toxic and cannot be consumed, therefore its often just as a denaturant for ethanol fuel. At atmospheric circumstances, it is a transparent liquid chemical which easily biodegradable. The combustion reaction of methanol is illustrated below.

$$\mathrm{CH_3OH} + \frac{3}{2}\mathrm{O_2} \rightarrow \mathrm{CO_2} + 2\mathrm{H_2O}$$

Methanol is an input material for numerous industrial production processes. At present, the global demand for methanol is tremendous with an amount of approximately 70 million tons per year. [25] As consequence result, there is a general well-developed understanding of how to handle, process and transport the chemical. Large amounts of methanol are globally transported by water, road, rail and pipe transported.

Ethanol
Ethanol is after methanol the smallest alcohol in the group of alcohol molecules. The molecule consists of an ethyl group bonded to an alcohol group. Ethanol is just like methanol a clear, transparent and volatile material. Additionally, ethanol is also liquid under atmospheric circumstances. Ethanol is produced by fermentation of carbohydrates. Ethanol is in small amounts not toxic and can be consumed by humans, it is the alcohol found in beverages. Ethanol is beside fuel and beverage also utilized as a solvent and feedstock in many industrial processes. Ethanol is a flammable substance of which the combustion reaction is shown below.

$$\mathrm{C_2H_5OH} + 3\mathrm{O_2} \rightarrow 2\mathrm{CO_2} + 3\mathrm{H_2O}$$

Gasoline
Gasoline is a product that is produced from crude oil. Crude oil is a substance constituting of all different hydrocarbon chains. Gasoline is produced from crude oil by distillation of the substance. In distillation molecules with different boiling temperatures are separated. In the case of crude oil and its hydrocarbon chains, the longer chains have higher boiling points. Gasoline consists only of carbon and hydrogen atoms with mainly hydrocarbon molecules containing 7 to 11 carbon atoms. The petroleum-derived fluid functions mostly as a transportation fuel.

$$2\mathrm{C_8H_{18}} + 25\mathrm{O_2} \rightarrow 16\mathrm{CO_2} + 18\mathrm{H_2O}$$

2.4.3 GEM fuels and Engine Performance
Figure 1-1 presents the different GEM fuels that can be operated in the E85 flexible fuel vehicle. The compositions are determined by drawing a vertical line, the ethanol content is pointed on the x-axis and the methanol and gasoline content is read from the y-axis. The vertical line can be drawn

all along the x-axis and the limit cases are the binary fuels M56 and E85. As a result, many different fuel compositions of the fuel can be implemented.

The various studies conducted on GEM fuel, showed that fuel has an improved energy vehicle energy utilization in comparison to gasoline. The average LHV of GEM fuel, that can be implemented in E85 vehicles, is 22.65 MJ per liter.[3] Thus, the energy density is around 38 percent lower than gasoline. When running, the energy consumption of the engine when implementing GEM fuel is approximately 5 percent lower in comparison to gasoline. [31] The improved energy utilization compensates partly the lower energy density of GEM fuel compared to gasoline. Thus, when implementing GEM fuel instead of gasoline in a passenger car, 33 percent more volume of fuel needs to be supplied to the passenger car owners in order to deliver the achieve the same performances.

When methanol is blended with gasoline, the vapor pressure increases significantly. This is due to the fact that methanol and gasoline have different properties regarding polarity. Methanol is extremely polar, since a significant part of the molecule consists of an alcohol group. Gasoline is on the other hand hydrophobic. As a result, methanol evaporates more readily when blended with gasoline. The interactions between alcohol-alcohol differ therefore from the interactions between gasoline and an alcohol. Between alcohols hydrogen bonds will be formed, resulting in relatively high boiling points for methanol and ethanol, especially for the corresponding molecular weights. When blended with gasoline the alcohols tend to act more like low-molecular-mass components, thus increasing the vapor pressure of the alcohols. The result is increased evaporative emissions of the gasohol compared to the pure alcohols. The evaporative emissions for low-blend alcohols are significantly higher than high-blend alcohols. [5] Figure 2-11 presents the relationship of the RVP and methanol content in the GEM fuel, the higher the RVP the higher the volatility rate.

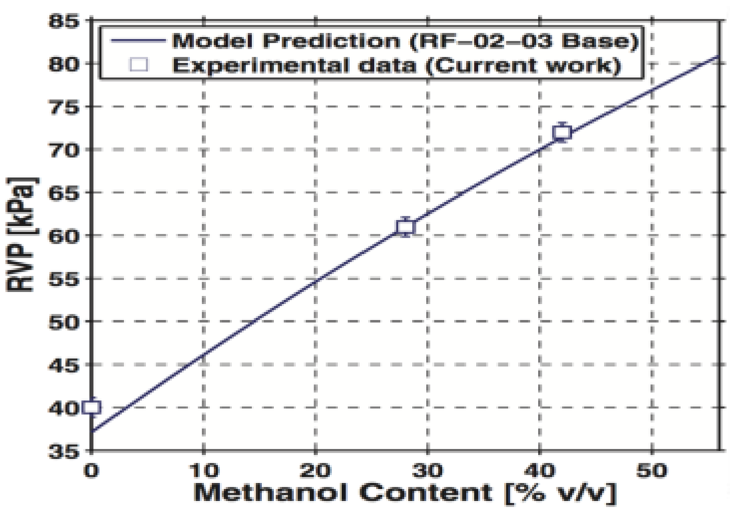


Figure 2-11: Relationship RVP and Methanol content [5]

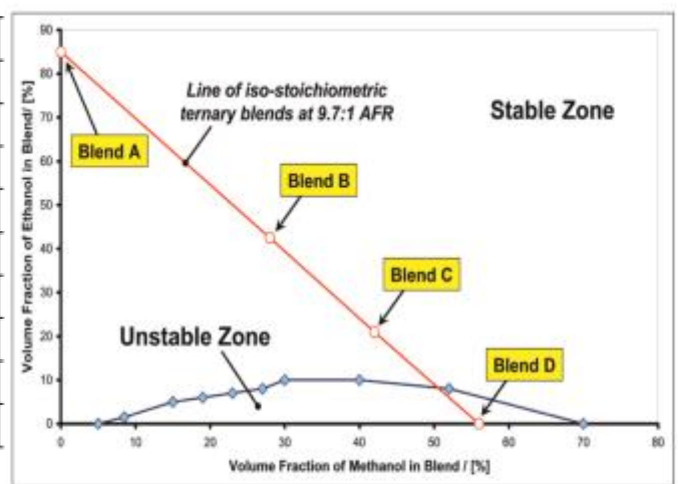


Figure 2-12: Phase stability at -15 ºC [5]

Furthermore, Pearson et al. conducted studies on the phase stability of the fuels at cold temperatures. GEM fuels that are iso-stoichoimetric with E85 and have a methanol content higher than 51 percent have the possibility of phase separation at temperatures of -15 º and colder. The result is presented in figure 2-12. As mentioned previously, gasoline is hydrophobic which means that is does not absorb water. For the other blends applies that when more is absorbed than the tolerance, the components fuel phase separation tends to appear. What can be seen in the graph is that the higher the methanol content in the GEM fuel, the lower the water tolerance. This implies that when high methanol GEM blends are implemented, it is tremendously important that the distribution network is a closed system, so that water is prevented from entering the system.

A benefit of adding methanol to the gasoline/ethanol mixture is that by adding methanol the cold start of the fuel improves significantly, because methanol ignites more readily than ethanol. [3] In Sweden, there is a special winter and summer blend for E85. The amount of ethanol in the blend is lowered from 85 to 75 percent, due to the cold start problems of the fuel. When implying GEM fuel, the no special winter blends are necessary. The energy utilization of the GEM fuel increases when methanol content increases.[3]

2.4.4 GHG Emissions of the secondary alcohols in GEM fuel

Methanol and ethanol are oxygenated molecules. This implies that both molecules contain oxygen atoms. When oxygenated molecules are combusted, less greenhouse gases are emitted, resulting in a cleaner burning than gasoline. According to Turner et al, GEM fuels emit 10 to 15 per cent less NOx than gasoline. [3] Furthermore, hydrocarbon and non-methane hydrocarbons emissions are slightly lower. The carbon monoxide emissions are approximately the same as gasoline.

When increasing the alcohol content in gasoline, the well-to-wheel GHG emissions of the fuel decrease significantly.[30] The 2009/28/EU of the European parliament states that when methanol is used as a fuel and produced from lignocellulosic feedstocks the GHG emissions decrease 91 to 94 per cent in comparison to the fossil alternatives. [17] Consumption of methanol fuel, produced from black liquor gasification decreases the amount of WTW-GHG emissions by 97 percent or more compared to gasoline, according to the EU RED method. [17] Regarding 2nd generation ethanol consumption, Ethanol fuel consumption of ethanol from forestry residues or industrial wood waste has typically 78 percent WTW-GHG emissions in comparison to gasoline fuel. [17]

2.4.5 Handling of the GEM fuel

When developing a GEM fuel distribution network, it is important to note that the properties of the different components, since these are determining the properties of the GEM fuel blend. The addition of methanol to gasoline requires more attention than ethanol, due to the fact that the properties of the chemical are more different from gasoline in comparison to ethanol. Implying that the properties of the GEM fuel are more influenced when increasing the methanol content than ethanol. Even though that methanol containing fuels are relatively new in Europe, the chemical is widely used as a solvent or chemical feedstock. Resulting in a substantial commercial experience in the handling of the alcohol. [25]

Although methanol and ethanol have many similar properties, there are a few differences. Methanol is a strong hygroscopic fluid, denoting that methanol is capable of absorbing or adsorbing from its surroundings. In order words, methanol takes up readily water vapor and water fluid. Subsequently the methanol has a strong tendency to dissolve in the absorbed/adsorbed water, this can lead to phase separation when the water toleration is exceeded. Furthermore, the methanol is more corrosive than ethanol, this is a result of contaminants which methanol fuel contains. The increase of methanol in the GEM fuel will change the corrosive, hygroscopic and conductive properties GEM fuel.

Therefore, blending gasoline with alcohols, decreases the water tolerance significantly. Gasohol's tend to separate in two phases, when the water tolerance is exceeded, resulting in an extremely corrosive and aggressive mixture. The separated water and alcohol mixture tends to sink to the bottom. Beside the material compatibility it also effects the vehicles performance negatively. In conclusion, when handling methanol containing fuels it is extremely important to prevent moisture from entering the mixture. In the entire supply chain of the GEM fuel should be accounted for water contamination by the construction of moisture barriers.

The gasohol fuels are clean products. Implying, that beside water also dirt should be prevented to enter the mixture. Therefore, extra actions should be taken in order to keep other materials out of contact with the GEM fuel. Some parts of the supply chain can possibly carry different fluids. For instance, a tanker trucks can be used to transport different types of fuels. When being a carrier i.e. GEM fuel, it is profoundly important that the equipment is carefully cleaned and dried in order to prevent the GEM fuel from contamination. So that GEM fuel is compartmentalized from other hydrocarbons along the entire distribution network.

3 Biofuel Production Pathways: Feedstock & Conversion Technologies

In this chapter, the production pathways of the advanced alcohols are evaluated, In the first part the feedstocks and the production pathways for both fuels are evaluated. In the second part an analysis is performed on the production costs of the advanced biofuels. The data implemented in this chapter is gathered through a comprehensive literature review and observations.

3.1 Feedstocks for 2nd Generation Ethanol & Methanol Production

Second-generation ethanol and methanol can be produced from a variety of different secondary biomass feedstocks. Most of the feedstocks are lingo-cellulosic and are suitable for the production of both alcohols. In this study, the emphasis is placed on second-generation feedstocks. This is due to the fact that the 1st generation ethanol industry is globally already well-established and the potential of conventional biofuels is limited by the EU agreement on a cap of 7 percent.[18] The implementation of non-food feedstocks for the production of biofuels is strongly advocated under the European legislation. Second-generation feedstocks that can be implemented for biofuel production are forestry residues, energy forest, straw, recovered wood and industrial lignocellulosic residues. The feedstocks need to be harvested and/or collected in order to be transported to the biofuel production plants. Furthermore, the feedstocks need to be pre-treated so that the feedstocks have the right properties for the conversion technologies of both fuels. Table 3-1 evaluates the different steps in the biofuel production process, spanning from the harvesting technique, the pre-treatment steps to the conversion technology. The conversion technologies are described in more detail in the next paragraphs.

3.1.1 Forestry residues

In Sweden, there is a large harvesting potential for untapped forestry residues due to the fact that Swedish forest covers 63 percent of the countries' surface area and of that 78 percent is available for active harvesting of forest residue.[9] Forestry residues from a single tree constitutes of stumps, pulp wood, tops and branches. Stumps is a bioenergy feedstock that is currently almost never harvested in Sweden, since stumps are usually left in the forest after final felling of the trees.[7] As a consequence, there is a large potential of the resource as a feedstock for the alcohols.[7] The stumps contain approximately 15 to 20 percent of the entire tree's energy.[46] Tops and branches are usually collected with the final felling and manufactured into woodchips. The tops and branches contain also around 15 to 20 percent of the total energy in the tree. Moreover, there is potential for brushwood, which is the growth of plants and small trees through natural succession and is spreading along roads, railway lines, edges zones between fields and forests, in power line corridors etc. [8] The brushwood has currently no function and can therefore be utilized as a feedstock of the alcohols.

3.1.2 Industrial residues

As previously mentioned, Sweden has large pulp and timber industries. Resulting in large amounts of lignocellulosic residues which consists of solid and liquid streams. The solid residues consist of shavings, sawdust and bark. The pre-treatment techniques of the solid residues are relatively similar to the pre-treatment techniques of the forestry residues. The liquid residue is only produced by the chemical pulp and paper plants and is called black liquor.[10] The black liquor does not need a pre-treatment technique before entering the conversion technology.

3.1.3 Other lignocellulosic feedstocks

An alternative lignocellulosic feedstock that can be converted to biofuels are are energy crops. Energy crops are plants that are grown in order to create energy feedstocks. Börjesson et al. estimates that 22 percent of the Swedish surface area is suitable and available for the production of energy crops by the year of 2030. [7] Energy forest is a lignocellulosic energy crop that is perfectly suitable for the production of both fuels. The energy forest requires the same pre-treatment techniques as forestry residues. Furthermore, recovered wood is a feedstock that can be implemented for biofuel production. Recovered wood is wood that primarily functioned as a building material, but that became a waste and is collected for bioenergy purposes. Straw is a lignocellulosic feedstock that is implementable as feedstock for ethanol production. The major function of straw is currently as feed and bedding in animal husbandry. [7] However, there is more straw available that it is demanded for the previously mentioned purposed. Therefore, the untapped potential can be used as a feedstock for ethanol.

Table 3-1: 2nd Biofuel production process(GoBiGas, ST1) [7]

			Methanol		Ethanol	
Feedstock Type	**Feedstock**	**Harvesting technique**	**Pre-treatment**	**Conversion BM to fuel**	**Pre-treatment**	**Conversion BM to fuel**
Forestry Residues	Tops & Branches	Thinning & Final felling	Chipping, Drying*	Gasification	Pre-hydration by Steam, Hydrolysis	Fermentation
	Stump	Final felling + Excavator	Chipping, Crushing, Drying*	Gasification	Pre-hydration by Steam, Hydrolysis	Fermentation
	Pulp Wood	Final felling	Chipping, Drying*	Gasification	Pre-hydration by Steam, Hydrolysis	Fermentation
	Brushwood	Cutting	Chipping, Drying*	Gasification	Pre-hydration by Steam, Hydrolysis	Fermentation
Industrial Residues	Black liquor	-	-	Gasification	-	-
	Wood Waste	-	Chipping*, Drying*	Gasification	Pre-hydration by Steam, Hydrolysis	Fermentation
Energy Crops	Energy Forest	Final felling	Chipping, Drying*	Gasification	Pre-hydration by Steam, Hydrolysis	Fermentation
Other Residues	Straw	Mowing & Collecting	-	-	Pre-hydration by Steam, Hydrolysis	Fermentation
	Recovered Wood	Collecting	Chipping, Drying*	Gasification	Pre-hydration by Steam, Hydrolysis	Fermentation

* Depends on the moisture content of the biomass

- Not possible/necessary

3.1.4 Competition of Feedstocks

Due to Sweden's national targets to fight climate change, the demand for biomass is most-likely going to increase.[47] Multiple industries will therefore rely more heavily on bioenergy. Table 3-2 presents an overview of the competing industries for the particular types of biomass which can be implemented as feedstock for the alcohols. As a result of the increase in demand for the biomass, the energy yield ratio from feedstock to fuel becomes a more and more important. The table indicates that forest residues, energy forest and industrial wood waste have the highest competitive use. Moreover, black liquor is currently mainly used for combustion purposes in pulp and paper plants. [22]However, due to the substance perfectly suitability for the production of the biofuels, methanol and DME, the competitiveness for black liquor can increase rapidly.

Table 3-2: Competition of feedstocks [7, 47]

Industry	**Forest Residues**	**Energy Crops**	**Straw**	**Industrial wood waste**	**Black liquor**
CHP Plants	X	X		X	
Animal Feed			X		
Liquid Biofuel	X	X	X	X	X
Biogas	X	X	X	X	
CHP of Pulp & Paper plants	X	X		X	X

Note:
The X implies that the industry demands the particular feedstock

3.2 Evaluation, Methanol & Ethanol Production Technologies

3.2.1 Methanol Production Technologies

The production of renewable methanol has experienced an increased interest among scientists. For the last decades, various studies have been conduction on the production of the fuel. As mentioned previously, methanol is generally derived from syngas. Renewable syngas is produced when the feedstock implemented for the syngas production is renewable. Renewable syngas is mostly derived through the partial oxidation of lignocellulosic biomass or from the mixture of renewable hydrogen gas and carbon dioxide. The syngas is converted, by a highly pressurized catalytic reaction, to methanol. The reactions that occur in the methanol synthesis process are together with the kinetics, presented below. The water shift reaction derives syngas from the water formed during the methanol synthesis reactions. What can be seen that all three reactions are exothermic, resulting in an excess of heat formed during the methanol production process.

Methanol synthesis reactions

1. $$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \quad \Delta H^{\circ}_{298} = -49.5\,\frac{MJ}{kmol}$$

2. $$CO + 2H_2 \rightarrow CH_3OH \quad \Delta H^{\circ}_{298} = -90.7\,\frac{MJ}{kmol}$$

Water shift reaction

1. $$CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta H^{\circ}_{298} = -41.2\,\frac{MJ}{kmol}$$

- **Methanol production from lignocellulosic feedstocks**

Renewable methanol can also be produced by the thermos-chemical gasification of lignocellulosic biomass feedstocks. The process flow chart of this production process is illustrated in figure 3-1. There are two types of lignocellulosic feedstocks that can be gasified, namely liquid and solid biomass. Solid biomass that can be gasified consists usually of woodchips, derived from trees and plants or industrial wood waste. In order for the solid biomass to gasify, the woodchips need to have a moisture content lower than 20 percent, therefore wet solid biomass needs to be dehydrated before it can be gasified. Black liquor is a liquid biomass that is gasified in order to produce methanol. The gasification process of solid and liquid biomass is essentially similar. During the gasification process, the feedstocks are partially oxidized in a gasification reactor. As depicted in the figure 3-1, pure oxygen is added and the byproduct of the process is slag. The gas produced in the gasifier is afterwards cooled down in order to carry out dry particle filtration. Subsequently the gas is purified by separating the Sulphur and carbon dioxide. The product after the purification step is clean syngas, consisting of mainly carbon monoxide and hydrogen gas. Lastly, methanol is produced by a pressurized catalytic reaction in which pure syngas is converted to methanol.

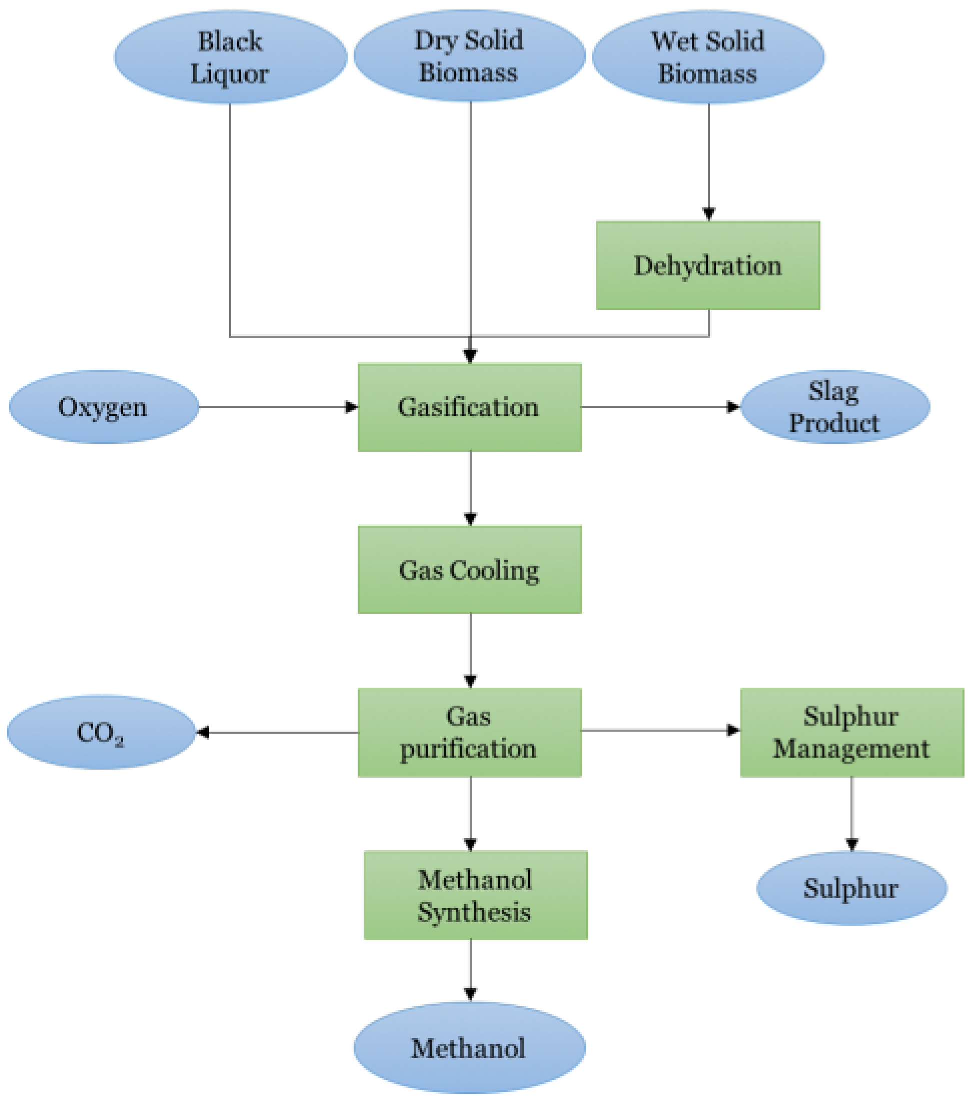


Figure 3-1: Methanol production process from lignocellulosic biomass

❖ **Methanol production from black liquor**

Figure 3-2 presents generally the process flow of materials in a conventional pulp and paper plant as well as in a transformed methanol producing pulp & paper plant. Black liquor is the by-product of the pulp & paper mill process. In a conventional pulp and paper plant, black liquor is combusted in a boiler plant in order to produce power and heat for the plant itself. The combustion process of black liquor, in the pulp and paper plants, is relatively inefficient. When black liquor is replaced by woody biomass as a heating source, only 69 percent of energy needed from black liquor is demanded from the woody biomass. [10] Subsequently, the black liquor can be implemented as a feedstock for the gasification process in order to produce methanol. The overall energy yield ratio from biomass to methanol is relatively high with 78 percent. In order to do so, the boiler is replaced by a boiler which is capable of combusting solid biomass. Since 2011, the company Chemrec produces renewable methanol successfully from black liquor. This is done by changing the conventional pulp and paper plant into a methanol producing pulp and paper plant and the facility produces 6 GWh of methanol annually. A process flow chart is of the plant is illustrated in the right chart in figure 3-2.

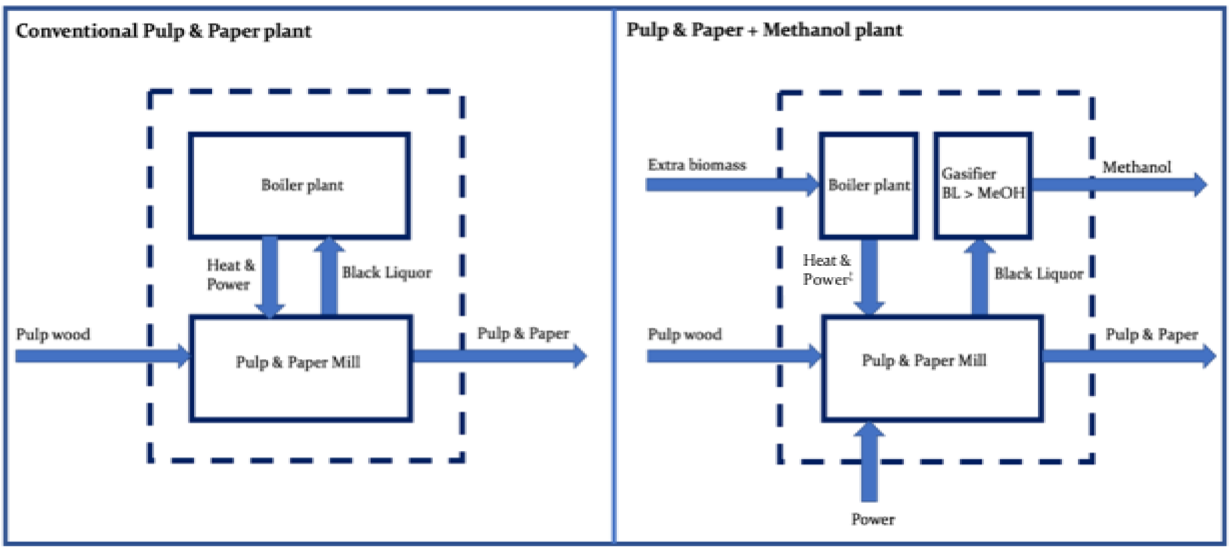


Figure 3-2: Overview conventional pulp and paper plant, methanol producing pulp & paper plant

3.2.2 Production Costs of Key Methanol Production Technologies

As mentioned in the previous paragraph, renewable methanol can be derived from several feedstocks and by different technologies. In this paragraph, the production costs and the energy yield ratio from biomass to methanol are evaluated. In the table 3-3, the results of key studies regarding the techno-economic feasibility of renewable methanol production are summarized. In the table, the production costs of the different production pathways are evaluated. As mentioned previously, renewable methanol can be produced from black liquor and lignocellulosic feedstocks. Furthermore, it can be produced from renewable hydrogen and carbon dioxide.

The production price of renewable methanol is mainly dependent on the cost of the input variables, the technology implemented and whether the technology is integrated with other industries. When analyzing the production cost of renewable methanol in Sweden, it is important that the costs of the input variables are comparable with the commodity prices on the domestic market. Furthermore, it is important that the way of integration of the technology is applicable in Sweden. The commodity prices of the input variables and technology description are illustrated in Table 3-

3. In the table, it can be seen what different costs are assumed for the input variables in the different studies. Beside the cost of biomass, the input costs of electricity are influencing the production price of methanol. Electricity is used in the different technologies to power utilities such as pumps, dryers, electrolyzers etc. In some of the technologies heat is produced and sold to the district heating network, therefore the price of district heat is depicted. In 2015, the electricity price for industrial consumers averaged on 59 euro per MWh.[48] Moreover, the price paid for heat delivered to the district heating system in Sweden varies between 16 and 27 euro per MWh. [49] It can be indicated from table 3-3 is these assumed values in the different studies are relatively similar to the values of the commodities in Sweden. Whether the assumed biomass can be achieved in Sweden is analyzed in chapter 5.

Various studies have analyzed the production costs of methanol from forestry residues. Though the assumed input variables of the different studies related to gasification of forest residues are relatively similar, the production costs of methanol by the technology varies largely. The production costs of methanol by the gasification of forest residues varies between 63 euro and 108 euro per MWh. The importance of energy integration with other industries is illustrated in the papers of Nataraja et al. and Hannula et al. the production price decreases when the production facility is connected to the district heating network and thereby the heat can be sold to the heat network. [50] [51] From the studies it can be concluded that the production cost of methanol benefits clearly from the integration. Though, the production costs determined in the studies varies significantly. The average production costs of methanol from forest residue gasification, among the different studies, is 84 euro per TWh. Furthermore, it is important to denote that the energy yield ratio from feedstock to methanol varies from 51 to 66.7 percent for the different technologies.

The production costs of methanol from the gasification of black liquor varies between 77 – 87 euro per MWh, the cost varies because of the economies of scale. The price corresponding to the average sized pulp and paper plant is 82 euro per MWh. The largest pulp and paper plants in Sweden have the potential to produce 6.5 TWh annually for the costs of 77 euro per MWh. In terms of the energy yield ratio from feedstock to methanol, black liquor gasification is the significant favorable production method. Table 3-3, illustrates that the energy yield ratio from the extra biomass to methanol is the highest with 78 percent. Implying that with a certain amount of woody biomass, the largest amounts of methanol can be produced if black liquor gasification is implemented.

Table 3-3: Evaluation production costs of renewable Methanol

Production Pathway	**Conversion Costs (€/MWh)**	**Energy yield Ratio(%)**	**Input costs (€/MWh)**		
			BM	**EL**	**DH**
Black liquor Gasification:					
Andersson et al,2016[10]	**77 – 87**, dependent of the size of the pulp and paper plant.	78	20	57	
Forest residue gasification					
Hannula et al, 2013[51]	**64 – 71** depending on whether the heat is sold.	60.8 – 66.7	20	50	30
Carvalho et al. 2017 [52]	**108**	66	20	57	
Peduzzi et al. 2013 [53]	**90**	58	22		
Natarajan et al. 2012[50]	**63 – 77**, depending on whether the heat is sold.	59	26		30

3.2.3 Ethanol Production Technologies

Ethanol is biochemically produced from all sugar containing biomass. This biomass can be divided into 1st and 2nd generation feedstocks. The process of producing first and second- generation ethanol is essentially similar, except from the pre-treatment process, which differs for different feedstocks. First-generation feedstock, consisting of mono- and disaccharides, needs to be boiled in order to extract the sugar from the feedstock, before it can be used to produce ethanol. First generation starch-based feedstock requires milling/grinding and a hydrolysis step in order to break down the polysaccharides molecules into simple sugar molecules, before ethanol can be produced. The second-generation lignocellulosic feedstocks require extra preparation steps before used for ethanol production. The more complex the molecules of the feedstock, the more complex the pre-treatment method prior to the fermentation process.

The production process of producing ethanol from lignocellulosic feedstocks is depicted in figure 3-3. Lignocellulosic feedstocks constitute of polysaccharides molecules, which are connected by hydrogen bonds. The long saccharide chains need to be broken down to monosaccharides in order to produce the ethanol. The feedstock consists partly of cellulose, lignocellulose and lignin. However, only cellulose can be converted to ethanol. The lignin is not suitable for ethanol production. The first pre-treatment step of the cellulosic feedstock is treatment with steam in the pre-hydration step. In the pre-hydration step the bonds between the molecules are broken. The next step of the pre-treatment is the hydrolysis by acid or enzymes in order to convert the cellulose into fermentable sugars. The first common step is the fermentation process. The yeast is added to the pre-mixture and converts the sugars anaerobically into the alcohol and carbon dioxide. The components are separated and the next two steps of the production process are to purify the diluted ethanol. First, de ethanol is purified by distillation. Subsequently, the ethanol concentration is increased further by the dehydration step. The end-product of the process is pure ethanol. Depending on the feedstock, different by products are produced. The by-product of the production process of ethanol from lignocellulosic feedstock is lignin and when the feedstock is starch based, the by-product is fodder.

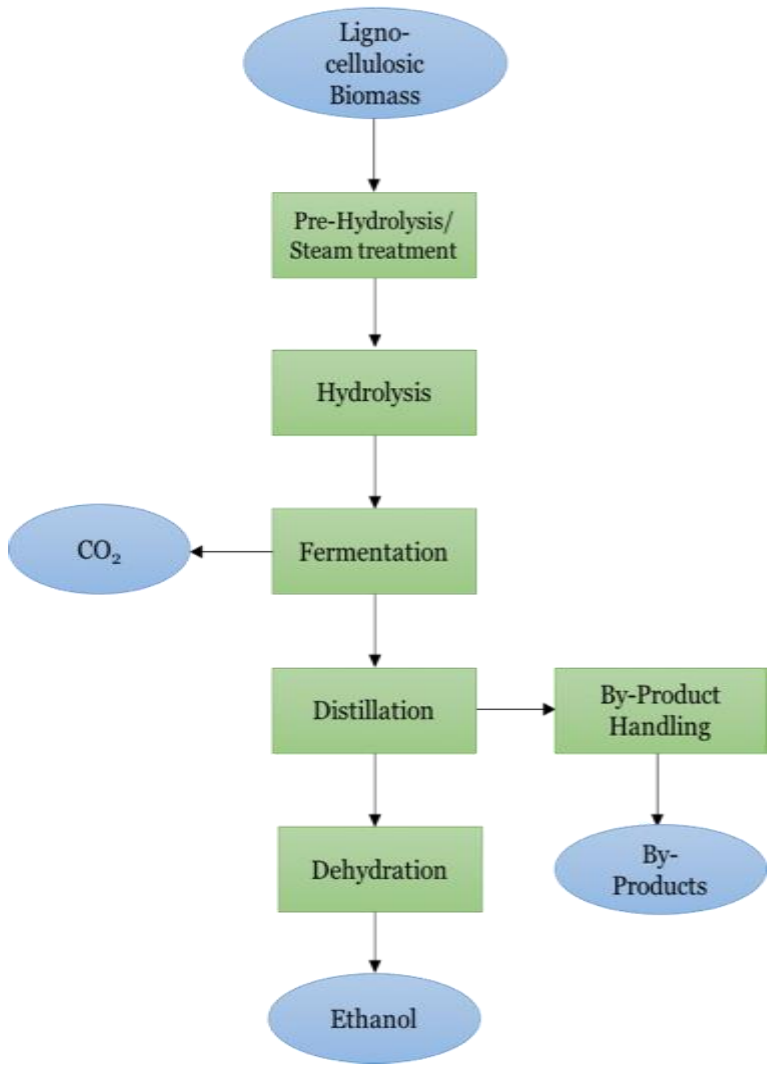


Figure 3-3: Ethanol production process from lignocellulosic biomass

3.3.2 Production Costs of key 2nd Generation Ethanol Production Technologies

Like for production of methanol, 2nd generation ethanol production has seen increased interest the last decade. Various studies are performed on the techno-economic feasibility of the fuel. Table 3-4 summarizes an analysis of key studies on the production costs of second-generation ethanol. It can be concluded from the table, that the energy yield ratio is relatively low in comparison to methanol, this is due to the limited amount of sugars in the wood.

Integration of the production process has a large effect on the production costs of the fuel. Cellulose, which constitutes approximately 40 percent of the wood is converted into ethanol. The remainder of the wood consists of lignin and hemicellulose. [54] The other parts of the feedstock could be used to produce heat, power, biogas or pellets so that the production cost of the ethanol would be further decreased, if the added value products can be sold. Therefore, the energy yield ratio regarding ethanol production is on average lower than the energy yield ratio of methanol production, due to the limited amount of cellulose.

The production cost of second-generation ethanol varies between 97 and 128 euro per MWh in the different studies. The articles studied indicate that the production cost is significantly dependent on the ability to sell the by-products. The transfers do not directly influence the direct cost related to the production of the fuel, but the revenue of the company is increased and therefore the price of the fuel can be decreased. Joelsson et al, calculated the production costs of ethanol to be 97 euro per MWh for a 55 MW production facility. The research conducted is a large-scale Swedish case study, the production costs depicted in the table 3-4 are based on a large production plant with forestry residues as its input. The most favorable production technology for the production of the 2nd generation ethanol in terms of production costs and energy yield ratio is the fermentation of lignocellulosic residues as studied by Joelsson et al. [11]

Table 3-4: Evaluation production costs of 2nd generation ethanol

Production Pathway	**Production Costs (€ MWh^{-1})**	**BM input costs (€ MWh^{-1})**	**Energy Yield Ratio(%)**
Fermentation of wood waste & forestry residues			
- Frankó et al. 2016[12]	**110** for sawdust & shavings **116** for fuel logs **121** early thinning **128** for tops & branches	20	34 for sawdust & shavings 32 for fuel logs 30 early thinning 27 for tops & branches
- Joelsson et al. 2015[11]	**97**	20	42
Fermentation of Straw:			
- Joelsson et al. 2016[55]	**122**	16.5	20.5

4 Analytical Framework and Data

This chapter presents the analytical framework, which is implemented in this study, in order to tackle the research questions described in the first chapter. First the methodological approach is described and subsequently the separate stages in the approach are described into detail with the applied models and assumptions.

4.1 Methodological Approach

Figure 4-1 outlines the methodological approach followed in this study to achieve the main research objective. The approach consists of 6 interrelated steps. In order to provide the required input parameters in the approach, primary and secondary data sources are gathered and analysed in the first step of the analysis. Subsequently, the biofuel production potentials of ethanol and methanol are assessed and the biofuel production pathways are selected. In step three, two GEM fuel scenarios are developed. In the fourth step, a Swedish GEM fuel distribution network is analysed. In the fifth and sixth step, the economic competitiveness of GEM fuels and the environmental impact of the implementation of GEM fuels are analysed. In the economic competitiveness and the environmental impact analysis, results and findings of the other steps are implemented as input parameters. The six inter-related steps are implemented in order to achieve the research objective, as illustrated in figure 4-1. The individual stages are described into more detail in the succeeding of this chapter.

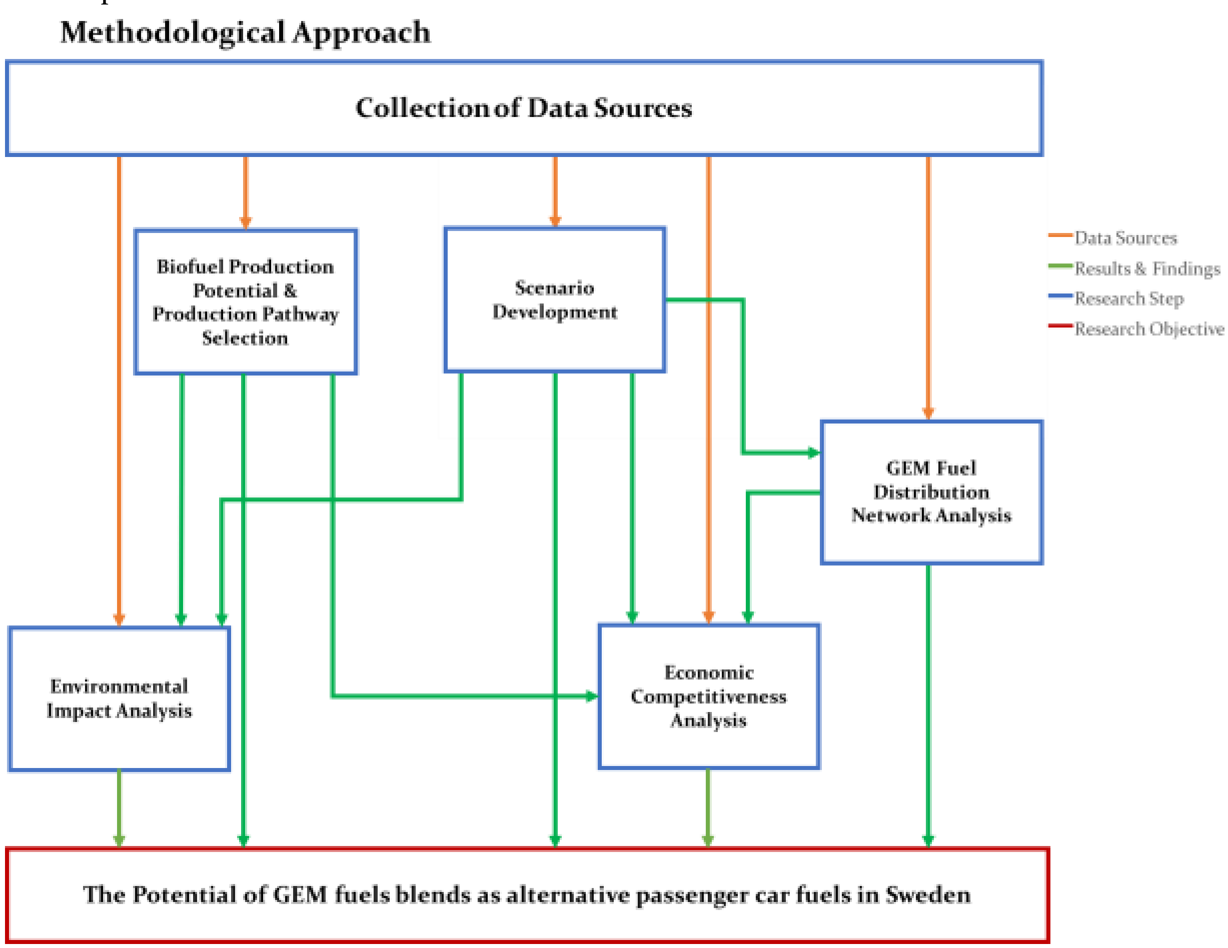


Figure 4-1: Methodological Approach implemented in this study

4.1.1 Primary & Secondary Data Collection

The data used in the analysis of this thesis is derived from multiple data collection methods, in which secondary and primary data is gathered. The main data collection methods implemented in this study are described in the succeeding of this paragraph.

⇒ **Primary Data Collection**

Throughout the duration of this thesis, primary data collection methods were implemented to gather data. Methods such as interviews, observations and e-mail conversations were held with professional's active in the supply chain of transportation fuels. Table 4-1, presents the companies or organizations that were approached in order to collect the data. The correspondents were carefully selected and some of the correspondents have answered the same questions about important issues in order to ensure accurate and appropriate data collection.

Table 4-1: Evaluation of the Primary Data Collection Methods Applied in this Research

Stakeholder	**Data Collection Method**	**Topic**
SEKAB, one of Europe's leading ethanol suppliers	Interview*	The blending process of E85, transportation of alcohols, pricing of 1st and 2nd generation ethanol, ethanol imports
Inter Terminals, the largest independent bulk liquid storage provider in Scandinavia	E-mail Contact	Gathering information on the storage capacity and cost of gasoline, ethanol and methanol.
Dover fueling solutions, leading supplier of i.e. fuel dispensers	E-mail Contact	Information on E85 dispensing pumps and the GEM fuel compatibility, E85 distribution network
SPT, Scandinavian Petroleum Technic Association	Interview**	Handling of alcohols, gasoline and E85 distribution network
Globecore GmbH, leading supplier of fuel blending systems	E-mail Contact	Price and design of a technical solution for the GEM fuel blending system
GoBiGas, biogas/syngas producer	Observation	Large scale production of syngas by gasification of forest residues, integrated with CHP

* see questionnaire in Appendix 12.7.2
** see questionnaire in Appendix 12.7.1

⇒ **Secondary Data Collection**

Secondary data plays an important role in this analysis and is gathered during various phases along the entire project, in the following fields(Ch. = Chapter):

- Potential of secondary biomass feedstocks (Ch. 5)
- The supply cost of secondary biomass feedstocks (Ch. 5)
- Bioalcohol production: energy yield ratio from biomass feedstock to fuel (Ch. 5)
- A GEM fuel distribution network (Ch. 7)
- Blending technologies capable of blending GEM fuel (Ch. 7 & 8)
- Forecast of the Swedish passenger car fleet (Ch. 6)
- Forecast of the energy consumption of ICE cars in the Swedish passenger car fleet (Ch. 6)
- Forecast of distance travelled by passenger cars in the Swedish passenger car fleet (Ch. 6)
- The GHG emissions of the consumption of the bioalcohols and gasoline (Ch. 8)

The literature reviewed consisted mainly of electronic sources such research papers, reports, country statistics, policy directives and proposals, books and websites.

4.1.2 Biofuel Potential Assessment & Selection Production Pathway

4.1.2.1 Biofuel Production Potential Assessment

This part of the study examines the biofuel production potential of both of the advanced alcohol fuels. The study incorporates all second-generation feedstocks which can be used for ethanol or methanol production. The theoretical production potential is based on the untapped potential of domestic feedstocks and the energy yield ratios of key conversion technologies. The biofuel potential is determined by equation 1. The input parameters for equation 1 are shown in table 4-2.

Equation 1

$$E_{biofuel} = \gamma * E_{feedstock}$$

With:

$E_{biofuel}$	Biofuel Production Potential [TWh]
$E_{feedstock}$	Theoretical Feedstock Potential [TWh]
γ	Energy yield ratio is the ratio between the energy content in the biofuels and the biomass feedstocks input[TWh/TWh]

⇒ **Biomass Feedstock Potential**($E_{feedstock}$)

The second column of table 4-2 presents the untapped potential of secondary biomass feedstocks, that can be implemented for the production of one of the alcohol fuels, by 2030. In table 3-1, all the feedstocks suitable for methanol and/or ethanol production are listed together with the harvesting techniques and biofuel production pathways. The data on the potential of the feedstocks is collected from multiple studies, which are shown in table 4-2. The studies analyzed the untapped potential biomass feedstocks that can be harvested/collected, in a sustainable manner, for bioenergy purposes by 2030. Black liquor is the only substance of which the shown potential is currently not untapped and which is utilized as a heat source in pulp and paper plants. However, if additional biomass is combusted instead of black liquor in the pulp and paper plants, the black liquor potential can become available for methanol production. Moreover, the black liquor cannot be used for ethanol production. Regarding methanol production from straw, no literature could be found on the production of methanol from straw and is therefore not considered in the analysis.

⇒ **Energy Yield Ratios from Feedstock to Biofuel**

The energy yield ratios are collected from studies which have analyzed key conversion technologies of the biofuels from the particular biomass feedstocks. Due to the pre-treatment processes, the solid biomass feedstocks derived from trees end up having relatively similar compositions and properties. As a consequence, the energy yield ratios are as well profoundly similar, especially in the gasification processes. From table 4-2, it can be concluded that methanol production has overall a higher energy yield ratio in comparison to ethanol. Hence, the production of methanol is more favorable in terms of energy. The lower energy yield ratio for ethanol production is due to the limited amount of sugars in the lignocellulosic feedstocks. Therefore, a large part of the energy of the feedstocks end up in the by-products of the production process such as lignin and biogas. Regarding black liquor gasification, the overall energy yield ratio, from the input biomass to the output methanol is 78 percent. The energy yield ratio from black liquor to methanol is 54 percent. Regarding methanol production from stumps, no exact energy yield ratio could be found in literature. However, according to B. Backlund, the cellulose content of stumps is approximately 28 percent lower than in pulpwood[56]. Thus, an energy yield ratio of 22 percent is chosen for stumps.

Table 4- 2: Input parameters for the biofuel potential assessment

Feedstock	$E_{feedstock}$ **in 2030 (TWh year^{-1})**	$\gamma_{BM\ to\ MeOH}$ **(%)**	$\gamma_{BM\ to\ EtOH}$ **(%)**
Forest residues			
Tops and branches	14 [A]	53 [D]	27 [H]
Stumps	18.1 [A]	53 [D]	22 [N]
Pulpwood, exl. Bark	1.9 [A]	53 [D]	30 [H]
Brushwood	7.2 [C]	53 [D]	28 [H]
Energy crop – alternatives			
Energy Forest	16 [A]	53 [D]	30 [H]
Recovered Wood	3 [A]	53 [D]	32 [H]
Straw	3 [A]	-	21 [K]
Industrial residues			
Black Liquor	50 [A]	(78)* 54 [L]	-
Wood Waste	27 [A]	53 [D]	34 [H]

[A] Adapted from Börjesson et al. (2015) [7]
[B] Adapted from De Jong et al. (2017) [47]
[C] Adapted from Edenhard et al. (2017) [8]
[D] Adapted from Morandin (2015) [58]
[H] Adapted from Frankó (2016) [12]
[K] Adapted from Saha (2015) [57]
[L] Adapted from Andersson (2016) [10]
[N] Assumed Value
* Is the Energy Yield ratio from extra biomass to MeOH[10]

4.1.2.2 Selection Biofuel Production Pathway

For the purpose of this thesis, the term 'production pathway' describes the combination of a biomass feedstock and conversion technology implemented to produce one of the biofuels. As evaluated in chapter 3, there are a variety of secondary biomass feedstocks and conversion technologies that can be implemented for the production of ethanol or methanol. In this part of the study the selection of biofuel production pathway is based on the following criteria:

1. *The energy yield ratio from biomass feedstock to biofuel of the conversion technology* (listed in table 4-2)

2. *The production costs of the biofuels*, the production costs of methanol and ethanol by key conversion technologies are evaluated in table 3-3 and 3-4.
3. *The biomass feedstocks costs,* the assessment on the biomass costs, of biomass feedstocks listed in table 4-2, is described below. In order to determine the production costs, determined in the different studies and listed in table 3-3 and 3-4, the studies have considered different biomass feedstock costs as input parameters. However, whether these biomass costs can be achieved by the Swedish biomass feedstocks listed in table 4-2, is not familiar yet. Therefore, the total costs of the biomass feedstocks, listed in table 4-2, are determined in order to justify the production costs of the biofuels listed in table 3-3 and 3-4. This is from importance, because the production costs of the biofuels are profoundly dependent on the biomass feedstock costs.

⇒ **Assessing the total cost of the feedstocks**

The total costs of the biomass feedstocks are based on the cost of the biomass feedstocks at the storage/forestry terminal and the cost of mobilization from the forestry/storage terminal to the biofuel plant(see equation 2). The cost of the biomass feedstocks at the storage/forestry terminal is shown in table 4-3. An estimation of the total cost of mobilization of individual biomass feedstocks is calculated by equation 3.

Equation 2

$$TC_{BM} = C_{BM\ at\ ST} + C_{mobilization}$$

With:

TC_{BM} = Total cost feedstock [€/MWh]
$C_{BM\ at\ ST}$ = The cost of the biomass feedstock at storage terminal [€/MWh]
$C_{mobilization}$ = Total cost related to the transport of feedstocks from storage terminal to biofuel production plant [€/MWh]

Table 4-3: The cost of the biomass feedstocks at the storage/forestry terminal

Feedstock	Reference	$C_{BM\ at\ ST}$ (€/MWh)
Forest residues		
Tops and branches	[47]	15.0
Stumps	[47]	21.4
Pulpwood, exl. Bark	[47]	15.2
Brushwood	*	10
Energy crop – alternatives		
Energy Forest	[7]	21.5
Recovered Wood	[7]	7
Straw	[7]	10
Industrial Residues		
Black Liquor	-	-
Wood Waste	[47]	10

* The cost of brushwood was not available in literature and is therefore assumed to be 10 euro per MWh. The relatively low value is chosen, because most of the brushwood is already managed and harvested.[8]

The total cost of mobilization is based on the cost of loading, unloading and transport of the biomass feedstocks. The input parameters of equation 3 are depicted in table 4-4. From table 4-4, it can be seen that different types of woody biomass, have different mobilization costs. Regarding methanol production from black liquor, a conventional pulp and paper plant is converted to a methanol producing pulp and paper plant. Therefore, the black liquor is at location and no mobilization costs are applied. However, additional biomass is necessary to be combusted instead of the black liquor. Hence, the mobilization costs are applied on the additional biomass.

Equation 3

$$C_{mobilization} = (C_{transport} * D) + C_{loading} + C_{unloading}$$

With:

$C_{transport}$ = The transport cost [€ km^{-1} MWh^{-1}]
D = Estimated distance from storage terminal to biofuel production plant [km]
$C_{loading}$ /$C_{unloading}$ = Cost of loading & unloading of the feedstocks [€/MWh]

The input parameters of equation 3 are shown in table 4-4 and are adapted from De Jong et al.[47]. From the input-data in table 4-4, it can be concluded that the type of transport determines the cost of transport. The access of a storage terminal to a harbor or rail station decreases the costs of mobilization of the biomass feedstocks significantly in comparison to road transport. However, whether the storage terminals have access to a harbor or train station is not familiar and therefore the average costs of the three different types of transport is taken into consideration as an estimation of the mobilization costs.

Regarding the covered distance(D), an average distance from storage terminal to biofuel production plant of 300 km is considered. This value is chosen, since the majority of Sweden is covered by forest except the low populated North-West.[9] Furthermore, most pulp and saw mills(which produce the wood waste) are mostly located in the middle and lower part of Sweden.[47] Therefore, it is assumed that the storage/forestry terminals are on average 300 km located from the biofuel production plant.

Table 4-4: $C_{transport}$ parameters, adapted from De Jong. et al[47]

Parameter	Unit	Road	Rail	Shipping	Average
Transport Cost					
Forestry Residues, Energy Forest	€/MWh·km	0.035	0.0029	0.0014	*0.013*
Wood waste streams, Recover Wood	€/MWh·km	0.035	0.0029	0.0014	*0.013*
Pulpwood	€/MWh·km	0.035	0.0029	0.0014	*0.013*
$C_{loading}$ and $C_{unloading}$					
Forestry Residues(wood chips)	€/MWh	1.12	1.91	0.10	*1.04*
Wood waste streams	€/MWh	0.58	1.91	1.40	*1.30*
Pulpwood	€/MWh	0.43	1.73	1.40	*1.19*

⇒ **Selection Biofuel Production Pathway**

Once the total costs of the secondary biomass feedstocks are estimated. The production costs of methanol and ethanol can be verified. Subsequently, the most suitable production pathways for both ethanol and methanol can be selected, since all the (1), (2) & (3) selection criteria are familiar.

4.1.3 GEM fuel Distribution Network Analysis

In this part of the study, a Swedish GEM fuel distribution network is investigated. In this thesis, the considered distribution network, constitutes of transportation from and to the storage terminal, and storage, blending and retailing of GEM fuel and its components. In this study, it is analyzed whether parts of the existing fuel distribution network of E85 and gasoline can be utilized in a GEM fuel network and if not, it is analyzed how the equipment can be converted to become capable of distributing GEM fuels and its components. If both is not possible, new-establishment of equipment is evaluated. Moreover, it is analyzed what capacity of the GEM fuel distribution network is needed in order to supply the projected GEM fuel energy demands in the scenarios, and how this capacity can be achieved. Regarding the capacity of the fueling pumps at retail stations, the amount of times that the fuel pumps need to be refilled is estimated by equation 4.

⇒ **Verifying the Refills of Fuel Pumps at Retail Stations**

Equation 4

$$\text{Refills}\left[\frac{\text{times}}{\text{month}}\right] = \frac{\text{Annual Demand of GEM fuel Blends}[m^3]}{\text{Number of Pumps} * \text{Volume Storage Tank}[m^3] * 12}$$

4.1.4 Scenario Development

The development of the Scenarios is performed in chapter 6. In this paragraph the methodology, data and assumptions related to the scenario development are briefly described. In the purpose of this analysis 'GEM cars' are described as E85 flex-fuel vehicles that are fueled with GEM fuel blends.

In this study, two scenarios are developed to project the share of GEM cars in the Swedish passenger car fleet. The scenarios are developed in order to verify the energy demand of GEM fuel blends, which is created by the shift of passenger cars running on neat gasoline to GEM fuel blends. Hence, when GEM cars obtain different shares in the Swedish passenger car fleet, different energy demands are projected. The energy demand is projected in a time frame of 2017 to 2030. Once the energy demand for GEM fuels is evaluated, the energy demand ethanol and methanol can be projected. The projected energy demand of ethanol and methanol are tested in comparison to the results of the biofuel potential analysis. Hence, it is investigated whether the projected energy demand of ethanol and methanol can be met by the biomass feedstock potentials listed in table 4-2.

The Scenarios are based on a business as usual forecast developed by the Swedish Transport Agency. In Scenario 1, it is considered that GEM cars overtake the entire, share of gasoline cars by 2030, in the business as usual forecast. In Scenario 2, GEM cars take over 75 percent of the share of gasoline cars. In both Scenarios, it is considered that E85 flex-fuel vehicle owners fuel their cars with GEM fuel blends and become therefore GEM cars. As mentioned previously, for the development of the scenarios, see chapter 6.

Moreover, since there are a variety of GEM fuel blends that can be utilized in E85 flex-fuel vehicles. Three different GEM fuel blends are selected and analyzed in both Scenarios. The first blend is a GEM fuel blend with a high methanol content(**Blend-HM)**, consisting of 36.5, 23.5 and 40 volume percent of respectively gasoline, ethanol and methanol.(**G36.5 E23.5 M40)** The second blend is a GEM fuel blend with a medium content of both biofuels (**Blend-ME**). consisting of 29.5, 42.5 and 28 volume percent of respectively gasoline, ethanol and methanol. **(29.5 E42.5 M28)** The third blend is a GEM fuel blend with a high ethanol content, (**Blend-HE**). consisting of 19.5, 71 and 9.5 volume percent of respectively gasoline, ethanol and methanol. **(G19.5 E71 M9.5)** The derivation of both blends, from figure 1.1, is shown in Appendix 12.8.

Due to the different energy densities of the components, the compositions of the GEM fuel blends in terms of energy differs from the compositions in terms of volume. The compositions of the fuels in terms of energy are shown in table 4-5 and the determination is depicted in Appendix 12.1.

Table 4-5: Energy Compositions of the selected GEM fuel blends

Energy Fraction(%)	Symbol	Blend-HM	Blend-ME	Blend-HE
Ethanol	E_E	22	40	66
Methanol	E_M	28	19	7
Gasoline	E_G	50	41	27

The combinations of the Scenarios and the three different GEM fuel blends implemented, are illustrated in table 4.6. The Scenarios in combination with the GEM fuel blends, are developed to evaluate and project the energy demand of GEM fuels and its components. The six different combinations of scenarios and GEM fuel blends lead to different energy demand projections for ethanol and methanol. As mentioned previously, when the energy demand for methanol and ethanol are projected, it can be investigated whether the demand can be met from Swedish second-generation feedstocks. Moreover, the biomass utilization in the scenarios is estimated after the energy demands for ethanol and methanol are projected.

Table 4-6: The combinations of Scenarios and the selected GEM fuel blends

GEM fuel Blend / Scenario	High Methanol Blend (HM)	Medium Blend (ME)	High Ethanol Blend (HE)
Scenario High Share GEM Cars (Scenario 1)	Scenario 1-HM	Scenario 1-ME	Scenario 1-HE
Scenario Low Share GEM Cars (Scenario 2)	Scenario 2-HM	Scenario 2-ME	Scenario 2-HE

The energy demand projections of the GEM fuel blends in the Scenarios, indicate the amounts of GEM fuels blends that needs to be distributed in order to meet the project energy demand. These amounts are used as the distribution capacity necessary in the Swedish GEM fuel distribution network analysis. Moreover, the Scenarios, in combination with the selected GEM fuel blends, serve to identify the economic competitiveness of GEM fuel blends and the environmental impact of the implementation of GEM fuels.

⇒ **Energy Demand Projections of GEM fuel**

As mentioned previously, the projected share of GEM cars in the Swedish passenger car fleet results inherently to an energy demand for GEM fuel blends. In this thesis, the GEM fuel energy demand projections are based on the share of GEM cars in the Swedish passenger car fleet, the total annual distance covered by passenger cars within Sweden, and the energy consumption of ICE cars.(see equations 5 & 6) In the scenarios, it is considered that the energy consumption of GEM cars is equal to the energy consumption of ICE cars. The input parameters of equations 5 and 6 are listed in table 4-7.

Equation 5

$$\text{Total Annual distance of GEM cars} = \text{Total Annual Distance of Passenger Cars} * \text{Share of GEM cars}$$

Equation 6

$$\text{Energy Demand GEM fuel} = \text{Energy Consumption ICE Cars} * \text{Annual distance GEM cars}$$

The Swedish transportation agency, has studied the forecast of the total annual passengers distance travelled by cars and public transport. [59] The estimates regarding the annual passenger distance travelled by passenger cars are shown in table 4-7. For further information on the forecast see the Appendix 12.5. The annual distance covered by passenger cars within the boundaries of Sweden is projected to increase with 19 percent between 2015 and 2030.

Regarding the energy consumption of ICE passenger cars, the Swedish Environmental Research Institute has forecasted the energy consumption of ICE passenger cars in the Swedish passenger car fleet.[15] The result is illustrated in table 4-7. According to the study, it is estimated that the energy consumption is going to decrease with 24 percent, between 2015 and 2030. In the scenarios, it is considered that the energy consumption of all types of ICE cars is similar.

Table 4-7: Input Parameters Demand Projections

Input Parameter	2010	2015	2020	2025	2030
Annual distance Cars(Billion pkm) [59]	109	115	123	130	137
Energy Consumption ICE cars (Wh per pkm) [15]	456	420	383	352	321

4.1.5 Economic Competitiveness Analysis

In this study, the GEM fuels blends are considered to be economic competitive if the consumption of the fuel pays-off in comparison to gasoline and E85. Pacini et al. developed the formula, depicted by equation 7, to investigate the pay-off limits of E85 in comparison to gasoline. [24] The formula is based on the pump price of gasoline and the average fuel economy of E85. The number 0.74 in equation 7 is the ratio between the fuel economy of E85 and gasoline fuel in E85 flex-fuel vehicles. According to Pacini et al. consumers decide to purchase the E85 fuel, if the pump price of the E85 fuel is lower than the E85 price limit curve. [30] According to Turner et al., the fuel economy of GEM fuels blends is similar to E85 fuel. Therefore, in this thesis, the limit cure created by equation 7 is used to investigate the economic competitiveness of GEM fuel blends. The pump prices in equation 7 are in terms of unit of price per unit of volume, for instance (€ per liter).

In the economic competitiveness study, first, the pump prices of the selected GEM fuel blends are verified. Subsequently, a limit curve for GEM fuel blends is developed. Lastly, the GEM limit curve is tested with the determined pump prices of the selected GEM fuel blends. The determination of the pump prices of GEM fuel blends is described in the succeeding of this paragraph.

Equation 7

$$\text{Limit Curve Pump Price E85/GEM} \leq 0.74 * \text{Pump Price Gasoline}$$

⇒ **Verifying the pump prices of the selected GEM fuel blends**

In order to analyse the economic competitiveness of the selected GEM fuel blends, the fuel pump prices need to be verified. Slade et al. have developed a supply-chain cost model that helps to determine the pump price(excluding taxes) of ethanol fuels[60]. The supply-chain cost model is illustrated in Appendix 12.9. Based on the model of Slade et al. and the performed interviews in this study, table 4-8 is developed by the thesis author to verify the pump prices of the individual components in the GEM fuel. In table 4-8 the different economic parameters are listed that determine the pump price of the components. Once the pump prices of the individual components are verified, the pump prices of the selected GEM fuel blend are determined by equation 10.

The first step in the pump price determination is to determine the pre-VAT pump prices of the individual components of GEM fuel. The economic parameters which determine the individual pre-VAT prices are listed in table 4-8. As mentioned previously, biofuels are in Sweden, under the current policies, exempted from the energy and carbon dioxide tax, which is considered as well in this thesis. The depicted values of the economic parameters for gasoline in table 4-8, are derived from table 2-2. The production costs of the biofuels are verified in the selection of the biofuel production pathway, chapter 5, which include the total costs of the biomass feedstocks. According to Preem, the retail cost and profit for gasoline in Sweden are around 1 percent of the total pump price, which is 1.7 € per MWh. [41] For GEM fuel blends, the same value is considered in this study. The distribution costs are estimated based on the findings in the Swedish GEM fuel distribution network analysis. The determination of the blending costs is described below.

Table 4-8: Pre-VAT determination GEM fuel components

Economic Parameter	Methanol	Ethanol	Gasoline
Production Cost	(?)	(?)	63.0
Distribution Cost	(?)	(?)	(?)
Blending Cost	(?)	(?)	(?)
Retailers Cost & Profit	1.7	1.7	1.7
Energy tax	↓	↓	43.9
Carbon dioxide tax	↓	↓	29.3
Pre-VAT Pump Price	(?)	(?)	(?)

Note:
Values with (?) are to be evaluated in the succeeding of this thesis

- *Estimation of the Blending Costs*

In order to verify the blending cost, a blending system that is capable of blending different compositions of GEM fuel is selected by the recommendation of the company Globecore GmbH, a leading supplier of fuel blending systems. The technical specifications are listed in table 4-9. The total blending cost includes the maintenance, operations and investment costs. All the costs are expressed in units of [euro per MWh]. The blending costs are determined by equations 8 and 9 and the input parameters are listed in table 4-9 and 4-10.

Table 4-9: Specifications In-line blending system of Globecore GmbH, for more specifications see Appendix.

Item	Symbol	Value	Unit
Nominal Power of the blending system	N_P	50	kW
Blending Capacity of GEM fuel	C	100	$m^3\ hr^{-1}$
Investment Cost	C_{inv}	63 965	€ per blending system

Table 4-10: Input parameters used for blending cost calculation

Item	Symbol	Value	Unit	Reference
Availability	A	50	%	[61]
Electricity Costs	C_E	59	€ MWh^{-1}	[48]
Maintenance Costs	C_M	4	%	[61]
Life Time	T	10	Years	[61]

Equation 8

$$\text{Annual Blending Capacity} = C * A * 8760$$

The value 8760 that is used in equation 8 is the number of hours in a year.

Equations 9

$$\text{Electricity Cost} = \frac{C_E * A * N_P}{C}$$

$$\text{Investment Cost} = \frac{\text{Cinv}}{T * 8760 * C * A}$$

$$\text{Maintenance Cost} = \text{Maintenance Costs} * \text{ Investment Cost}$$

$$\text{Blending Costs} = \text{Electricity Cost} + \text{Investment Cost} + \text{Maintenance Cost}$$

- *Estimation of the Pump Prices of the Selected GEM fuel blends*

After the pre-VAT pump prices of the individual components are determined, the pre-VAT pump prices of the GEM fuel blends are calculated by equation 10. Equation 10 is created by the thesis author to determine the pump price of GEM fuel blends. In order to derive the pump price of the GEM fuel blends, the pump prices, in terms of price per energy, and the energy fractions of the individual components are considered.

Equation 10

$$\text{Pump Price GEM fuel(without VAT)} = (P_G * E_G) + (P_E * E_E) + (P_m * E_m)$$

With:

P_G = Pre-VAT price Gasoline [€/MWh]

P_E = Pre-VAT price Ethanol [€/MWh]

P_M = Pre-VAT price Methanol [€/MWh]

E_G, E_E, E_M = See table 4-5, energy fractions in the different blend of gasoline, ethanol and methanol [-]

⇒ **Investigating Economic Competitiveness of the GEM fuel blends**

After the pump prices of the selected GEM fuel blends are estimated. The prices are tested in comparison to the developed GEM limit curve. With the help of equation 7, a GEM limit curve is developed with the pump prices of gasoline of between 2007 and 2017.

4.1.6 Environmental Impact Analysis

The environmental impact can be divided into impact from production of the feedstocks, production from any of the three fuels constituting GEM, from the blending, distribution and the use of the fuel. Further, the impact can be divided between local emissions to air, water and ground and to emissions of GHG (which has global impact).

In this thesis, the environmental impact is assessed based on the avoided GHG emissions resulting from the utilization of GEM fuel blends instead of neat gasoline by passenger cars. In order to estimate the total GHG emissions avoided, the well-to-wheel(WTW) methodology is used. The WTW methodology considers the GHG emissions resulting from the production, transport, distribution and combustion of transportation fuels. [62]

In order to estimate the total GHG emissions avoided in the scenarios, the WTW GHG emissions savings factors(%) of the selected GEM fuel blends are determined. In this study, 'GHG emissions savings factors' are described as the well to wheel GHG emissions avoided, in percentage, when GEM fuel blends are consumed instead of gasoline fuel. The GHG savings factor of the GEM fuel blends are verified by equation 11. The GHG savings factors of the GEM fuel blends are based on the energy fractions of ethanol and methanol in the fuel GEM fuel blends(depicted in table 4-5) and the WTW-GHG savings of ethanol and methanol. The WTW-GHG saving of ethanol and methanol are shown in table 4-11 and are dependent on the production pathway.

Equation 11

$$\text{WTW GHG}_{\text{Savings\_GEM\_factor}} = \left(\text{WTW GHG}_{\text{Savings\_E}} * \text{E}_{\text{E}}\right) + \left(\text{WTW GHG}_{\text{Savings\_M}} * \text{E}_{\text{m}}\right)$$

With:

WTW $\text{GHG}_{\text{savings\_GEM\_Factor}}$	WTW-GHG emissions savings factor of the GEM fuel blends in comparison to neat gasoline [%]
WTW $\text{GHG}_{\text{savings\_E}}$	WTW-GHG emissions savings factor of ethanol fuel in comparison to gasoline [%]
WTW $\text{GHG}_{\text{savings\_M}}$	WTW-GHG emissions savings factor of methanol fuel in comparison to gasoline [%]
E_E, E_M	See table 4-5, for the energy fractions of ethanol and methanol in the GEM fuel blends[%]

Table 4-11: GHG savings per fuel component compared to fossil fuels

Item	(%)	Production Pathway
WTW $\text{GHG}_{\text{savings\_M}}$	97	Methanol produced, black liquor gasification, with waste wood as input[17]
WTW $\text{GHG}_{\text{savings\_E}}$	78	Ethanol produced from wood residues[17]

The total amount of GHG emissions avoided in by the scenarios is estimated by equation 12. The input parameters of equation 12 are shown in table 4-12. In addition, the WTW GHG emissions savings factors(%) of the selected GEM fuel blends are used in equation 12. The amount of GHG emissions avoided is dependent on the GHG emissions savings factors of the GEM fuel blends, the total energy replaced by GEM fuels in the Scenarios and the WTW GHG emissions of gasoline fuel. The total energy replaced of neat gasoline by GEM fuels is estimated in the scenario development chapter (Ch. 6).

Table 4-12: Input parameters of equation 12

Parameter	Amount	Unit
Scenario 1, $E_{tot,}$	(?)	TWh
Scenario 2, $E_{tot,}$	(?)	TWh
WTW $GHG_{gasoline}$ [62]	0.314	$kgCO_2eq\ kWh^{-1}$

Note:
Values with (?) are to be estimated in the in the succeeding of this thesis

Equation 12

$$\text{Total GHG}_{\text{Savings\_GEM}} = E_{\text{tot}} * \text{WTW GHG}_{\text{gasoline}} * \text{WTW GHG}_{\text{Savings\_GEM\_factor}}$$

With:

E_{tot}	Total energy replaced by GEM fuel blends instead of neat gasoline in the scenarios[TWh]
WTW $GHG_{gasoline}$	WTW GHG emissions of gasoline fuel consumption [kg/TWh]
Total $GHG_{Savings\_GEM}$	Total amount of WTW GHG emissions avoided by the utilization of GEM fuel blends in the scenarios[kg]

5 Assessing Biofuel Production Potential

This chapter presents the biofuel production potential of both methanol and ethanol from secondary domestic feedstocks. Moreover, this chapter includes the production pathway selection of both biofuels. The results and findings of the biofuel production potential assessment and the biofuel production pathway selection are presented.

5.1 Biofuel Production Potential Assessment

This chapter represents the assessment of the production potential of both ethanol and methanol from domestic secondary biomass feedstocks. The biofuel production potential analysis is based on the theoretical untapped feedstock potential and the energy yield ratios of key conversion technologies.

- **Biofuel Production Potential**

A summary of the results on the estimated theoretical production potential of both alcohol fuels is depicted in table 5-1. The theoretical potential is shown per individual biofuel derived from a particular biomass feedstock by 2030. It can be concluded that most feedstocks are suitable for the production of both alcohol fuels. Implying that the theoretical potential for GEM fuel cannot be determined by adding up the sum of both individual biofuels. Hence, the total theoretical production potential is only achieved when a single alcohol is produced. Regarding the methanol production, the different production potentials can also not be added up to determine the total methanol production potential, since methanol can only be produced from black liquor if additional biomass is added to the process, so that the biomass is combusted instead of black liquor. Since the black liquor is at present not untapped. As mentioned previously, in this thesis black liquor is not considered as a feedstock for ethanol and straw not as a feedstock for methanol.

Table 5-1: Determination of theoretical production potential of methanol and ethanol

Feedstock	$E_{Methanol}$ by 2030 (TWh)	$E_{Ethanol}$ by 2030 (TWh)
Forest residues		
Tops and branches	7.4	3.8
Stumps	9.6	4.0
Pulpwood, exl. Bark	1.0	0.6
Brushwood	3.8	2.0
Energy crop – alternatives		
Energy Forest	8.5	4.8
Recovered Wood	1.6	1.0
Straw	-	0.6
Industrial residues		
Black Liquor	27	-
Wood Waste	14.3	9.2

Since in the process of methanol production from black liquor gasification has the highest biomass to methanol energy yield, the maximum production potential of methanol is achieved when all the black liquor is utilized for methanol production. Therefore, additional biomass feedstocks are implemented as heating source replacements of black liquor in the pulp and paper plants, in order to be combusted and to produce heat and power. As previously mentioned, due to the improved efficiency of the combustion of solid biomass feedstocks instead of black liquor, only 69 percent of the energy input of black liquor is necessary from solid biomass feedstocks. Therefore, in order to use the 50 TWh of black liquor, 34.5 TWh of solid biomass feedstocks are necessary to produce the heating and power demand of the pulp and paper plants. As depicted in table 5-1, the total potential of methanol derived from black liquor, by the year of 2030, is 27 TWh. The potential of solid biomass feedstocks that are suitable for the methanol production is 87.2 TWh. The straw feedstocks, which are in this study is not considered as a direct methanol feedstock, are used as a solid combustion fuel in the pulp and paper plants. Since, in order to reach the maximum methanol production potential, 34.5 TWh of the biomass feedstocks is utilized as solid combustion fuel in the pulp and paper plants, 55.7 TWh can be gasified for direct methanol production. The result is a methanol production potential, from the solid biomass feedstocks, of 29.5 TWh by the year 2030. According to this thesis, the maximum potential of secondary biomass feedstocks that can become utilized for methanol production is 105.7 TWh by the year 2030. Hence, the total methanol production potential of secondary biomass feedstocks, determined in this thesis, is 56.5 TWh by 2030.

Regarding the production of 2nd generation ethanol, the potential of secondary biomass feedstocks than can be utilized for the ethanol production is 90.2 TWh by 2030. According to this thesis, the total potential of 2nd generation ethanol from these biomass feedstocks is 25.9 TWh by the year of 2030. The production potentials of the alcohol fuels, by 2030, are presented in table 5-2.

Table 5-2: Theoretical Production Potential by 2030 of the individual bioalcohols

Bioalcohol	**Total** $E_{biofuel}$ **(TWh)**
Methanol	56.5
Ethanol	25.9

5.2 Selection Methanol and Ethanol Production Pathway

In this paragraph, the production pathway for both methanol and ethanol is selected. Again, for the purpose of this thesis, the selection of the 'production pathway' is described as the feedstock and conversion technology selection. The selection of the biofuel production pathway in this thesis, is based on three criteria: (1) the energy yield ratio of the conversion technology from feedstock to biofuel, (2) the production costs of the conversion technology and (3) the cost of the biomass feedstocks. As mentioned previously, the energy yield ratios are evaluated in table 4-1 and the production costs of the biofuels are evaluated in table 3-3 and 3-4. However, the depicted production costs can only be achieved if the Swedish biomass feedstocks can be supplied for a cost similar as the biomass costs used as input parameters in the studies listed in table 3-3 and 3-4. In the succeeding of this paragraph, the biomass feedstock costs of feedstocks implemented in the biofuel production potential analysis are investigated and once the total biomass feedstock costs are familiar, the production pathways of the biofuels are selected.

⇒ **Analyzing the total Biomass Feedstock Costs**

The biomass costs at storage/forestry terminals, as shown in table 4-3, include the harvesting, forwarding, crushing(stumps), chipping, transport to a local storage site and storage costs.

However, the biomass feedstocks need to be transported from the storage/forestry terminal to a biofuel production plant. Therefore, first the mobilization costs of the biomass feedstocks related to the transport from the storage/forestry terminals to the biofuel production plants, needs to be verified. Subsequently, the mobilization costs are added to the cost of the biomass feedstocks at the storage/forestry terminal (table 4-3) in order to estimate the total biomass feedstock costs. Regarding the biomass feedstock costs of forestry residues and energy forest, the cost varies depending the potential of the feedstock harvested. This is due to the fact that parts of the same feedstocks are more easily harvested and therefore have lower harvesting costs. Therefore, the average cost is taken into consideration in this study for these biomass feedstocks.

As mentioned previously, the cost of mobilization is based on costs of unloading and loading the biomass feedstocks into the means of transport, and the cost of the transport. Moreover, the mobilization costs differ for the different types of biomass feedstocks. The results of this study on the mobilization costs of the different biomass feedstock types are illustrated in table 5-3.

Table 5-3: Results mobilization costs

Feedstock	**Mobilization Costs (€/MWh)**
Forestry Residues, Energy forest	4.9
Wood waste streams, Recovered Wood	5.3
Pulpwood	5.1

The mobilization costs are added to the cost of the biomass feedstocks at the storage/forestry terminal in order to estimate the total costs of Swedish biomass feedstock. The results on the total biomass feedstock costs, estimated in this study, are shown in table 5-4.

Table 5-4: Result on the total feedstock costs

Feedstock	TC_{BM} **(€ MWh⁻¹)**
Forest residues	
Tops and branches	19.9
Stumps	26.3
Pulpwood, exl. Bark	22.3
Brushwood	14.9
Energy forest	25.9
Recovered wood	12.3
Straw	14.9
Industrial wood waste	14.9

⇒ Selection of the production pathway of the biofuels

The production pathway describes the implemented feedstock and biofuel production technology. As mentioned previously, the three main criteria for selecting the production pathway are: (1) the energy yield ratio of the conversion technology from feedstock to biofuel, (2) the production costs of the conversion technology and (3) the cost of the biomass feedstocks. Now that the biomass feedstock costs are estimated, all the three criteria are familiar.

❖ **Methanol**

Based on criterion (1), as depicted in table 4-2, methanol production by black liquor gasification is the most beneficial conversion technology with an energy yield ratio of 78 percent. Based on criterion (2), from table 3-3, it can be concluded that as well black liquor gasification is, is the most beneficial conversion technology for the production of methanol. The production costs of black liquor gasification are slightly more favorable over forestry residue gasification, with an average production costs of 82 euro per MWh for black liquor gasification and 84 euro per MWh for forestry residues gasification.

Regarding criterion (3), due to the fact that all types of solid biomass feedstocks can be implemented as a combusted fuel, instead of black liquor, the variety and potential of the biomass feedstocks in the process are higher comparison to the forestry residue gasification process. Therefore, also in terms of criterion (3) methanol production from gasification is the most beneficial. Hence, black liquor gasification is in this study selected as the most suitable production pathway of methanol. A schematic overview of the production pathway is depicted in figure 5-1. As shown in table 3-3, the biomass cost assumed in the study of Andersson et al. is 20 euro per MWh. Table 5-4 illustrates that multiple types of solid biomass feedstocks can be supplied for a biomass feedstock costs lower than the 20 euro per MWh[10]. According to this study, the most suitable solid biomass feedstocks, that should be implemented in a methanol producing pulp and paper plant(as a solid combustion fuel) so that the black liquor can be utilized for methanol production, are shown in figure 5-1. As mentioned previously, the production potential of methanol by black liquor gasification, if additional biomass feedstocks are delivered to the process, is 27 TWh annually by 2030.

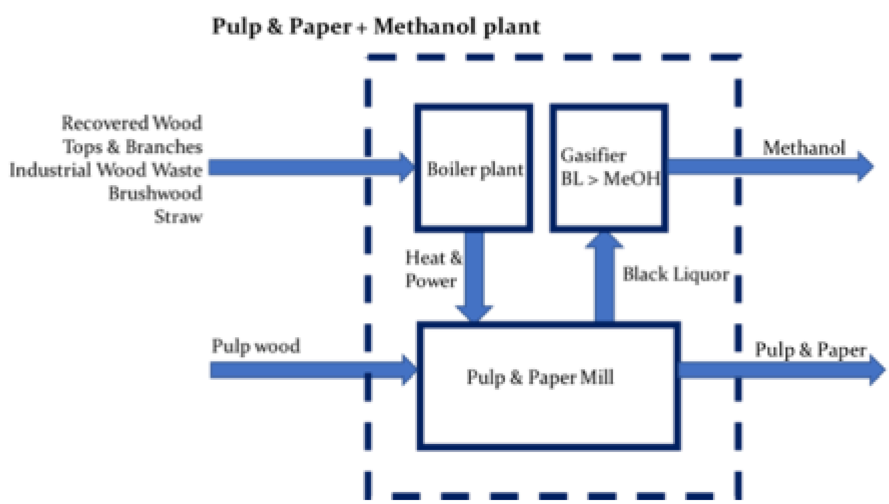


Figure 5-1: Production pathway methanol

❖ **Ethanol**

Table 3-4, evaluates the production costs of second-generation ethanol and it can be concluded that there are different results found on in the individual studies. From table 3-4, it can be concluded that the fermentation of wood waste and forest residues has a higher energy yield and lower production costs in comparison to the fermentation of straw and is therefore more favorable in terms of criteria (1) and (2) in comparison to the fermentation of straw. Joelsson et al., described a lignocellulosic residue conversion technology which is based on a Swedish case study[11] and the production costs of ethanol from wood waste and forest residues are therefore considered in the continuation of the report. The production costs of the process are 97 euro per MWh. Moreover, as shown in table 3-4, the considered biomass costs in the studies of Joelsson et al. and Franko et al., are 20 euro per MWh. From table 5-4, it can be concluded industrial wood waste, recovered wood, brushwood and tops & branches can become available for a lower cost lower than the 20 euro per MWh. However, from table 3-4 and 5-4, it can be concluded that recovered wood and industrial wood waste have the lowest biomass costs and the highest energy yield ratios. (1) (3) Therefore, industrial wood waste and recovered wood are selected as the most beneficial biomass feedstocks. Hence, the ethanol production pathway selected is the fermentation of industrial wood waste and recovered wood. As shown in table 3-4, the energy yield ratio of the fermentation of industrial wood waste is 34 percent. Due to the significantly larger potential of industrial wood waste in comparison to recovered wood, the 34 percent energy yield ratio is taken into consideration in the succeeding of this report. The production potential of ethanol from industrial wood waste and recovered wood is 10.2 TWh.

6 Scenarios for Projecting the Share of GEM cars in the Passenger Car Fleet

In this chapter, two scenarios are developed to project the share of GEM cars in the Swedish passenger car fleet in the time span of 2017 to 2030. In Scenario 1, it is considered that GEM cars obtain a high share and in Scenario 2 GEM cars obtain a low share. For both scenarios, three GEM fuel blends are selected to be analyzed in the continuation of this thesis: a high methanol GEM fuel blend, a GEM fuel blend with a medium content of both alcohols and a high ethanol GEM fuel blends. The Scenarios in combination with the GEM fuel blends serve to project the energy demand for GEM fuels and its components. Subsequently, the energy demand projections of methanol and ethanol are tested with the results of the biofuel potential assessment. Lastly, the biomass utilization in the scenarios is verified.

6.1 Scenario Development and Descriptions

If it is decided to introduce GEM fuel to the passenger car market, it is uncertain what the future share of GEM cars will be in the Swedish passenger car fleet. Therefore, two scenarios are developed for projecting the share of the GEM cars in the Swedish passenger car fleet, considering a time horizon from 2017 to 2030. For the purpose of this thesis, E85 flex-fuel vehicles that fuel the cars with GEM fuels are described as GEM cars. In an effort to construct Scenarios 1 and 2, a business as usual scenario projection of the Swedish passenger car fleet is evaluated. Based on the business as usual projection, the two GEM car Scenarios are developed. In both Scenarios, GEM cars take over the share of gasoline and E85 cars in the BAU projection of the Swedish Transportation Agency.

In Scenario 1, GEM cars obtain a high share in the Swedish passenger car fleet. As mentioned previously, in Scenario 1 it is considered that GEM cars take over 100 percent of the share of gasoline cars by 2030. In Scenario 2 a low share of GEM cars is obtained. In Scenario 2, 75 percent of the share of gasoline cars is taken over by GEM cars. Moreover, in both Scenarios it is considered that E85 flex-fuel vehicles are fuelled by GEM fuel blends. As mentioned previously, GEM fuels blends can be implemented in E85 flex-fuel vehicles without any modifications on the vehicle. Gasoline vehicles can be converted to E85 flex-fuel vehicles with minor adaptions[29]. Moreover, alcohol containing fuels have proven to be perfectly implementable alternative fuels for spark ignition engines. For these reasons, in the Scenarios, GEM cars take over the share of gasoline and E85 cars in the Swedish passenger car fleet. The business as usual projection of the Swedish passenger car fleet and the GEM car Scenarios are comprehensively described in the succeeding of this paragraph.

Since there are a variety of GEM fuel blends that can be utilized in E85 flex-fuel vehicles, three GEM fuel blends are selected and analysed in the Scenarios. The combination of the Scenarios and the selected GEM fuel blends serve to identify the economic, environmental and biomass utilization impacts of the implementation of a high methanol, a high ethanol and a medium methanol/ethanol GEM fuel blend. Since the varying contents of the alcohol fuels in GEM fuel blends, results in different environmental, economic and biomass utilization impacts. For policy makers, these impacts can be from varying importance. Therefore, the analysis on the GEM fuel blends, in combination with the Scenarios, provide insights on which of these GEM fuel blends is the most beneficial in terms of the individual impacts. Moreover, the GEM fuel blends are selected to derive which blend would be the most favorable GEM fuel blend and to verify whether one the biofuels is more favorable as part of the blend. Hence, based on the results of this study, policy makers can decide whether to direct policy support into the production of advanced ethanol and/or methanol.

6.1.1 Forecast Composition Passenger Car Fleet in Business as Usual

Forecasting the future share of passenger cars in a passenger car fleet is generally extremely difficult. Due to the fact it is influenced by various factors such as population growth, other alternative fuels, policies, public transport, oil price, efficiency of the engines etc. On behalf of the Swedish Transportation Agency, SWECO has developed a business as usual forecast of the Swedish passenger car fleet for the year of 2030. [16] The Swedish Transportation Agency itself studied the forecast till 2020. [63] Hence, the in this study considered business as usual projection of the Swedish passenger car, which is based on these both forecasts, is presented in figure 6-1. Note that the share of passenger car vehicles in the Swedish passenger car fleet in 2020 and 2030 is created by interpolation. In the business as usual projection, the share of E85 fuels is going to decrease from 5 percent in 2015 to 2 percent in 2013. Furthermore, it can be seen that the share of gasoline cars between 2010 and 2030 will decrease from 63 percent in 2015 to 20 percent in 2030. Although the share of diesel engine vehicles is projected to increase between 2015 and 2020, the share is projected decrease between 2020 and 2030 from 37 to 20 percent. The share of electric vehicles is forecasted to increase rapidly. By 2030, the share of plug-in hybrid, electric hybrid and EV is going to increase to 13, 37 and 6, respectively. Therefore, accounting for the majority of the Swedish vehicle fleet with a combined share of 56 percent.

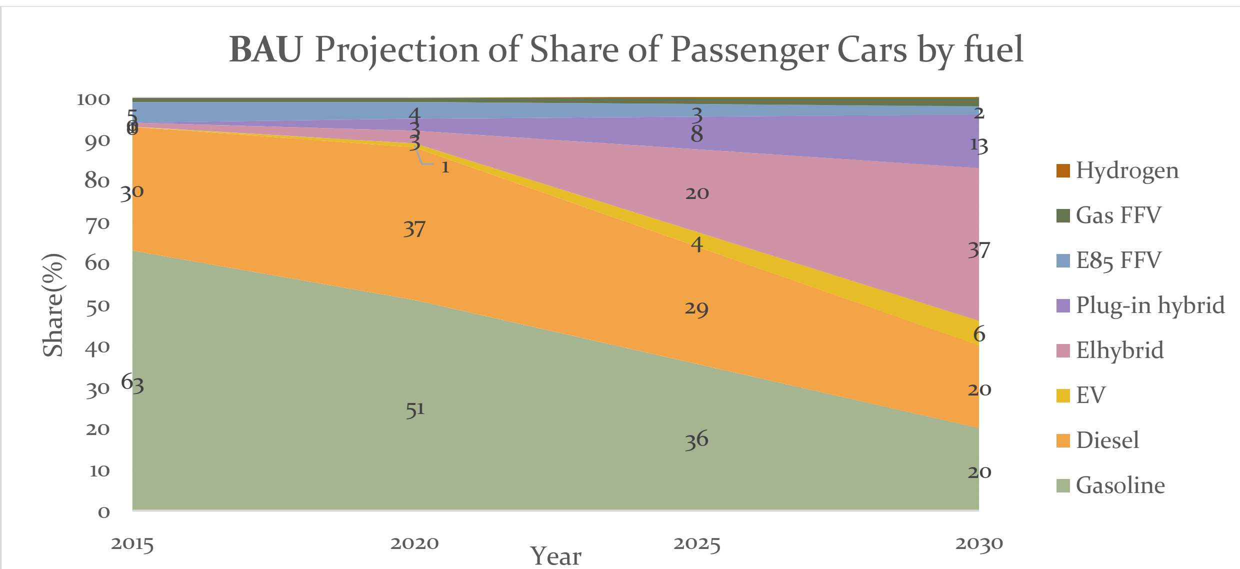


Figure 6-1: Swedish Vehicle Fleet, Business as usual forecast till 2030 [16, 63]

6.1.1 Development of the Scenarios

6.1.1.1 Scenario 1, a high share of GEM cars in the Swedish passenger car fleet

The projection of passenger cars in the Swedish passenger car fleet, in Scenario 1, is illustrated in figure 6-2. In Scenario 1, the Swedish governments prohibits gasoline cars on the road by 2030. It is considered that the GEM cars take over the entire share of the projected gasoline cars by 2030, as depicted in figure 6-1. Therefore, gasoline car owners are obliged to convert their vehicles to GEM fuel vehicles. It considered that instead of the new sales of gasoline cars, GEM cars are purchased. As depicted in figure 6-1, the share that GEM cars take-over of the projected share gasoline cars, in the business as usual projection, is 20 percent by 2030, together with the forecasted share of 2 percent of E85 cars, the resulting share of GEM cars becomes **22 percent** by 2030. Figure 6-4, shows the share of GEM cars in the Swedish passenger car fleet in Scenario 1 in comparison to Scenario 2.

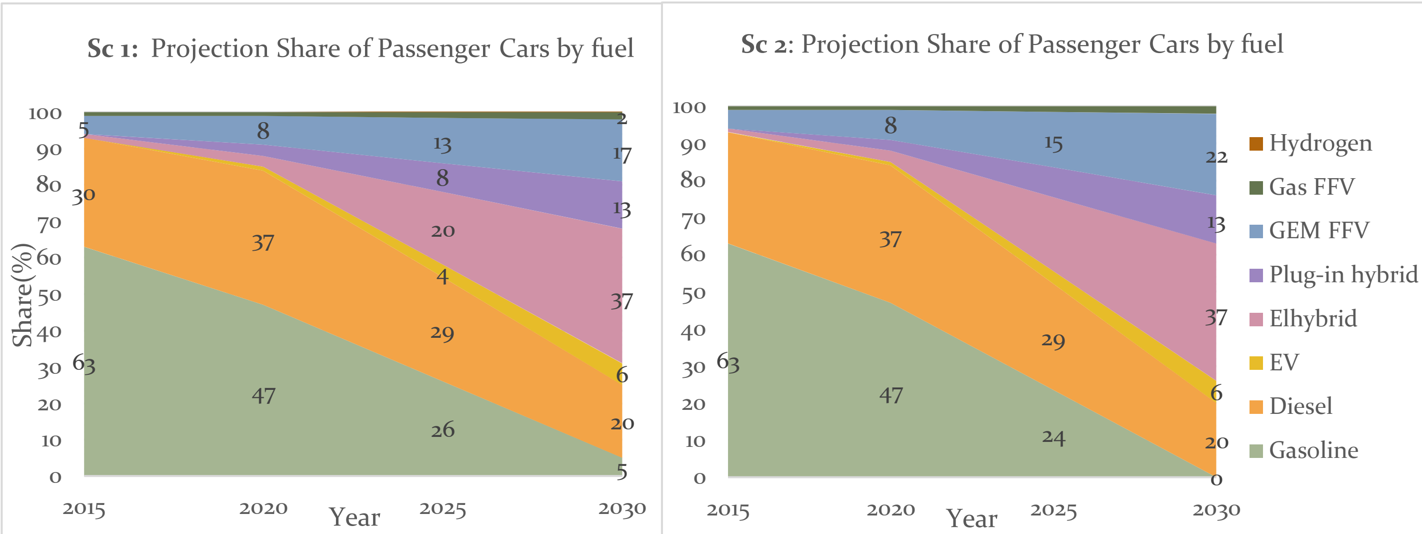


Figure 6-2 & 6-3: Share of Passenger Cars in the Swedish passenger car fleet in the GEM fuel scenarios

6.1.1.1 Scenario 2, a low share of GEM cars in the Swedish passenger car fleet

The projection of passenger cars in the Swedish passenger car fleet, in Scenario 2, is illustrated in figure 6-3. In Scenario 2, it is considered that the Swedish government does not prohibit gasoline cars on the Swedish roads, but that the government provides many political supports in the implementation of GEM cars. Due to the political support, it is assumed that 75 percent of the projected share of gasoline cars, in the business as usual projection, is taken over by GEM cars. This implies, that the average of (1) people purchasing a GEM fuel car instead of gasoline cars and (2) gasoline car owners that convert their gasoline cars to GEM fuel, is 75 percent. In the business as usual projection, the share of gasoline cars is 20 percent by the year of 2030. Since, it is considered that 75 percent of the share is taken over by GEM fuels, the share of GEM cars from gasoline cars is 15 percent. Together with the forecasted 2 percent of E85 cars by 2030, the share of GEM cars becomes **17 percent** by 2030. Figure 6-4, shows the share of GEM cars in Scenario 2 in comparison to Scenario 1.

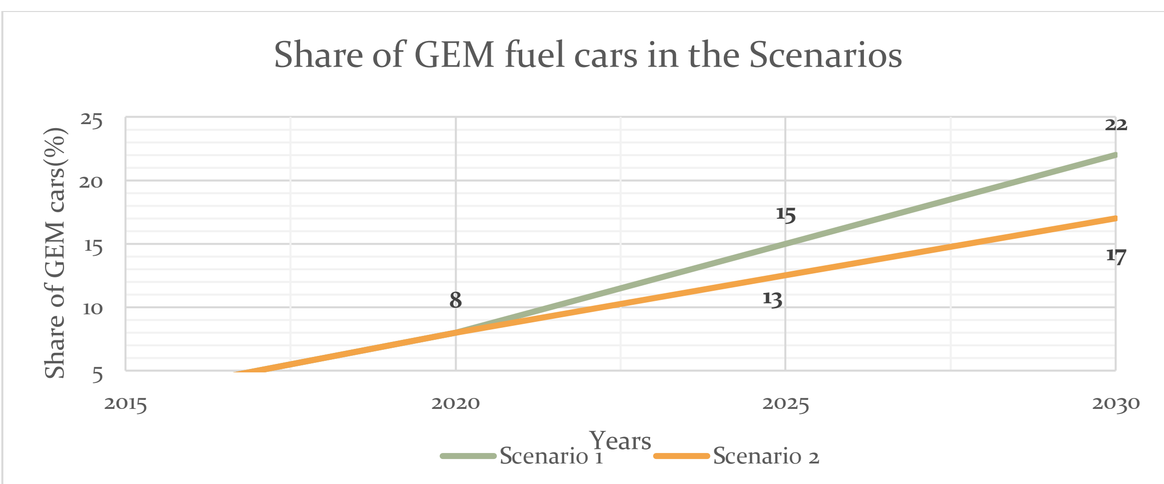


Figure 6-4: Share of GEM cars in both Scenario 1 and Scenario 2

6.2 GEM fuel blends selected and analyzed in the Scenarios

Figure 6-(5-7) show the selected GEM fuel blends in terms of volume fractions of the components: gasoline, ethanol and methanol. As mentioned previously, the following GEM fuel blends are chosen: **(Blend HM)** a high methanol containing blend, **(Blend ME)** a medium methanol and ethanol containing blend and a high ethanol containing blend **(Blend HE)**. Due to the differences in energy densities of the gasoline, ethanol and methanol in GEM fuel blends, the composition of the GEM fuels in terms of volume and energy differ. Figure 6-(8-10) show the selected GEM fuel blends in terms of energy composition. Details regarding the derivation of the energy composition of the blends are illustrated in Appendix 12.8.

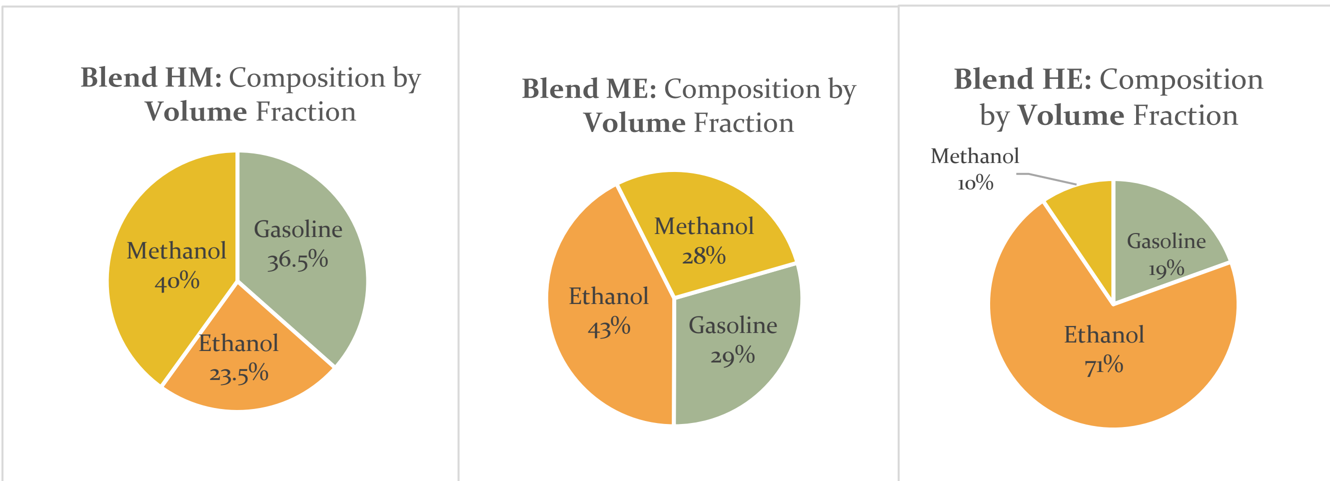


Figure 6-(5-7): The selected GEM fuel blends by volume fractions

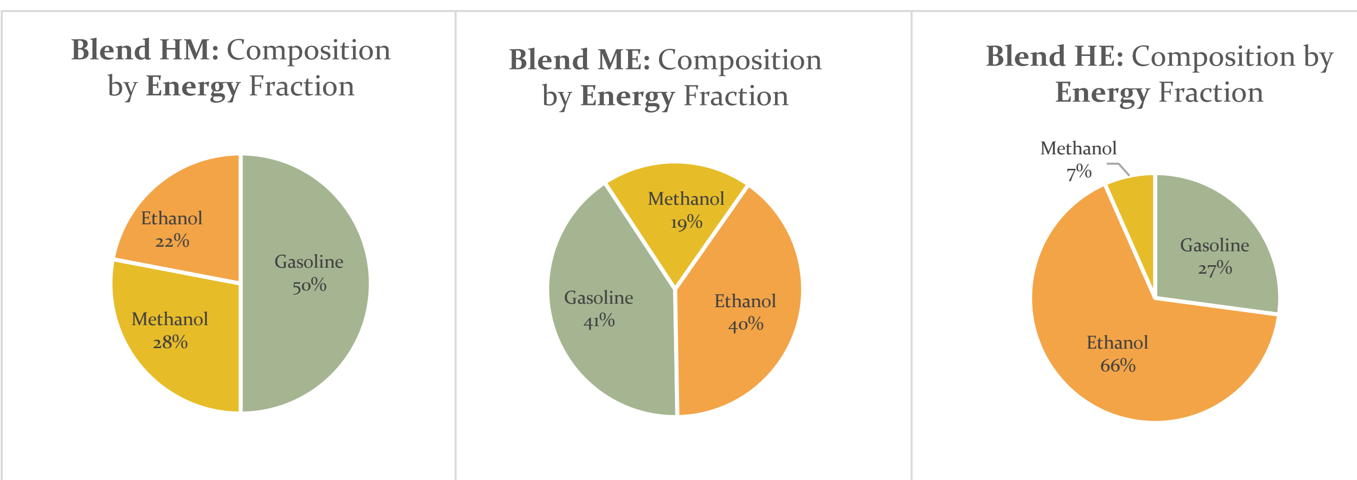


Figure 6-(8-10): The selected GEM fuel blends by energy fractions

A summary of the properties of the selected GEM fuel blends are shown in table 6-1. An important factor for selecting the GEM fuel blends are the Reid Vapour Pressures of individual blends. As mentioned in paragraph 2.2.2., the maximum RVP allowed for transportation fuel in Sweden is 70 kPa. Therefore, a maximum methanol content of 40 percent by volume in GEM fuels is allowed in Sweden. This is because GEM fuels with a methanol content higher than 40 percent, have higher RVP's than 70 kPa, as illustrated in figure 2-11. Moreover, Sweden is a country with a cold climate and GEM fuel blends with a methanol content of more than 51 percent tend to separate during cold temperatures and are therefore not suitable in Sweden during the winter months, as shown in figure 2-12. For simplicity, the same blend composition is chosen during winter and summer time in this thesis. Therefore, the maximum methanol content in the GEM fuel for this scenario is 40 percent. The volumetric energy densities of the GEM fuel blend, depicted in table 6-1, are derived in Appendix 12.1.

Table 6-1: Summary of the properties of the selected GEM fuel blends

GEM fuel blend	RVP [kPa]	LHV [MJ/l]	Volume Fractions [%]			Energy Fractions [%]		
			Gasoline	Ethanol	Methanol	Gasoline	Ethanol	Methanol
Blend (HM)	70	22.74	36.5	23.5	40	50	22	28
Blend (ME)	61	22.70	29	43	28	41	40	19
Blend (HE)	45	22.64	19.5	71	9.5	27	66	7

6.3 Projections Energy Demand of GEM fuel and its Components

With the projected shares of GEM cars in the Swedish passenger car fleet in both Scenarios, energy demands for GEM fuel blends are created. In this paragraph, the created energy demand is evaluated. The projections of the energy demand for GEM fuel blends, in both Scenarios, are shown in figure 6-11. By 2030, the annual energy demand for GEM fuels in Scenario 1 is 29 percent higher than the energy demand for GEM fuels in Scenario 2. The annual energy demand by 2030, in Scenario 1 is 9.7 TWh and in Scenario 2 it is 7.5 TWh. The total energy demands for GEM fuels, during the time horizon of the Scenarios, is 73.2 in Scenario 1 and 62.2 TWh in Scenario 2.

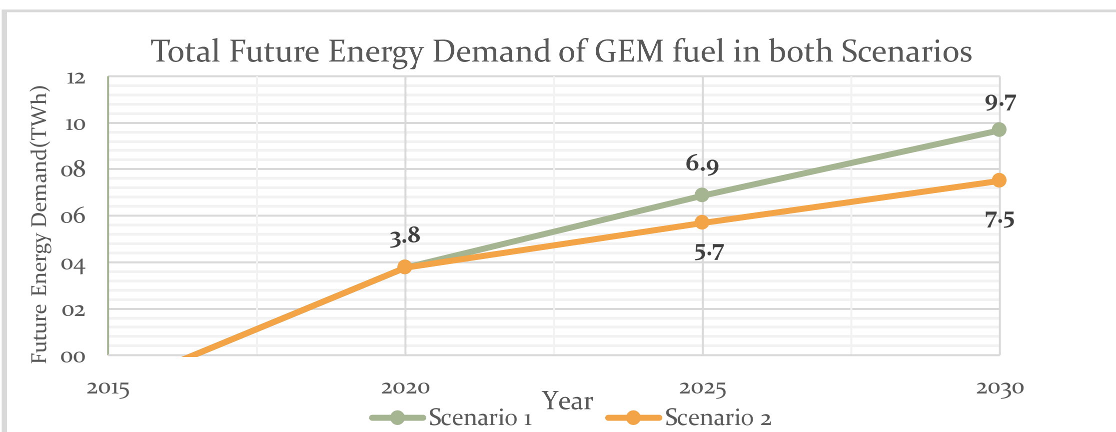
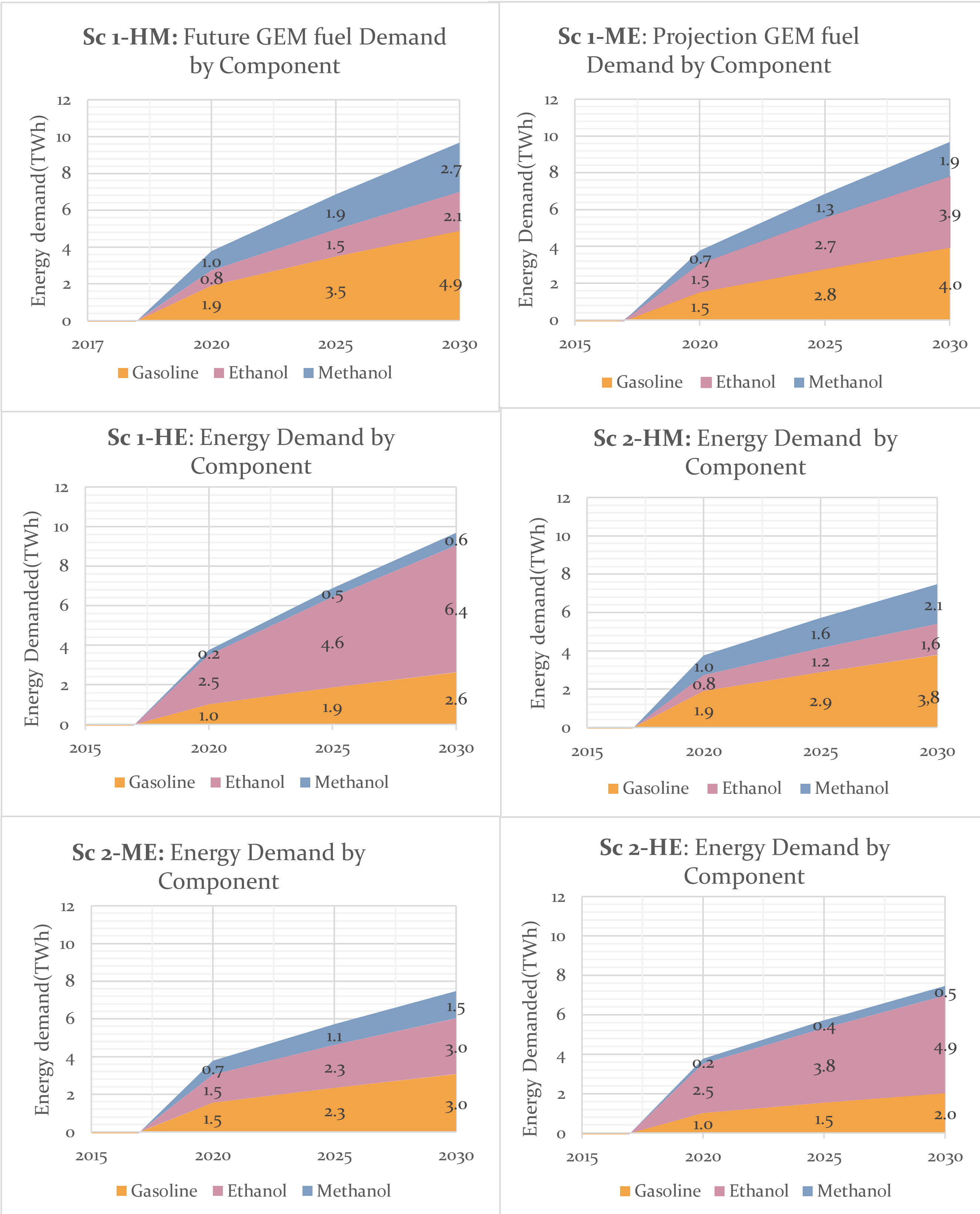


Figure 6-11: Projection GEM fuels Energy Demands

Figures 6-(12-17) present the energy demand projections per component in the Scenarios when the different GEM fuel blends are implemented. Due to the different energy fractions of the components in the blends, the energy demands projections of the components within the scenarios differ. It is important to note that the largest energy demand for the biofuels is created in Scenario 1-HE with 7.0 TWh annually by 2030. Moreover, this study finds that the smallest energy demand of biofuels is created in the Scenario 2-HM, with 3.7 TWh annually by 2030. The largest energy demand for gasoline is created in Scenario 1-HM, with 4.9 TWh, by 2030. The largest annual demand for ethanol is created in Scenario 1-HE with 6.4 TWh and for methanol in Scenario 1-HM with 2.7 TWh.



Figures 6-(12-17): Energy Demand Projection per component in the Scenarios for the different GEM fuel blends

Figure 6-18, represents the individual biofuel demand by 2030 in the scenarios with the different GEM fuel blends. This study indicates that by comparing figure 6-18 and table 5-1, the energy demand of both methanol and ethanol can be met from Swedish secondary biomass feedstocks. This implies, that the potential share of GEM cars in the Swedish passenger car fleet is higher than 22 percent in term of theoretical production potential of second-generation ethanol and methanol.

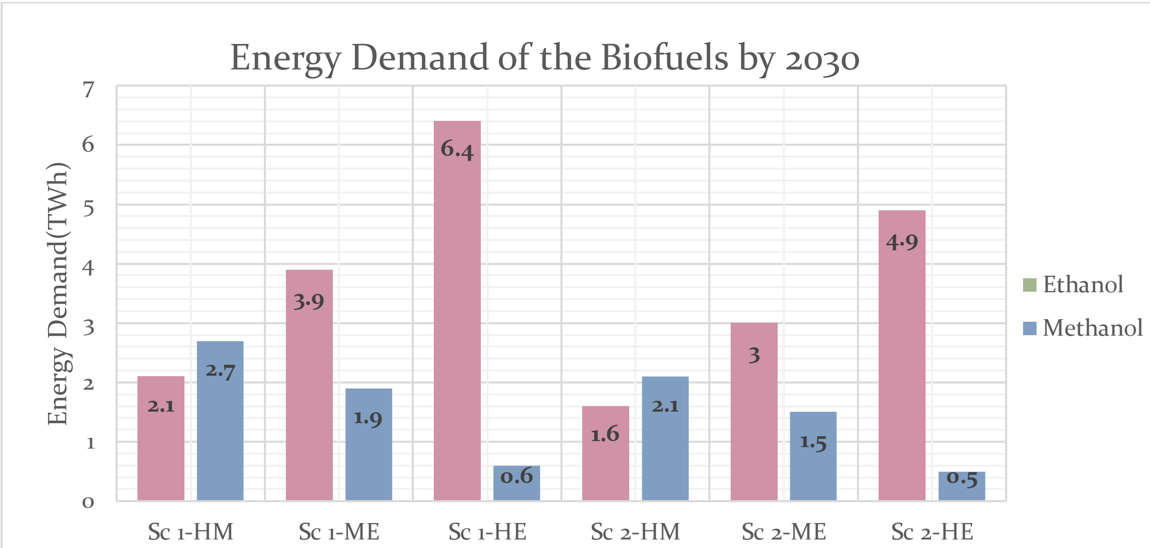


Figure 6-18: Methanol and Ethanol Energy Demand by 2030 in the Scenarios

6.4 Biomass Utilization in the Scenarios

The biomass utilization in the Scenarios by 2030, in combination with the GEM fuel blends, is depicted in figure 6-19. The energy flow diagrams by 2030, corresponding to figures 6-(12-17), are depicted in Appendix 12.11. This study finds that the biomass utilization is the highest in the Scenarios in which blend HE is implemented. The highest biomass utilization is in Scenario 1-HE. Moreover, figure 6-18 indicates that the lowest biomass utilization is in scenarios where blend HM is implemented. Scenario 2-HM utilizes the lowest amount of biomass of all the scenarios.

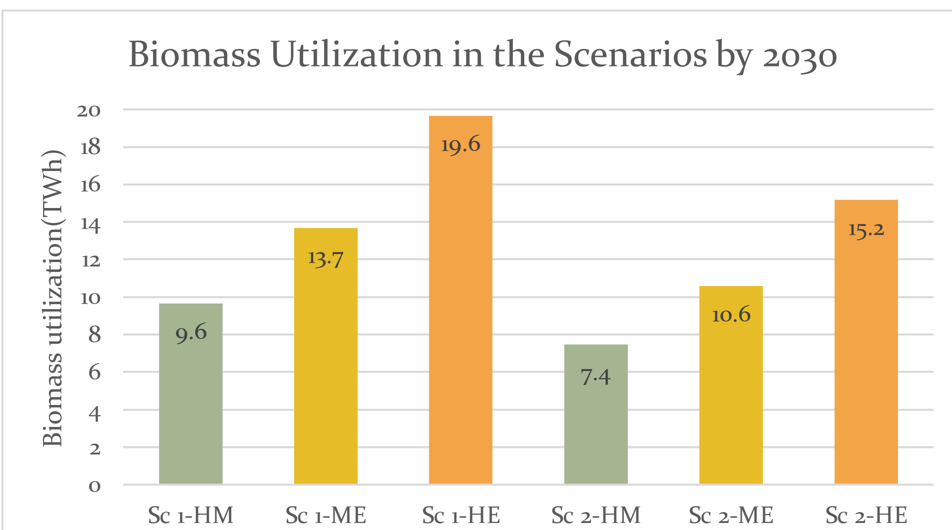


Figure 6-19: Biomass utilization in the Scenarios by 2030

Table 6-2 presents the biomass utilization per individual alcohol fuel in the GEM fuel blend, in the different scenarios by 2030. From table 6-2, it can be concluded that generally demand for ethanol requires more biomass utilization in comparison to methanol.

Table 6-2: Biomass Utilization in the Scenarios per biofuel by 2030

Scenarios	**Biomass Utilization[TWh]**		
	Ethanol	Methanol	**Total**
Scenario 1			
Blend HM	6.2	3.4	**9.6**
Blend ME	11.3	2.4	**13.7**
Blend HE	18.8	0.8	**19.6**
Scenario 2			
Blend HM	4.8	2.7	**7.4**
Blend ME	8.7	1.9	**10.6**
Blend HE	14.5	0.6	**15.2**

7 A Swedish GEM fuel Distribution Network

In this chapter, a Swedish GEM fuel distribution network is analyzed. It is investigated if parts of the existing fuel distribution network of gasoline and E85, at the current state, can be implemented in a GEM fuel distribution network and if not, how the equipment can be converted to equipment that is capable of distributing GEM fuel blends. If both is not possible, the new-establishment of equipment is verified. Moreover, it is analyzed if the capacity of the existing distribution network is sufficient to supply energy demand in the different scenarios.

7.1 GEM fuel Distribution Network Analysis

In order to create a demand for GEM fuel as an alternative fuel, it is a key priority that the fuel can be supplied to vehicle owners. In order to do so, a Swedish distribution network for GEM fuels is required, spanning from upstream to downstream activities, which enables the supply of the GEM fuel blends. When a distribution network of a new fuel needs to be newly-established, major investments are required, which leads inherently to an increase in the distribution costs in comparison to fuels of which there is already an existing distribution network in place. Therefore, in this part of the research, it is analyzed if the existing distribution network of E85 and gasoline can be used for distributing GEM fuel blends. The findings of the analysis are presented this chapter.

The GEM fuel distribution network considered in this study, is illustrated in figure 7-1. The distribution network constitutes of the activities: transport, storage, blending and retailing of GEM fuels or its components. For every individual activity, it is analyzed if the existing equipment in the gasoline and E85 distribution network is capable of distributing GEM fuel blends and if not, how the parts can be converted to equipment that is capable of distributing GEM fuel blends.

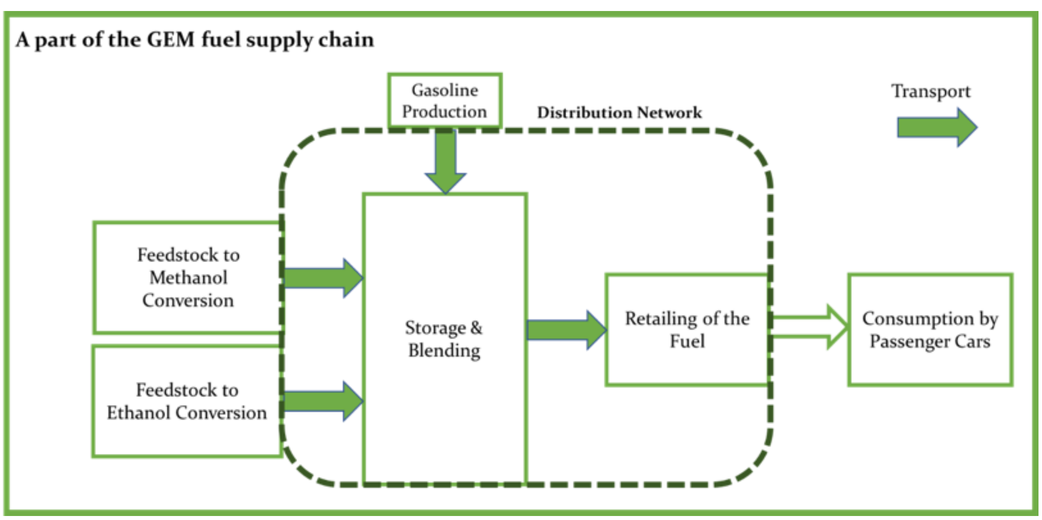


Figure 7-1: Distribution Network GEM fuels

As shown in figure 2-6, in 2015, 3.5 million cubic meters of gasoline was distributed and consumed in the road transportation sector in Sweden.[25] According to SPT, this was mainly consumed in the passenger cars fleet. As mentioned previously, multiple studies forecast the consumption of fossil fuels to decrease with values of 40 to 70 percent, between 2015 and 2030. [15, 16] This implies that the consumption of gasoline is forecasted to decrease with a value of that lays between 2.4 and 1.4 million cubic meters in the same period of time. Therefore, if there will not be another purpose of the gasoline distribution network, a significant over-capacity is going to appear. In addition, it is important to note that there is at present an over-capacity in the E85 distribution network and in particular E85 pumps at retail stations.

In Scenario 1 and 2, the projected annual GEM fuel energy demand 9.7 and 7.5 TWh, respectively, by 2030. The corresponding amounts of GEM fuels that will be demanded and therefore need to be distributed, are 1.53 and 1.18 million cubic meters for Scenario 1 and Scenario 2, respectively. As mentioned previously, in Scenario 1 the entire gasoline consumption of passenger cars is taken over by GEM fuels and in Scenario 2, 75 percent is taken over. The implementation of GEM fuels instead of gasoline, will decrease the gasoline consumption further in comparison to the previously mentioned forecasts on the oil consumption in Sweden. This implies, that if GEM fuel can be distributed in the existing fuel distribution network of gasoline and E85, the current capacity of the distribution network for E85 and gasoline is sufficient to handle the distribution of the forecasted energy demands of GEM fuels.

In the continuation of this paragraph, it is per activity in the distribution network of GEM fuels investigated whether the activities in existing distribution network of gasoline and E85, can be implemented in a GEM fuel distribution network and if not, how the activities can be converted to equipment capable of distributing GEM fuels.

7.1.1 Transportation of GEM Fuel Blends

The transport of the GEM fuel and its components is done similarly as gasoline and E85.[29] This implies, that the current equipment utilized in the different means of transportation in the distribution of gasoline and E85, can be utilized for distributing GEM fuels and its components. GEM fuels and its components can therefore be successfully distributed by truck, train, barge and pipe. The transport mode is dependent on the distance that has to be covered and the amount to be transported. For short distance transport, it is more likely make use of tanker trucks. For longer distances and large amounts in is more convenient to make use of water or rail transport. According to SPT, the only difference between gasoline and GEM fuel is that for water transport, GEM fuel must be transported by chemical tankers, while gasoline is transported by product tankers. The transport of fuels by chemical tankers is regularly done and does therefore not require major investments.

Moreover, in this study, the biofuel production plants are located within the interior of Sweden. Therefore, both alcohols are transported from the biofuel production plant to the storage terminal and after the three components in GEM fuel are blended, the fuels are transported from the storage terminal to the retail station. The transport of the fuels will most likely rely on truck transport, due to the fact that truck transport is generally the most cost-effective type of transport when distances are less than 500 kilometers.[64]

7.1.2 Storage of GEM Fuel Blends

In order to gain a deeper understanding of the storage of GEM fuel components, the company Inter Terminals, the largest independent storage terminal provider, was interviewed. According to Inter Terminals, the current Swedish storage gasoline capacity is feasible for the use of methanol and ethanol. Moreover, the components can be stored above and underground, just like gasoline. Implying, that storage tanks at Swedish terminals are built from the alcohol compatible materials listed in Appendix 12.3 and that the tanks are constructed in a closed system so that water is prevented from entering the tanks. However, due to different characteristics of the alcohols and gasoline, more dry-maintenance is required when storing the alcohols. The European Union considers ethanol and methanol as explosive atmosphere chemicals and are therefore be handled according to the ATEX directive.[65] The ATEX directive is a European Directive containing safety requirements for hazardous areas. The extra handling and maintenance of the alcohols results in incremental storage costs of GEM fuels in comparison to gasoline.

7.1.3 A GEM fuel Blending System

Based on the interviews held with professionals in the industry, it can be concluded that GEM fuel blending systems need to be newly-established. There are multiple technologies available to blend alcohol fuels with gasoline, which are described into detail in Appendix 12.1. In this report, an important criterion for selecting a blending technology is the flexibility of a blending machine in terms of producing different GEM fuel blends. Based on the advice of the company Globecore GmbH(leading supplier of fuel blending technologies) and the interviews held with professionals in the industry, in-line blending systems are selected as the most suitable technologies to blend GEM fuel blends. A schematic overview of a GEM fuel in-line blending system is depicted in figure 7-2.

The in-line blending system constitutes of a hydrodynamic mixing unit, in which the components are dispensed in a controlled manner so that the required composition is guaranteed. The recommended blending system is capable of supplying different composition of the GEM Fuels. More technical details of the blending machines are shown in the Appendix 12.2. The blending system must be located at a storage terminal and connected to three separate tanks which are filled with the GEM fuel components. The blended GEM fuel can either directly be pumped into a tanker truck or a storage tank. Subsequently, the GEM fuels are transported to the retail stations. The blending machines would be implemented in or near the larger storage terminals, so that large quantities can be blended and possibly be stored before transported.

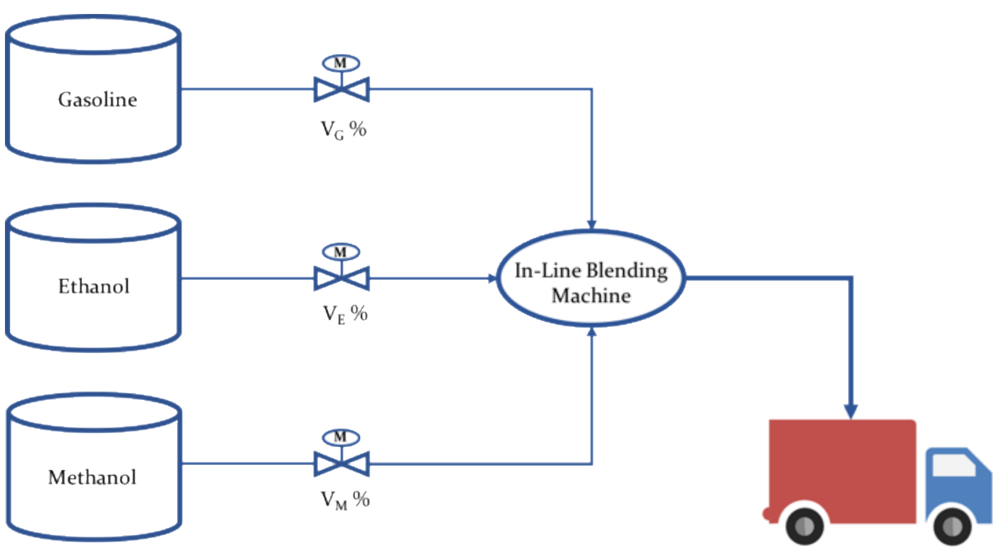


Figure 7-2: Schematic Overview of GEM fuel in-line blending system at distribution terminal

7.1.4 Retailing of GEM Fuel Blends

As mentioned previously, around two thirds of the Swedish retail stations supply at their pumps at present. The large amount of highly developed E85 pumps are spread around the whole country, as depicted in figure 2-9. The E85 pumps are constructed of materials that are compatible with high alcohol blends. According to SPT, The E85 pumps with minor changes be implemented as GEM fuel pumps. The GEM fuel blends can cause problems to the gaskets used in the E85 dispensing pumps. This implies that the gaskets, a small ring in the pump, are not made of one of the methanol compatible materials depicted in Appendix 12.3. Gaskets are small mechanical seals located in the pumps. The replacements of the gaskets are therefore considered as minor adaptions.

At present, Sweden has 1749 E85 pumps. [25] The average volume of the storage tank is 10 cubic meters and is refilled 1 to 3 times a year, depending on the local demand per retail station. In 2016, the amount of E85 supplied by the E85 pump was 0.34 TWh.[13] However, the capacity of the pumps in Sweden is higher than the current amount of E85 consumed. Simply by filling up the storage tanks more often, the capacity enhances significantly. According to SPT, the total capacity of the E85 pumps at present in Sweden, is sufficient to supply the current annual gasoline demand of 29 TWh. Hence, the capacity exceeds the capacity needed to supply the projected energy demand of GEM fuel from both scenarios. Table 7-1 presents the results on how many times on average the E85/GEM pump should be refilled in the different scenarios by 2030. As shown in table 7-1, in Scenario 1, the pumps need to be refilled around 7 times a month. In Scenario 2, the pumps need to be refilled around 6 times per month.

Table 7-1: Estimation times refill of fueling pumps

Scenario	E85 Pumps Refill by 2030 (times per month)
Scenario 1	7
Scenario 2	6

8 Economic Competitiveness and Environmental Impact Analysis

In the first part of this chapter, the economic competitiveness of the selected GEM fuel blends, in the scenarios, is investigated. In the second part of this chapter, the environmental impact, resulted from the implementation of the selected GEM fuel blends both scenarios, is investigated. The environmental impact is based on the GHG emissions avoided.

8.1 Economic Competitiveness Analysis of GEM fuel

An important aspect for an alternative fuel to become a successful fuel, is that demand for the fuel should be created. The demand for a fuel is highly dependent on the economic competitiveness of the fuel in comparison to alternative of the fuel. This part of the study presents the results on the economic competitiveness analysis of the GEM fuel blends in comparison to alternatives for GEM fuel blends, namely gasoline and E85. As mentioned in chapter 4, first, the pump prices of the individual components of GEM fuels are estimated. Secondly, the pump prices of the GEM fuel blends are verified. Subsequently, the limit curve of GEM fuels is developed. Lastly, the estimated pump prices of the GEM fuel blends are compared with the GEM limit curve in order to investigate the economic competitiveness of the GEM fuel blends. Lastly, a sensitivity analysis is performed on the effects of variation of the production costs of methanol and ethanol on the pump prices of the GEM fuel blends.

8.1.1 Estimation of the Pump Prices of the Individual GEM fuel Components

In order estimate the pump prices of the individual components of GEM fuel blends, all the input economic parameters need to be familiar. As mentioned in chapter 4, the economic parameters considered in this thesis for the pump price estimation are the costs related to the production, distribution, blending and retailing of the fuels. Regarding the pump price of gasoline, the carbon dioxide and the energy tax are as well considered as economic parameters.

The production costs of both ethanol and methanol are found in chapter 5, which are 97 and 77 euro per MWh, respectively. The cost related to the retailing of the GEM fuel are estimated in chapter 4 and are considered to be 1.7 euro per MWh. The cost of distribution and blending of the GEM fuel blends are assessed in the continuation of this paragraph. Once the costs of distribution and blend are estimated, the pump prices of the individual components are assessed.

⇒ *Estimation Distribution Costs of GEM fuel Blends*

In this paragraph, it is aimed to make an estimation of the distribution costs of GEM fuel in Sweden. The estimation of the distribution costs of GEM fuel blends is based on the findings of chapter 7 and the current distribution of gasoline and E85 in Sweden. From the previous chapter, it can be concluded that the majority of the current distribution for gasoline and E85 can be implemented for distributing GEM fuel and its components, including the storage terminals, the tanker trucks, the barges & the retail fueling pump (minor adaptions). Nevertheless, in-line blending systems need to be newly-established in order to blend the GEM fuel components into GEM fuel blends at the distribution terminals. According to Scandinavian Petroleum Technic Association, the distribution costs for E85 and gasoline are 10 and 15 euro per cubic meter, respectively.

As mentioned in chapter 2, the implementation of methanol in the GEM fuel results in strong hygroscopic fluid in comparison to E85 and gasoline. Denoting, that it is profoundly important to prevent dirt and water from coming in contact with the GEM fuel blends along the entire distribution network, since the GEM fuel blends readily take up the dirt and water which leads to phase separation. Therefore, extra handling costs regarding dry-maintenance are necessary when distributing GEM fuel in comparison to E85 and especially gasoline. Moreover, as shown in paragraph 2.4.3, in comparison to gasoline, 33 percent more of GEM fuel is consumed by cars, in terms of volume, in order to achieve the same vehicle performances. Therefore, 33 percent more of GEM fuel blends need to be distributed in comparison to gasoline. Regarding gasoline distribution, at present, most of the gasoline is after refining directly stored at a refinery storage terminal and from there transported to the retail stations or transported in large quantities from the refinery to the storage terminals by water transport.

For these reasons, this study considers the distribution costs of GEM fuel to be 20 euro per cubic meter, corresponding with **3.2 euro per MWh**. The value is 25 percent higher than the distribution of E85 and 100 percent higher than the distribution of gasoline.

⇒ *Estimation Blending Costs of the GEM fuel blends*

Table 8-1, represents the results on the estimation of the blending cost of GEM fuel blends. It can be concluded from the results presented in table 8-1, that the blending costs are extremely low. This is due to the fact that one unit has the capacity to blend up to 5.5 TWh annually, resulting in a total cost for blending of GEM fuel less than 1 cents per MWh. By the year of 2020, two blending units are required to blend the demanded GEM fuel and by 2025 three blending machines would be needed.

Table 8-1: Total cost calculation of the blending process of GEM fuel

Cost Parameter	**(€ MWh^{-1})**
Investment	0.002
Maintenance	0.000
Operation	0.002
Total Blending Costs	**0.005**

⇒ *Assessing the Pump Prices of the Components of GEM fuels*

Table 8-2 presents the determination of the pre-VAT pump prices of the individual of the GEM fuel blends. It can be concluded that methanol has the lowest pump price with 81.9 euro per MWh, followed by ethanol with 101.9 euro per MWh. Gasoline has the highest pump price with 141.1 euro per MWh.

Table 8-2: Pre-VAT pump price determination GEM components

Economic Parameter(€ MWh^{-1})	**Methanol**	**Ethanol**	**Gasoline**
Production Cost	77.0	97.0	63.0
Distribution Cost	3.2	3.2	3.2
Blending Cost	0.01	0.01	0.01
Retailers Cost & Profit	1.7	1.7	1.7
Energy tax	↓	↓	43.9
Carbon dioxide tax	↓	↓	29.3
Pre-VAT Price	81.9	101.9	141.1

8.1.2 Analyzing the Pump Prices of the GEM fuel blends

Table 8-3 presents the results on the identification of the pump prices of the selected GEM fuel blends. In table 8-3, the Pre-VAT pump prices are shown together with the final pump prices. In Sweden, the VAT tax is 25 percent[23]. Hence, 25 percent VAT tax is added to the Pre-VAT pump price in order to estimate the final pump price of the GEM fuel blends. This study indicates that the higher the ethanol content in the blend, the lower the final pump price of the blend. The higher pump price of GEM fuel blends with higher methanol contents is a result of the higher gasoline content in the blends.

Table 8-3: Results on GEM fuel pump price

Economic Parameter	Blend HM	Blend ME	Blend HE
Pre-VAT pump price(€ MWh^{-1})	116.2	114.1	111.0
Final pump price(€ MWh^{-1})	145.2	142.6	138.8

8.1.3 Assessing the Economic Competitiveness of the Selected GEM fuel blends

Figure 8-1, illustrates the estimated pump prices of the selected GEM fuel blends in comparison to historical pump prices of gasoline and E85 between 2007 and 2017. Figure 8-1, indicates that for the last seven years, the pump prices for both gasoline and E85 has been higher than the estimated pump prices of the GEM fuel blends.

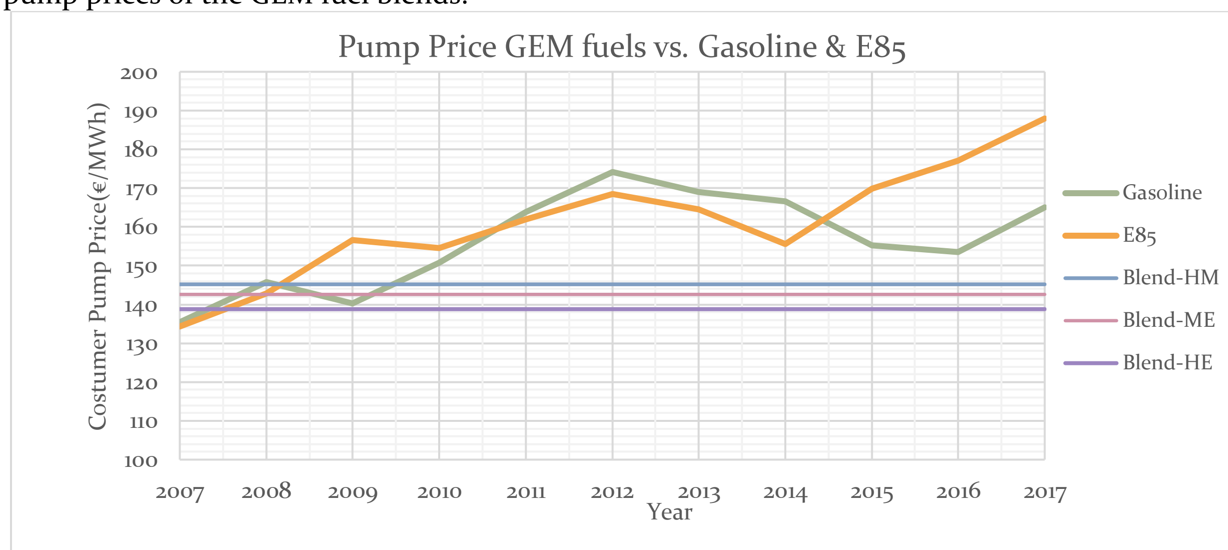


Figure 8-1: Price Development gasoline and E85 and the price of the GEM fuel scenarios

Figure 8-2, presents the results on the economic competitiveness analysis of the selected GEM fuel blends. The corresponding pump prices, in terms of price per unit of volume, are 0.92, 0.90 and 0.87 for Blend HM, Blend ME and Blend HE, respectively. The developed GEM fuel limit curve is presented together with the estimated pump prices of the GEM fuel blends. As mentioned in chapter 4, the GEM fuel blends pay-off if the pump prices are lower than the GEM limit curve. Figure 8-2 shows that the pump prices of the all GEM fuel blends are lower than the GEM fuel limit curve for the last 8 years. Regarding Blend HM, figure 8-2 indicates that the pump price of blend HE is lower than the GEM limit curve between 2017 and 2017. Hence, according to this study, it is concluded be that GEM fuel blends are economic competitive with the alternatives gasoline and E85.

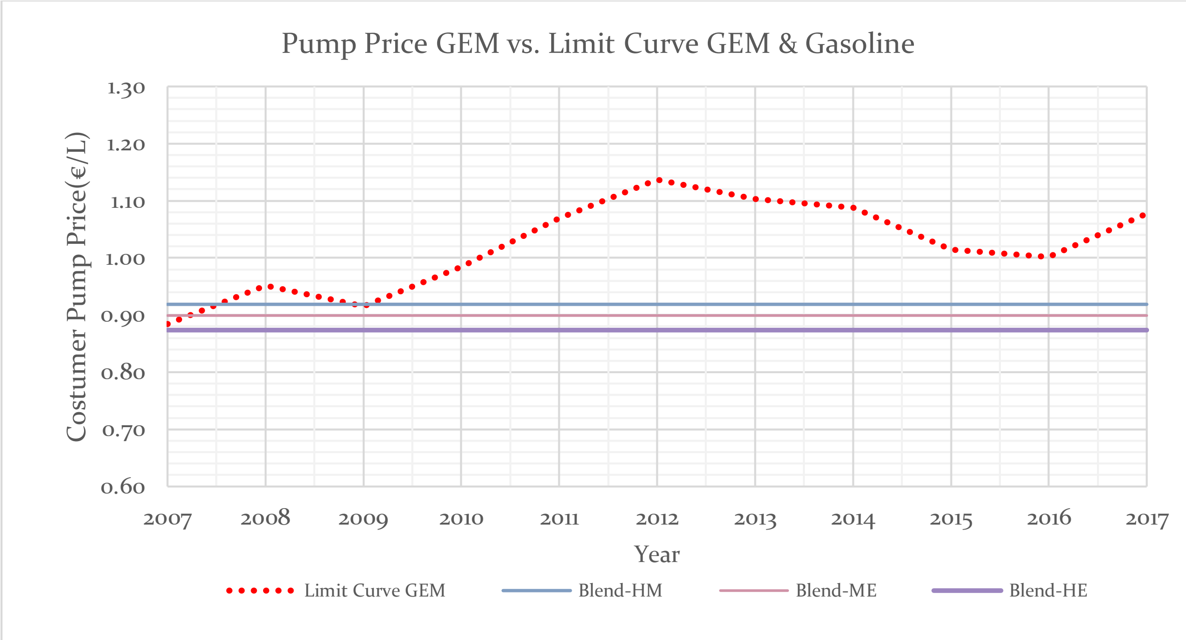


Figure 8-2: Costumer Prices of the selected GEM fuel blends vs the limit curve GEM

8.1.4 Sensitivity Analysis

In this paragraph, a sensitivity analysis has been performed in order to evaluate the effects of variations in the production costs of methanol and ethanol on the pump prices of the GEM fuel blends. Figure 8-3 and 8-4 show the effects of the variations on the pump prices of GEM fuel blends. It can be indicated that the pump prices of GEM fuel blends are profoundly dependent on the production costs of methanol and ethanol. In figure 8-3, the production costs of methanol are varied with -20 and 20 percent.

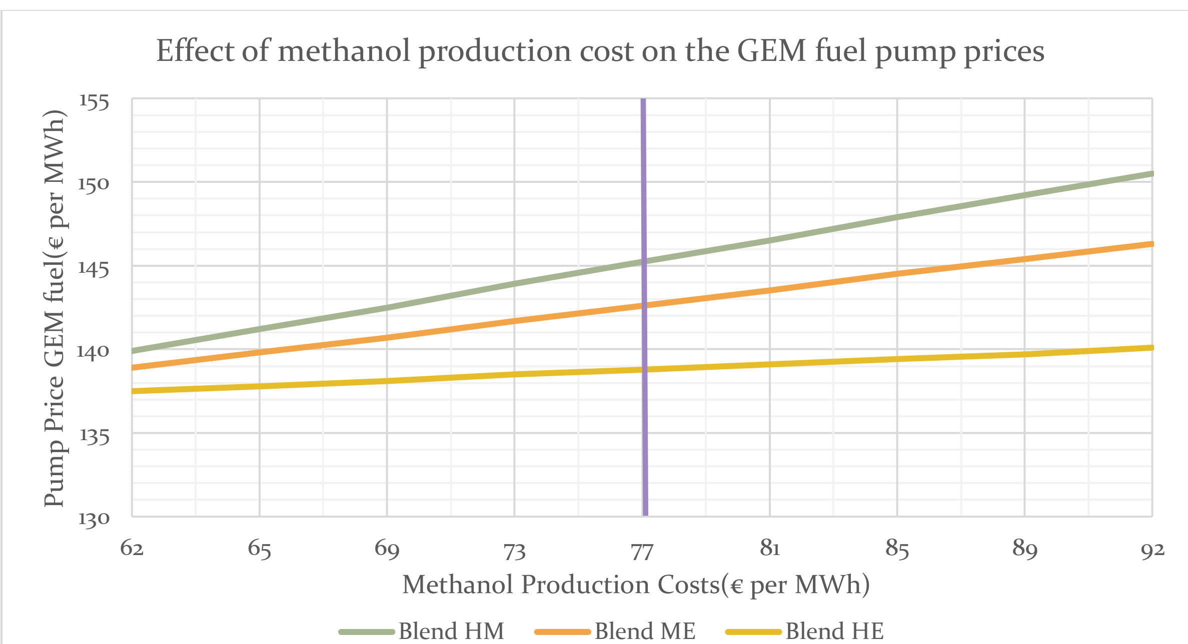


Figure 8-3: Sensitivity analysis on the effect of variation of the methanol production cost on the GEM fuel pump prices

In chapter 3, the evaluation on the production costs of second-generation ethanol shows that different production costs of ethanol are found among the different studies. Therefore, the effects of a variation of -30 and 30 percent on the ethanol production costs on the pump prices is shown in figure 8-4.

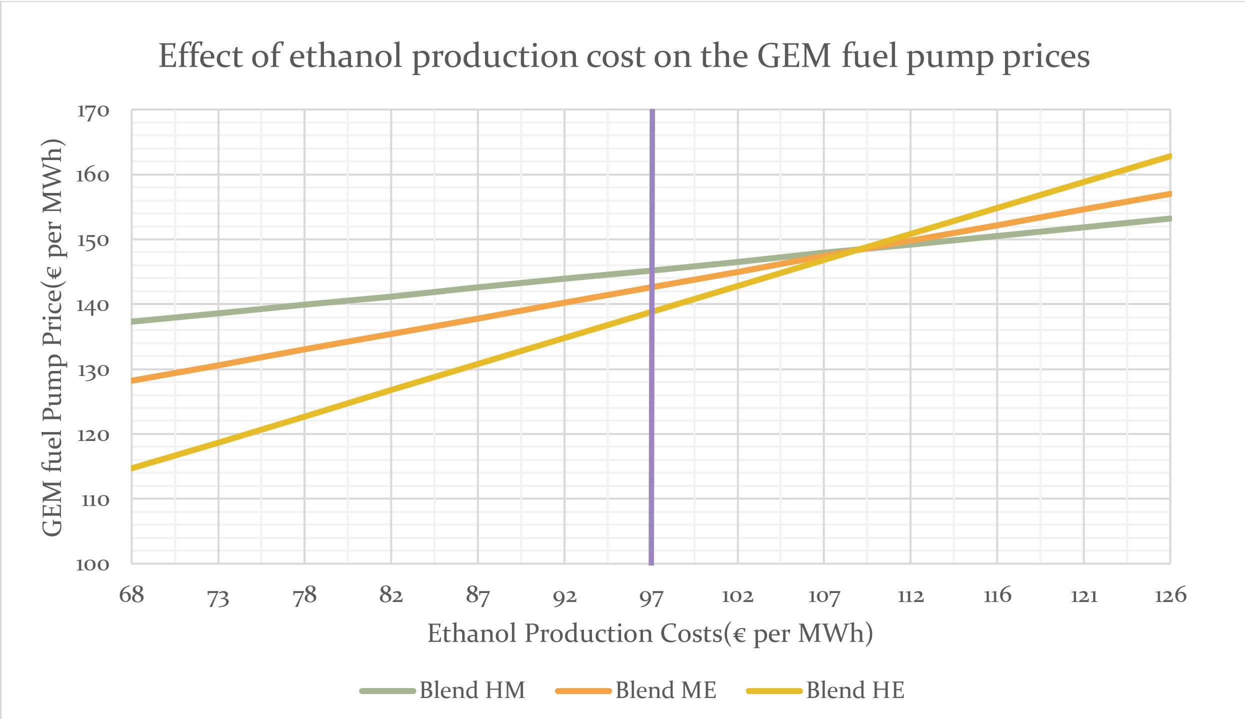


Figure 8-4: Sensitivity analysis for the effects of variations of the ethanol production cost on the GEM fuel pump prices

8.2 Environmental Impact Analysis

This paragraph presents the results on the environmental impacts resulted from implementation of the selected GEM fuel blends in Scenario 1 and 2. In this study, the environmental impact is based on the GHG emissions. As mentioned previously, the well-to-wheel methodology is considered in this study in order to estimate the GHG emissions avoided. The well-to-wheel methodology considers GHG emissions from the production, transportation, distribution and combustion of transportation fuels. In order to perform the calculations on the total amount of GHG emissions avoided, the total energy replaced by GEM fuels in the scenarios needed to be found. The total energy replaced by GEM fuels in the individual Scenarios are illustrated in table 8-4.

Table 8-4: Input parameters for the estimation of GHG emissions avoided

Parameter	Amount	Unit
Scenario 1, $E_{tot,}$	73.2	TWh
Scenario 2, $E_{tot,}$	62.2	TWh

In order to estimate total GHG emissions avoided, over the time span of the scenarios, the GHG emissions savings factors of the blends are verified. Table 8-5, presents the results on the GHG emissions savings factors of the selected GEM fuel blends. It can be concluded that the higher the ethanol content in the GEM fuel blends, the higher the GHG savings when consuming the GEM fuel blend.

Table 8-5: Results on GHG savings factor for both scenarios

Factor	Unit	Blend-HM	Blend-ME	Blend-HE
WTW $GHG_{savings\_GEM}$	[%]	44	50	58

Figure 8-5 presents the results on the total amount of GHG emissions avoided by the implementation of the selected GEM fuel blends in the different scenarios. This study indicates that the highest environmental benefits, in terms of climate change mitigation, are achieved with the implementation of Blend HE in Scenario 1, with GHG savings of 13.3 million metric tons CO_{2eq}. Moreover, this study indicates that the implementation of Blend HE in Scenario 2, leads to higher GHG savings than the implementation of Blends HM and ME in Scenario 1. The lowest environmental benefits are achieved with the implementation of the blend HM in Scenario 2 with 8.6 million metric tons CO_{2eq}.

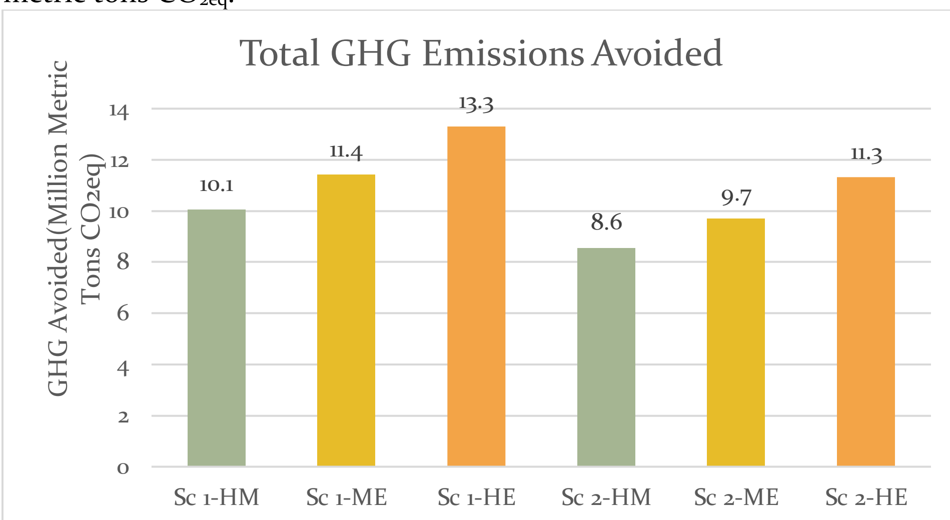


Figure 8-5: Total GHG emissions avoided in the Scenarios

Table 8-6 presents the annual GHG savings by 2030 that are achieved when the scenarios in combination with the selected GEM fuel blends are implemented. It can be concluded that the annual GHG savings in the different Scenarios in combination with the selected GEM fuel blends varies between 1.0 and 1.8 million metric tons CO_{2eq}.

Table 8-6: Annual GHG savings by 2030 in the different Scenarios

Scenario	Blend	GHG savings by 2030 [Mt CO2-eqv]
Scenario 1	Blend HM	1,3
	Blend ME	1,5
	Blend HE	1,8
Scenario 2	Blend HM	1,0
	Blend ME	1,2
	Blend HE	1,4

Figure 8-6 depicts the annual GHG emissions savings in the Scenarios in combination with the GHG emissions of the transportation sector in Sweden. In figure 8-6, the GHG emissions in Sweden between 2010 and 2015 are shown. Between 2010 and 2015, the GHG emissions of the transportation sector in Sweden has decreased with 11 percent. If the reduction between 2010 and 2015 would continue in the same amount, the total GHG emissions between 2010 and 2030 will decrease with 44 percent. The annual emissions that can be saved by implementing the GEM fuel blends in the Scenarios varies between 9 to 5 percent. Hence, if the GHG emissions of the Swedish transportation sector will continue to reduce in the same rate as between 2010 and 2015, and the Scenarios considered in this report are implemented, 49 to 53 percent of the GHG emissions of the total transportation sector in Sweden can be achieved.

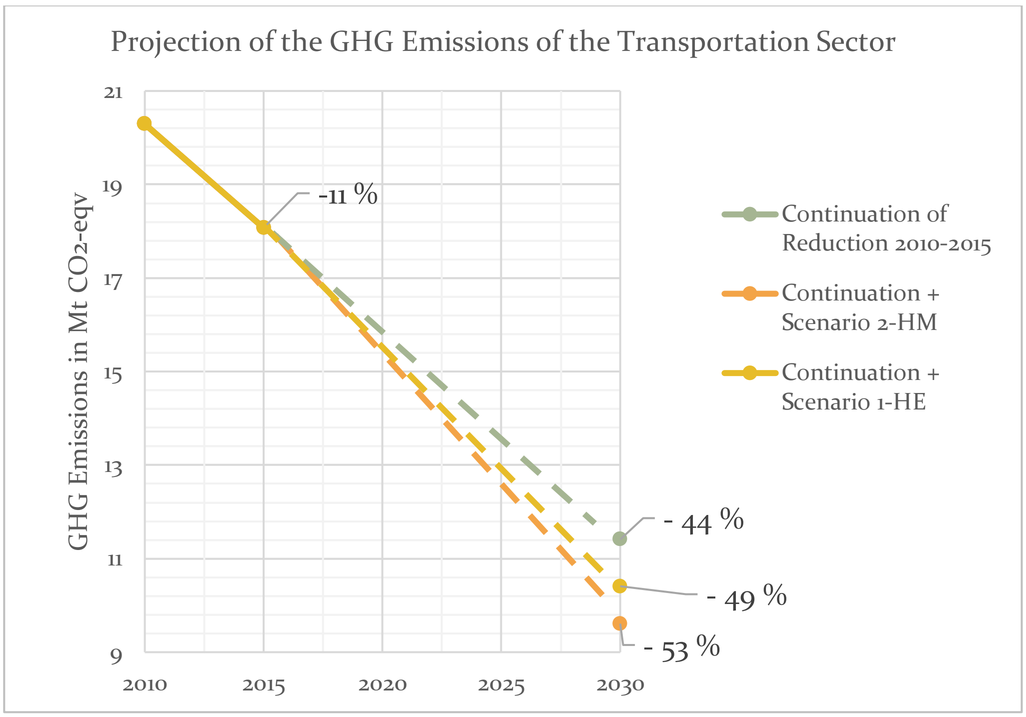


Figure 8-6: Projection of the GHG emissions of the transportation sector in Sweden

9 Discussion

This study explores the potential of GEM fuel as an alternative passenger car fuel for gasoline and E85 in Sweden. Alternative fuels have the potential to become a successful alternative fuel for fossil fuels if the fuel can overcome significant barriers such as availability of fuels, vehicles and feedstocks, infrastructural and financial challenges. [38] In the first chapter of this thesis, a main objective and four sub-objectives are raised which are aimed to test whether GEM fuel can overcome these barriers. In addition to the previously mentioned barriers, it is from importance what the implementation of the fuel for impact has on the climate and therefore an environmental impact analysis is performed. In order to test whether GEM fuel can overcome the previously mentioned barriers, the methanol and ethanol production potential & costs, the potential of a Swedish GEM fuel distribution network and the economic competitiveness of the fuel is assessed.

- **Availability of Vehicles**

Regarding the vehicle availability, GEM fuel can be implemented in spark ignition engines. Since, E85 flexible car vehicles, at present consist of 5 percent of the passenger car fleet and can run on the fuel without any modification. Regarding gasoline cars, the vehicles can converted to a E85 flexible fuel vehicle with minor adaptions. [29] At present, SI cars hold a share of 65 percent in the current Swedish passenger car fleet. Therefore, since there is a large potential market in the Swedish passenger car fleet, it is shown that availability of vehicles is no obstacle for the implementation of GEM fuel. Nevertheless, the current sales of E85 cars has decreased significantly in comparison to the year 2011. [41] Car dealers usually only offer car types of which there is a demand for on the passenger car market. Therefore, it is most likely that most of the car dealers in Sweden do not offer a selection of E85 flex-fuel vehicles. This can be a constraint for the implementation of GEM fuel blends.

- **Biofuel Production Potential & Selection Production Pathway**

To test the fuel availability, the biofuel production potentials and costs for the advanced ethanol and methanol are assessed. The biofuel production potentials are established by a combination of the potential availability of feedstocks and the energy yield ratios of key conversion technologies. To test a financial barrier, the production costs of the biofuels are verified. The production costs are verified by analyzing the total costs of the feedstocks at the biofuel plant and by evaluating the biofuel conversion cost. The production pathways of the biofuels are selected based on the energy yield ratios, the feedstocks availability and costs, and the conversion costs.

In tables 4-1 and 5-1, the results on the availability of the feedstocks, the energy yield ratios and the biofuel production potentials are shown. This study shows that there is a large potential of untapped feedstocks, resulting in a large biofuel potential for both biofuels. This study finds that the individual production potential of both methanol and ethanol is 56.5 and 25.9 TWh, respectively. Due to common suitable feedstocks, the production potentials are only achieved when only one of the biofuels is produced. Moreover, the study on the biomass feedstocks costs indicate that tops and branches, brushwood, recovered wood, straw and industrial wood waste all can become available for a total cost lower than 20 euro per MWh. The combined potential of the feedstocks is more than 50 TWh annually by the year of 2030.

Regarding methanol production, the study shows black liquor gasification is the most favorable production pathway of producing methanol. The production costs of methanol are 78 euro per MWh. The overall energy yield ratios of biomass to biofuel is relatively high with 78 percent and all the different types of lignocellulosic feedstocks can be implemented as a heating source process. As mentioned previously, black liquor is currently combusted in order to produce power and heat. However, the black liquor can perfectly be implemented for methanol production if the current heating demand of the fuel is replaced by biomass. In the study of Andersson et al. the cost of biomass are assumed to be 20 euro per MWh. [10] Biomass costs are an important parameter that influences the production costs of the biofuel. This study indicates that there is a large potential of biomass that could become available for replacing the current heating demand of black liquor, so that the black liquor can be utilized for the GEM fuel production. Moreover, it shows that large amounts of feedstocks can become available for a biomass cost lower than the cost assumed in the study and therefore potentially resulting in a lower production cost of the methanol.

Regarding ethanol production by the fermentation of forestry residues and wood waste, the study of Joelsson et al. indicated that the production cost are 97 euro per MWh. [11] The energy yield ratio of the fermentation of ethanol from industrial wood waste is 34 percent. The energy yield ratios of the process of second-generation ethanol production relatively low, due to the limited amount of cellulose in the wood and the production of by-products. In the process biogas and pellets are produced and therefore the energy is not wasted. However, to produce the same amount of 2nd generation ethanol as methanol from lignocellulosic feedstocks, much larger quantities of biomass are necessary.

Uncertainties

To show the theoretical production potential, it is assumed that all the feedstocks are implemented for the biofuel production. However, due to Sweden's targets to increase the amount of renewable energy, it is expected that the demand for lignocellulosic biomass is going to increase. Resulting in a higher cost and a less availability of the feedstocks. Furthermore, the import and exports of biomass is not taken into consideration. However, in reality this could influence the price and the availability of the feedstocks.

Regarding the transportation costs of the biomass from the storage terminal to the biofuel production plant, it is assumed that the average distance is 300 km. However, when carefully selecting the location of a biofuel production plant the distribution costs can be decreased significantly by minimizing the distance from the storage terminal to the biofuel production plant. Moreover, the location selection close to a harbor or train station site is truly favorably, since the biomass can also be transported by barge or train and therefore lowering the transportation costs significantly in comparison to truck transport.

- **A Swedish GEM fuel distribution network**

To test the infrastructural barrier of GEM fuel as an alternative fuel, the outlook of a Swedish GEM fuel distribution network is assessed by analyzing the suitable equipment in a GEM fuel infrastructure and by evaluating whether the equipment in the current fuel distribution network fulfills the GEM fuel requirements. If the equipment does not meet the requirements it is analyzed whether the equipment can be adapted or newly needs to be established. It can be concluded from the analyzes that most of the equipment in the existing distribution network for fuels can be implemented for GEM fuel and is therefore constructed of materials that are compatible for high alcohol containing fuels. Nevertheless, a new in-line blending system needs to be established that mixes the three components. In order to blend the energy demand of GEM fuel, by the year 2030, three blending machines at distribution terminals are necessary. Furthermore, the gaskets in the E85 fueling pumps at retail stations can potentially cause problems when GEM fuel blends with high methanol contents are applied. However, these are relatively small adaptions in comparison to the construction of a new pump.

Moreover, as mentioned previously, multiple studies forecast a decrease of 40 to 70 percent in the consumption and distribution of petroleum fuels, between 2015 and 2030. [14-16] Therefore, creating a tremendous over-capacity in the network, if the network would not be used for another purpose. In addition, there is currently a significant over-capacity in the existing distribution network of E85. As mentioned previously, the network has the capacity to supply near the current gasoline demand. However, it supplies less than 0.34 TWh, in comparison to 29 TWh of gasoline supplied in 2016.[23] At present, around to thirds of the current retail stations supplies E85 fuel. However, due to GEM fuels comparatively physiochemical characteristics to E85 and gasoline, the fuel can be used in the existing distribution network. Therefore, offering an alternative use of the equipment in the existing distribution network. Major investments have been made to establish the existing distribution network and the implementation of GEM fuel could prevent the loss of the valuable assets. For these reasons, it can be concluded that there is no infrastructural barrier related to the implementation of GEM fuel.

This study estimates the costs of distribution of GEM fuel to be 20 euro per MWh. The distribution cost of gasoline and E85 are respectively 10 and 15 euro per MWh. Hence, the distribution costs of GEM fuel are estimated to be significantly higher, this based on the extra handlings necessary regarding dry maintenance, the lower energy density and the domestic production of the biofuels within the borders of Sweden and therefore extra transportation costs. As mentioned previously, currently most of the E85 and gasoline is imported or produced very close to a distribution terminal. [23]

Regarding the blending costs, the costs are determined to be extremely low in comparison to the other economic parameters considered in this report. The blending costs determined are 0.005 euro per MWh. This is the result of the high capacity of the blending machines. Therefore, it is more beneficial to purchase more than three blending units in Sweden. Since more blending units at more storage terminals, decrease the transport distance of biofuels from and to storage terminals.

Uncertainties

Due to the low number of machines needed to blend the GEM fuel, the transportation costs of biofuels to and from the distribution terminal could be significantly higher than estimated in this report. By 2030, three machines are required, so that means from the distribution terminals the entire country needs to be supplied with GEM fuel. This could lead to a significantly higher transportation cost that previously estimated. Therefore, potentially it could be more beneficial to purchase more blending machines, in order to minimize the transportation cost of transport from and to the distribution terminal. As mentioned previously, the blending costs are extremely low, so it could be more beneficial to increase the blending costs by purchasing more machines.

Moreover, there are uncertainties regarding the gaskets in the fueling pumps. Gaskets are small mechanical seals located in the pumps. The current gaskets, implemented in the E85 pumps, could give problems when the high methanol blend is implemented. However, the replacement of the gaskets is a relatively small adaption and will therefore not result in a significant cost increase in the GEM fuel.

- **Economic Competitiveness of GEM fuel**

In order to test the economic competitiveness of GEM fuel blends, the pump prices of the selected GEM fuel blends are estimated. The determined pump prices for GEM fuel blend HM, ME and HE are 145.2, 142.6 and 138.8 euro per MWh(0.92, 0.90 and 0.87 euro per liter), respectively. This study shows that for the last 8 years, the pump prices of all the selected GEM fuel blends are economic competitive. The economic competitiveness analysis shows that when the current policy instruments are implemented, GEM fuel blends can become economically competitive in the passenger car fuel market. However, this report shows additionally that the production costs of 2nd generation ethanol and methanol, are still higher than the production costs of gasoline. Therefore, policy instruments, such as the current energy and carbon dioxide tax, are necessary in order to make the GEM fuel economic-competitive with gasoline. As indicated from the results of the economic competitiveness analysis, the higher the ethanol content in GEM fuel blends, the more favourable blends become in terms of economy.

Uncertainties

Short term policies, there are uncertainties regarding the policy support towards biofuels and especially to methanol. Implying, that the fuel now can be economically feasible, but with the implementation of new policies this could change.

- **Environmental Impact**

In this report, the environmental benefits are based on the GHG emissions avoided by the shift from cars running on neat gasoline to the GEM fuel. The results of this study indicate that large amounts of GHG emissions are avoided by the implementation of GEM fuel. This study indicates that the GHG savings for Scenario 1, when the selected GEM fuel blends are implemented, are 10.1, 11.4 and 13.3 million metric tons CO2eq for blend HM, blend ME and Blend HE, respectively. For Scenario 2, this study shows that 8.6, 9.7 and 11.3 million metric tons $CO2_{eq}$ are avoided if respectively Blend HM, Blend ME and Blend HE are implemented. Hence, in terms of environmental impact, high ethanol GEM fuel blends are more favorable. This is due to the lower gasoline content in the GEM fuel blends.

To have a perspective on how emissions are saved, in 2015 the annual consumptions of the total transportation sector were around 19 million tons of CO2 equivalent emissions. [21] Hence, in both scenarios close to a half of the annual emissions of 2015 could be saved be implementing GEM fuel.

General Challenges and Opportunities

Challenges:

- It can be learned from the past, that even though price of the fuel is competitive with gasoline, that FFV owners not necessarily fuel the car with the GEM fuel, but can chose to fuel with conventional fossil fuel.

- The economic feasibility of GEM fuel is truly dependent on the policy instruments applied in Sweden. As mentioned previously, in the current policies GEM fuel is economically competitive, however policies change rapidly and are therefore not stable. This implies that GEM fuel can be now economically feasible, but in the future, this can change when biofuels lose the political support. From this study, it is learned that the production costs of the biofuels in GEM fuel are higher than gasoline, so political is necessary.

- The costs of the biomass can rise by the expected increased demand for the feedstocks. Furthermore, the imports and exports are not taken into consideration in this report. This has also an effect on the cost and availability of the feedstocks.

- Before GEM fuel can be introduced to the Swedish E85 market, new fuel standards for the fuel should be developed. A possible way to this is, is by adapting the Swedish E85 Standard SS 15 54 80:2006, to an GEM fuel standard. [66]

- The sales of E85 flex-fuel vehicles has decreased significantly between 2011 and 2017. Therefore, car dealers supply most likely less E85 FFV's at the showrooms. However, for people to purchase an E85/GEM FFV, the cars need to be offered at the showrooms.

Opportunities:

- The implementation of GEM fuel in the existing distribution network offers a solution of the current over-capacity in the E85 infrastructure and the expected over-capacity in the fossil fuel infrastructure. Therefore, there lays already an existing infrastructure for GEM fuel blends.

- By introducing GEM fuel to E85 flexible fuel vehicle, which currently fuel their cars with gasoline, a rapid increase of the share of renewable in the Swedish road transportation can be created and with that a reduction of the GHG emissions

- The introduction of GEM fuel to the market offers business opportunities for bioalcohol production plants, such as the planned production plant of Södra or pulp and paper plants. As mentioned previously, Södra plans to start with the production of 5000 tons of Methanol by the year of 2030. Introducing GEM fuel to the market creates a market for the biofuels.

- Though first-generation ethanol is not taken into consideration, Sweden has in Lantmännen a successful first-generation ethanol producer of which the WTW GHG savings are more than 97 percent in comparison to conventional fossil fuels. [67] The plant currently produces around 1.5 TWh of ethanol annually. [67] The ethanol produced is perfectly suitable as a component of GEM fuel.

- Though not taken into account in this report, GEM fuel has the potential to become 100 percent renewable. According to Haro et al., renewable gasoline can be produced for a price of 146 euro per MWh. The renewable gasoline can be blended together with the advanced alcohols in order to form a 100 percent renewable fuel. [68] Therefore, the GEM fuel could contribute to the total phase out of fossil fuels in the transportation sector.

10 Conclusions, Recommendations & Future Work

This chapter represents the last chapter of this report and constitutes of the conclusions, future work and recommendations found during the duration of this study regarding the shift from gasoline to GEM fuel.

10.1 Conclusions

This study evaluated whether GEM fuel, produced from domestic inedible feedstocks, has the potential to become a successful alternative fuel to gasoline in Sweden. The potential of the fuel is analyzed by assessing: the biofuel production potential of methanol and ethanol, a Swedish GEM fuel distribution network, the economic competitiveness of GEM fuel and its components. Based on the results of this study, it can be concluded that GEM fuel in both scenarios has the potential to be a successful long-term alternative for gasoline in terms of biofuel potential, distribution infrastructure, economic competitiveness. In addition, the environmental impact of the shift from neat gasoline to GEM fuel is analyzed and this study shows that the implementation of GEM fuel leads to direct environmental benefits.

This thesis finds that there is a large production potential for both advanced bioalcohols, produced from Swedish feedstocks. It can be concluded, that there is a large potential availability of the currently untapped second-generation feedstocks that can be implemented for the biofuel production. This thesis estimates that the untapped potential of secondary biomass feedstocks, that is suitable for ethanol production, is around 90 TWh annually by 2030. Moreover, it estimates, that the corresponding annual production potential of second-generation ethanol is 25.9 TWh. Regarding methanol production, this study estimates that the annual potential of biomass feedstocks, that could become available for methanol production, is 106 TWh by 2030. This study estimates that the total annual production potential of methanol is 56.5 TWh by 2030. Due to the fact that most of the biomass feedstocks can be utilized for the production of both bioalcohols, the estimated production potentials of the individual biofuels can only be achieved if only one of the biofuels is produced. Therefore, the estimated production potentials of both ethanol and methanol cannot be added up in order to determine the GEM fuels potential. Nevertheless, the biofuel potential study identifies that there is a large theoretical production potential for both bioalcohols. According to this study, the most suitable pathway of methanol production is by black liquor gasification, in which the heating demand of the previously combusted black liquor is replaced by one of the previously mentioned biomass feedstocks. The production costs of the methanol are 78 euro per MWh(0.35 euro per liter). Regarding 2nd generation ethanol production, this study shows that fermentation industrial wood waste such as sawdust and shavings is the most suitable production way. The production cost of the ethanol are 97 euro per MWh(0.57 euro per liter).

In order to perform this analysis, two scenarios were developed for projecting the share of the GEM cars in the Swedish passenger car fleet, considering a time horizon from 2017 to 2030. In Scenario 1, a high share of passenger cars running on GEM fuel is obtained with 22 percent by 2030. In Scenario 2, a low share of cars running on GEM fuel is obtained with 17 percent by 2030. In both scenarios, the passenger cars running on GEM fuel take over the share of cars running on gasoline. The scenarios serve to project the energy demand for GEM fuels. By 2030, the projected energy demand for GEM fuels is 9.7 and 7.5 TWh for Scenario 1 and Scenario 2, respectively. The projected energy demand of GEM fuels, that is created by the shift and needs to be satisfied by GEM fuel blends, is 9.7 TWh in Scenario 1 and 7.5 TWh in 2030, respectively.

Since a variety of GEM fuel blends can be implemented in flex-fuel vehicles, in this study, three different GEM fuel blends were considered in combination with the two scenarios. In Blend HM, one GEM fuel blend with a high methanol content was analysed, consisting of 36.5, 23.5 and 40 volume percent of respectively gasoline, ethanol and methanol. In Blend ME, one GEM fuel blend with a medium content of methanol and ethanol is considered, consisting of 29.5, 42.5 and 28 volume percent of respectively gasoline, ethanol and methanol. In Blend HE, one GEM fuel blend with a high ethanol content is considered, consisting of 19.5, 71 and 9.5 volume percent of respectively gasoline, ethanol and methanol. This study indicates that the highest energy demand for alcohol fuels is created by Scenario 1 in combination with the high ethanol containing GEM fuel blend.(blend HE) Moreover, this study shows that the biomass utilization in the GEM fuel blends with high ethanol contents, in combination with the scenarios, are significantly higher than low ethanol containing GEM fuel blends. In order to satisfy the GEM fuel demand in Scenario 1 and Blend HE, a biomass utilization of 19.6 TWh is required. In comparison, in order to satisfy the energy demand in Scenario 1 in combination with Blend HM, a biomass utilization of 9.6 TWh is necessary. Moreover, the largest amounts of gasoline can be replaced when implementing the high ethanol containing GEM fuel blends. This is due to the low gasoline content in the fuels in comparison to the high methanol containing GEM fuel blends.

Regarding the analysis on a Swedish GEM fuel distribution network, it can be concluded that the majority of the current distribution infrastructure of E85 and gasoline is capable of distributing GEM fuel. Moreover, it is expected that, beside the current over-capacity in the E85 distribution network, an over-capacity is going to appear in the distribution network of transportation fossil fuels. This is the expected result of the, by recent studies, forecasted decrease of consumption of fossil fuels in the Swedish transportation sector. Moreover, this study indicates that the equipment implemented in the existing distribution network is compatible with high alcohol blends. This implies that there is no need for major investments in order to create a GEM fuel distribution infrastructure and that the capacity of the current infrastructure is sufficient. In Sweden two thirds of the retail stations contain E85 pumps, and these fuelling pumps can be, after minor adaptions on the gaskets, implemented as GEM fuel pumps. In addition, this study indicates that an in-line fuel blending system needs to be established at the storage terminals in order to blend the GEM fuel components. The distribution costs of GEM fuel are estimated to be 3.2 euro per MWh.(0.02 euro per liter) Moreover, this study indicates that the capacity of the existing fuel distribution network of E85 and gasoline is sufficient to supply the projected energy demand of GEM fuel in the scenarios.

From the economic competitiveness studies, it can be concluded GEM fuel blends are economic-competitive with gasoline and E85. In order to test the economic competitiveness of the estimated pump prices of the GEM fuel blends, a pay-off limit curve was developed based on the gasoline price and the fuel economy of GEM fuels in comparison to gasoline. The determined pump prices for GEM fuel blend HM, ME and HE are 145.2, 142.6 and 138.8 euro per MWh(0.92, 0.90 and 0.87 euro per liter), respectively. This study shows that for the last 8 years, the pump prices of all the selected GEM fuel blends are economic competitive. The economic competitiveness analysis shows that when the current policy instruments are implemented, GEM fuel blends can become economically competitive in the passenger car fuel market. However, this report shows additionally that the production costs of 2nd generation ethanol and methanol, are still higher than the production costs of gasoline. Therefore, policy instruments, such as the current energy and carbon dioxide tax, are necessary in order to make the GEM fuel economic-competitive with gasoline. As indicated from the results of the economic competitiveness analysis, the higher the ethanol content in GEM fuel blends, the more favourable blends become in terms of economy.

In this study, the environmental impact is based on the GHG emissions avoided by the shift from cars running on neat gasoline to GEM fuel(with both high methanol and high ethanol content options). The scenarios, in combination with the selected GEM fuel blends, show that significant amounts of GHG emissions are avoided with the implementation of GEM fuel instead of gasoline. Since both ethanol and methanol in the GEM fuel are produced from second-generation feedstocks, the GHG savings are high, in comparison to other alternative fuels. [6] The well to wheel GHG savings of ethanol produced from forestry residues and methanol produced from black liquor are respectively 78 and 97.[17] This study indicates that the GHG savings per individual blend are 44, 50, 57 percent for Blend HM, Blend ME and Blend HE, respectively. The larger amount of GHG emissions avoided in the GEM fuel blends with a higher ethanol content, is due to the higher biofuel content in the GEM fuel blends. This study indicates that the GHG savings for Scenario 1, when the selected GEM fuel blends are implemented, are 10.1, 11.4 and 13.3 million metric tons $CO2_{eq}$ for blend HM, blend ME and Blend HE, respectively. For Scenario 2, this study shows that 8.6, 9.7 and 11.3 million metric tons $CO2_{eq}$ are avoided if respectively Blend HM, Blend ME and Blend HE are implemented. Hence, this study shows that high ethanol containing GEM fuels are favourable in terms of GHG emissions avoided. Moreover, this study shows that by implementation of the Scenarios in combination with the selected GEM fuel blends, the total GHG emissions of the Swedish transportation sector can be decreased with a value of 9 to 5 percent by 2030.

In conclusion, from the thesis, it can be indicated that GEM fuel has the potential to become a successful alternative passenger car fuel in Sweden. The biofuel production potential assessment proves that the projected energy demands for GEM fuel blends, created by the shift with a time horizon to 2030, can be met from Swedish secondary sources. Moreover, it can be concluded, that with minor investments, the existing fuel distribution network of gasoline and E85 can be implemented for the distribution of GEM fuel and that the capacity is sufficient. Blend HM, is the most beneficial in terms of bioenergy utilization, implying that less biomass feedstocks are necessary in order to meet the future energy demand of GEM fuel. Furthermore, it can be concluded that, with the current policy instruments, GEM fuel can be supplied for an economic-competitive pump price. Blend HE, has a slightly lower pump price in comparison to Blend HM and Blend ME, and is therefore more favorable in terms of economic competitiveness. Regarding the environmental impact, this thesis indicates that the implementation of GEM fuel blends in the scenarios can save up to 13.3 and 8.6 $CO2_{eq}$million metric tons $CO2_{eq}$. The higher the ethanol content in the GEM fuel blends the more GHG emissions are saved. Hence, this report indicates that there are no obstacles for GEM fuel to become a successful alternative fuel. However, political support is needed in order to make the economic-competitive. Therefore, it is recommended that policy instruments will be implemented that make the GEM fuel economic-competitive. Regarding economy and GHG savings, high ethanol GEM fuel blends are favorable. Regarding the biomass utilization, high methanol containing GEM fuel blends are favorable.

10.2 Future Work

In this report, some assumptions and simplifications are made in the analysis on GEM fuel as a potential alternative fuel for gasoline. Moreover, this thesis primarily focused on the technical, environmental and economic impacts of the implementation of GEM fuel. Therefore, an extra analysis on the following topics may improve the robustness of the conclusion stating that GEM fuel has the potential to become an alternative fuel for gasoline.

- An important parameter that influences the production costs of the alcohols, are the costs of the feedstock. In this report is shown that the amount of biomass required to meet the demand of the GEM fuel is available for the cost assumed in the conducted studies on the production costs of the alcohols. However, this reports shows that various feedstocks can potentially be delivered for a cost lower the values assumed in the studies. This implies, that the alcohols probably can be produced for a production cost lower than determined in the studies and assumed in this report. Resulting, in a lower pump price of GEM fuel in both scenarios. Moreover, the demand is expected to grow for biomass feedstocks, resulting in an increase of the price. The forecast of the price and availability of the biomass should comprehensively be investigated, since it has a profoundly large effect on the GEM fuel price and availability.

- Though, the study on the production of 2nd generation ethanol showed that the results on the production costs vary among different studies, in this report than the production costs of the Joelsson et al. are taken into account as the costs of the ethanol production. [11] The costs estimated by Joelsson et al. are lower in comparison to the results of the other studies. However, the report conducted a case study for Sweden and was therefore assumed to be the production costs of ethanol in this report. The pump price of GEM fuel is significantly determined by the production cost of the ethanol and therefore the large-scale 2nd generation ethanol production should need some more attention, to analyze whether 97 euro per MWh can be achieved.

- In this report, it assumed that a market for GEM fuel and FFV's is created due to political support. Political support is one of the key factors whether an alternative fuel becomes a successful fuel. Therefore, it is important that extra studies are performed on the most suitable political support in order to promote GEM fuel. It is important that the support to stakeholders along the entire supply chain of the GEM fuel are carefully selected. Investors need to be willing to invest in the biofuel production plants, distributors are needed to be willing to distribute the fuel, retail stations need to be willing to supply the GEM fuel and car owner should be willing to purchase E85/GEM FFV's and to fuel the car with GEM fuel.

- Future work should be done on the implementation of renewable gasoline in the GEM fuel mixture in order to test the potential of the fully renewable GEM fuel. Significant reductions of the GHG emissions of the transportation sector can be achieved when fully renewable GEM fuel would be implemented instead of gasoline.

- An important part of reducing the transportation cost of feedstocks and fuels is determined by the location selection of fuel production plants and storage terminals. Therefore, the locations of biofuel plants should be carefully selected, so that the most optimal location is chosen in terms of transportation costs. The distance between the storage terminals and the biofuel plants should be minimized and the location should preferably have access to a port or train station.

10.3 Recommendations

From this study, it can be concluded that GEM fuel has the potential to successfully replace gasoline as a passenger car fuel. Therefore, it is advised that Sweden puts political support activities related to supply chain activities of GEM fuel. The fuel needs active promotion, because the fuel needs to be introduced. Moreover, a fuel standard of GEM fuel needs to be established. In the succeeding of this paragraph pros and cons of the implementation of GEM fuel, found during this study, are listed.

As mentioned previously, the majority of the current Swedish passenger car fleet is power by spark ignition engines. GEM fuel can be without any modifications be utilized in E85 flexible fuel vehicles, which have a share of 5 percent on the Swedish passenger car fleet. However, gasoline cars require minor modifications in order to run on GEM fuel. Hence, it is recommended that policy instruments in the form of financial incentives are provided to gasoline car owners, in order to promote the conversion from gasoline to GEM cars. Resulting, in an increased share of GEM/E85 flexible fuel vehicles in the Swedish passenger car fleet.

GEM fuel can be utilized in the majority of the current well-established distribution network of E85 and gasoline, therefore no major investments are necessary in a GEM fuel distribution network. The fuel can be implemented E85 FFV, which at present have a share of 5 percent in the current Swedish passenger car fleet. Furthermore, the GEM fuel can as well be, by minor adaptions to the car, be utilized in gasoline cars.

Moreover, there is a large production potential of the domestically produced 2nd generation ethanol and methanol in the GEM fuel. Therefore, with the implementation of the fuel, the fuel dependence of the Swedish passenger car fleet reduces significantly. Furthermore, as this study indicates, the biofuels can be economically produced from second-generation feedstocks.

As mentioned previously, due to the Pump law the majority of the Swedish retail station invested large amounts of money into the construction of new E85 pumps and the belonging storage tanks. However, the low demand for the fuel results in incoming cash flow for the retail stations. An alternative usage for the pumps can be the GEM fuel, so that the pumps can become profitable. GEM fuel has the advantage that it can be used in the existing distribution network and therefore saving tremendous investments in comparison to other renewable alternatives.

This report shows that there is a large potential for methanol produced from black liquor as a transportation fuel. The process has a high biomass to fuel yield with 78 percent and can be produced for prices slightly higher that the production costs of fossil fuels. As mentioned previously, due to Sweden's targets to fight climate change, the demand for biomass is expected to increase and it will become more and more important that the energy is efficiently used. With the countries' objective to move towards a more sustainable society, it is a smart decision to produce the transportation fuel methanol from black liquor to blend it into GEM fuel so it can become an alternative for the conventional fossil fuels.

The issues found during this thesis found, related to the implementation of the GEM fuel, are that there are no assurances that FFV owners will fuel the car with GEM fuel. Lessons can be learned from the past when E85 FFV owners decided to fuel the cars with car. Moreover, even though GEM fuel largely constitutes of biofuels, the fuel still contains fossil fuels. Furthermore, it expected that the demand on the biomass feedstocks is going to increase due to competing industries.

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12 Appendix

12.1 Energy Demand in Scenarios

In this paragraph, it is described how the volumetric energy density(LHV) of the blends in the different scenarios are determined. Moreover, how the energy fractions of the individual components are in the GEM fuel mixtures. Lastly, it is described how the energy demand in the scenarios is derived.

The energy volumetric density of the GEM fuel blends in the scenarios is calculated by equation 1. [30]

Equation 1

$$Q_{LHV} = \sum((\frac{V_i}{V}) * Q_{LHV_i})$$

With:

- Q_{lhv} is the LHV of the total blend in (MJ/L)
- $Q_{LHV\,i}$ is the LHV of the individual component of GEM fuel(MJ/L)
- V_i/V is the ratio between the volume fraction of a components divided by the total volume of the GEM fuel blend(%)

The energy volumetric density of the GEM fuel blends in the scenarios is calculated by equation 1.

Equation 2

$$E_i = \frac{\left(\left(\frac{V_i}{V}\right) * Q_{LHV_i}\right)}{Q_{LHV}}$$

With:

- Ei Energy fraction in (%)

❖ **Blend HM**

In Blend HM, the volume fraction of gasoline, ethanol and methanol are respectively 36.5, 23.5, and 40 percent.(G36.5 E23.5 M40). The Q_{LHV} of the mixture is calculated by equation 1 and is for Blend HM, **22.77 MJ per litre**. After the LHV of the total blend is familiar, the energy ratios can be calculated.

Table 1: Results on Energy ratio determination Blend ME

Item	Unit	Gasoline	Ethanol	Methanol
Q_{LHVi}	(MJ/L)	31.52	21.15	15.75
Volume ratio (Vi/V)	(%)	36.5	23.5	40
Energy fraction (Ei)	(%)	51	22	28

❖ **Blend ME**

In Blend ME, the volume fraction of gasoline, ethanol and methanol are respectively 29.5, 42,5, and 28 percent. (G29,5 E42,5 M28) The Q_{LHV} of the mixture is calculated by equation 1 and is for blend ME, **22.70 MJ per litre**. After the LHV of the total blend is familiar, the energy ratios are calculated.

Table 2: Results on Energy ratio determination Blend ME

Item	Unit	Gasoline	Ethanol	Methanol
Q_{LHVi}	(MJ/L)	31.52	21.15	0.1575
Volume ratio (Vi/V)	(%)	0.295	0.425	0.28
Energy Ratio (Ei)	(%)	0.41	0.40	0.19

❖ **Blend HE**

In Blend HE, the volume fraction of gasoline, ethanol and methanol are respectively 19.5, 71, and 9.5 percent. (G19.5 E71 M9.5) The Q_{LHV} of the mixture is calculated by equation 1 and is for blend ME, **22.66 MJ per litre**. After the LHV of the total blend is familiar, the energy ratios are calculated.

Table 3: Results on Energy ratio determination Blend HE

Item	Unit	Gasoline	Ethanol	Methanol
LHV(MJ/L)	(MJ/L)	31,52	21,15	15,75
Volume Ratio(Vi/V)	(%)	19,5	71	9,5
Energy Ratio from total(Ei)	(%)	0,27	0,66	0,07

12.2 Information on the GEM fuel Blending Technology

In this paragraph, the technical characteristics of the blending machine are depicted. Moreover, picture of the machine is provided.

No	Parameter	Value
1.	Number of fluid streams for mixing	3
2.	Mixer capacity, m^3/hour, no less than	100
3.	Calculated main component nozzle capacity (heavy oil), $м^3$/час, not less than	80
4.	Additional component No 1 (hydrocarbon additive) flow range by flow meter R1, m^3/hour	0,25…2,5*
5.	Additional component No 2 (light crude oil fraction) flow range by flow meter R2, m^3/hour	5…50*
6.	Mixer volume, m^3	0.03
7.	Relative vacuum in the vacuum chamber, bar, max	-1
8.	Main fluid charge pressure, bar, max	10**
9.	Blend supply head, m, max	10**
10.	Nominal power, kW	45-55
11.	Power supply	380V/50Hz 480V/60Hz
12.	Unit container dimensions, mm, max - length - width - height	 2850 2230 2120
13.	Weight, kg, max	2800

12.3 Material Compatibility of GEM fuel

The material compatibility is dependent of the alcohol concentration in the fuel. The higher the alcohol content, the higher the compatibility problems with certain equipment materials. Table 3-4 represents equipment materials which are compatible with methanol containing fuels and is adapted from the Methanol Institute. [25] In Sweden, most materials in the current gasoline distribution network are compatible with methanol. Metals that are often used in the gasoline infrastructure and that are compatible with methanol are stainless steel, bronze, aluminum carbon steel or fiberglass.

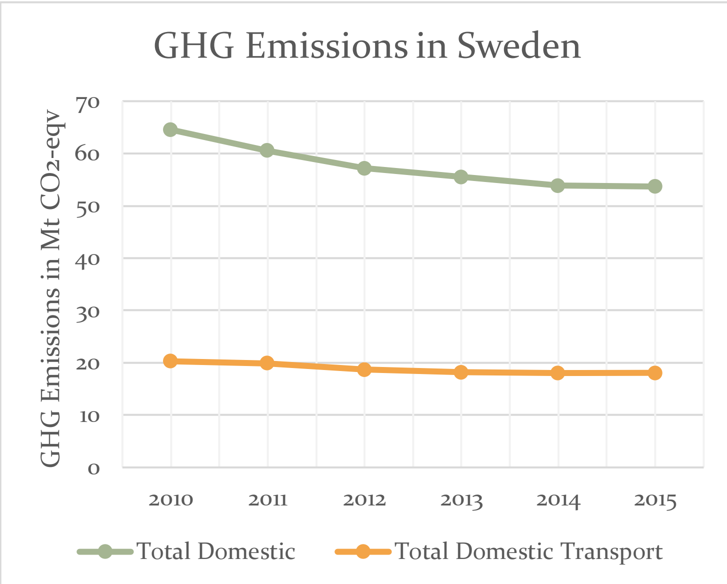
Table 4: Recommended equipment materials in the distribution network for GEM fuel, adapted from Methanol Institute[25]

Metals	Aluminum Stainless Steel Carbon Steel Bronze
Elastomers	Viton Fluorosilicone Polysulfide Rubber Neoprene* Flurel ™ Buna – N ™ *
Polymers	Acetal Nylon Polyethylene Teflon ™ Fiberglass-reinforced

* Can be implemented as hoses and gasket materials, but not at seals materials

12.4 GHG emissions in Sweden

The figures 5 and 6 represent the domestic GHG and separate CO2 emissions for the years 2010-2015. The transportation sector contributed to a significant share of the countries" GHG emissions. The sector accounted for respectively 41 and 34 percent of the national carbon dioxide and GHG emissions. The emissions of the transportation sector are relatively high, considering that only 23 percent of the final energy was consumed by the sector. Per unit of energy consumed in the transportation sector, 37 percent more carbon dioxide was emitted than the same unit of energy consumed in the other sectors. The total national GHG and carbon dioxide emissions decreased with respectively 17 and 18 percent between the years 2010 and 2015. In the same period of time, the GHG and carbon dioxide emissions in the transportation sector decreased both with 11 percent. The total national final energy consumption decreased with 6 per cent between 2010 and 2015 and the energy consumed in the transportation sector decreased with 5 per cent. [22] Showing that larger improvements have been made in the other sectors, regarding GHG emission, in comparison to the transportation sector.



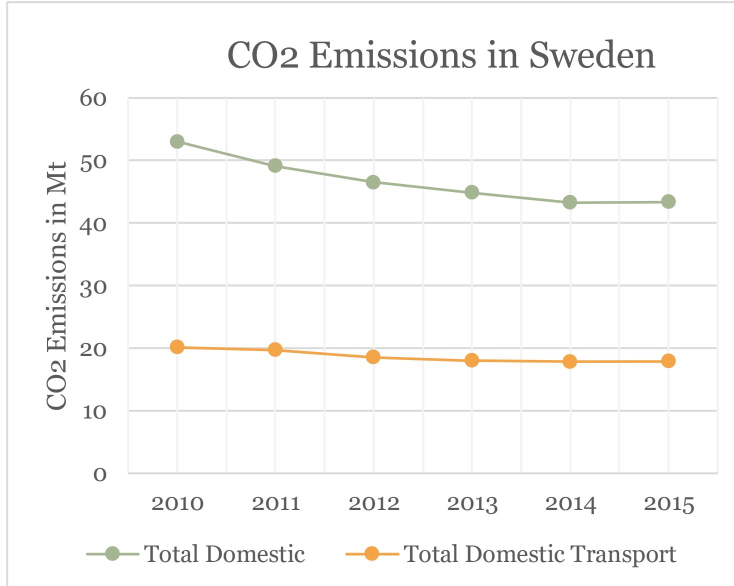


Figure 5 & 6 Domestic GHG Emissions [21]

12.5 Forecast Distance Travelled by Different Types of Transport

In the picture below, the results are depicted of the forecast of the Swedish traffic agency on the distance travelled by different types of transport. Included are public and private transport.

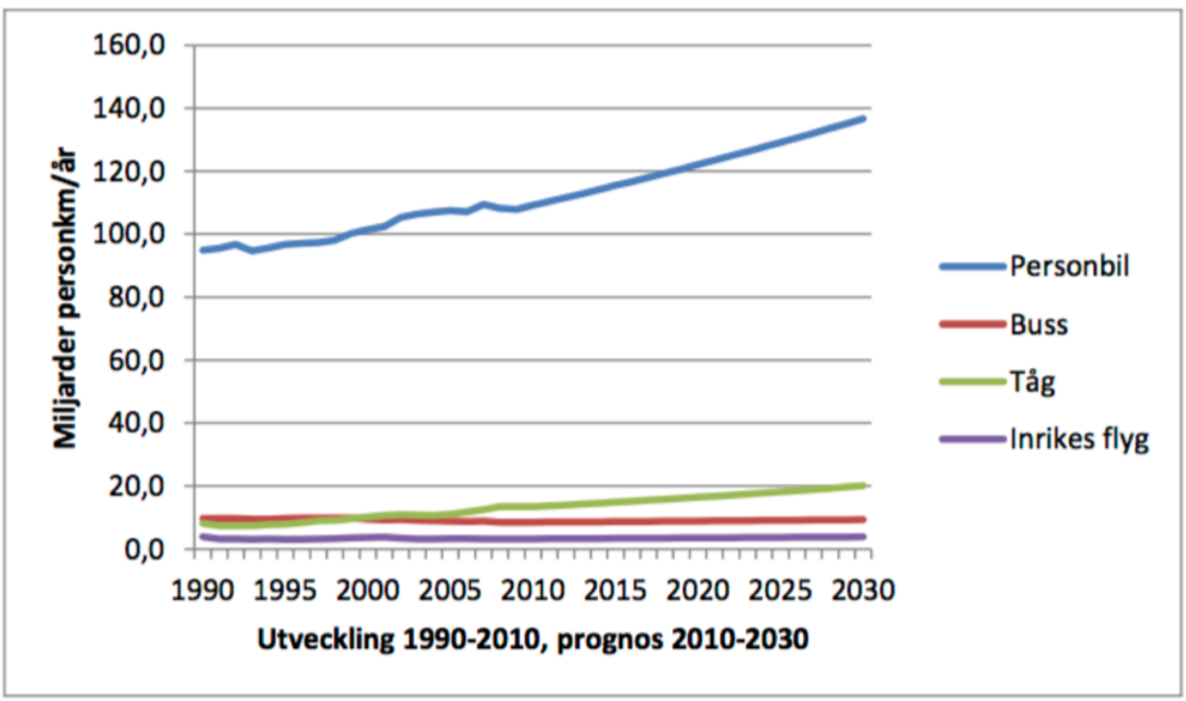


Figure 7: Forecast Trafa on travelled passenger km[59]

12.6 Swedish Oil Consumption Forecasts

In this paragraph, multiple studies on the forecasted oil consumption are evaluated. The Swedish Environmental Research Institute(IVL) has developed a scenario in which it is aimed to reach a 100 percent supply of the energy from renewable energy sources by the year of 2050. [15, 16] The forecast of the oil supply is depicted in the figure 8. As mentioned previously, Sweden has set the target to have a fossil-free transportation sector by 2030. The oil supply forecast if the objective is reached, is shown in the figure 8.[16] IVL scenario the oil supply decreases with 40 percent between 2015 and 2030, in the EU-scenario it decreases with 12 percent and in the Swedish-Fossil free scenario with 71 percent. Even though, the results of the studies differ, all scenarios have in common that supply of fossil fuels in the transportation sector is going to decrease significantly. This implies that an overcapacity of the existing distribution network of transportation fossil fuels is expected to appear.

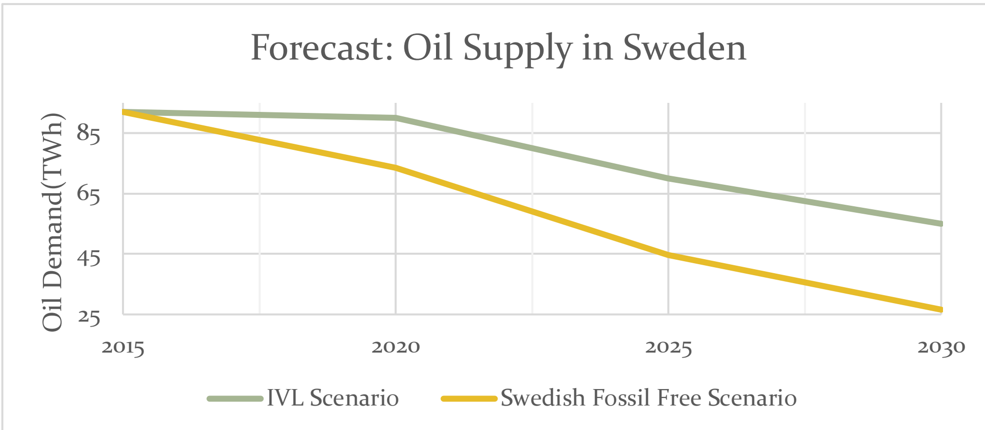


Figure 8: Swedish Oil Supply Forecast Scenario's by European Commission & IVL [14-16]

12.7 Questionnaires

In this paragraph, the questionnaires implemented in the interviews with SPT and SEKAB are presented.

12.7.1 SPT, Scandinavian Petroleum Technic Association

Questionnaires
1) Can E85 be stored in similar tanks as gasoline? 2) What is the capacity of the current E85 distribution network in Sweden? 3) How does the ethanol pump differ from the gasoline pump? 4) Can methanol be stored the same storage tanks as ethanol? 5) Can GEM fuel be implemented in the E85 pumps? 6) Can methanol be transported in a similar manner as ethanol and gasoline? 7) Is all the gasoline in Sweden only used for road transport or are there also other purposes?

8) What actions are done in order to prevent water mixing with the E85/ethanol along the distribution channel? 9) How is dealt with E85 with the electric conductivity, flammability- & water sensibility issues? 10) Can the E85 blending systems be used for GEM fuel blending?

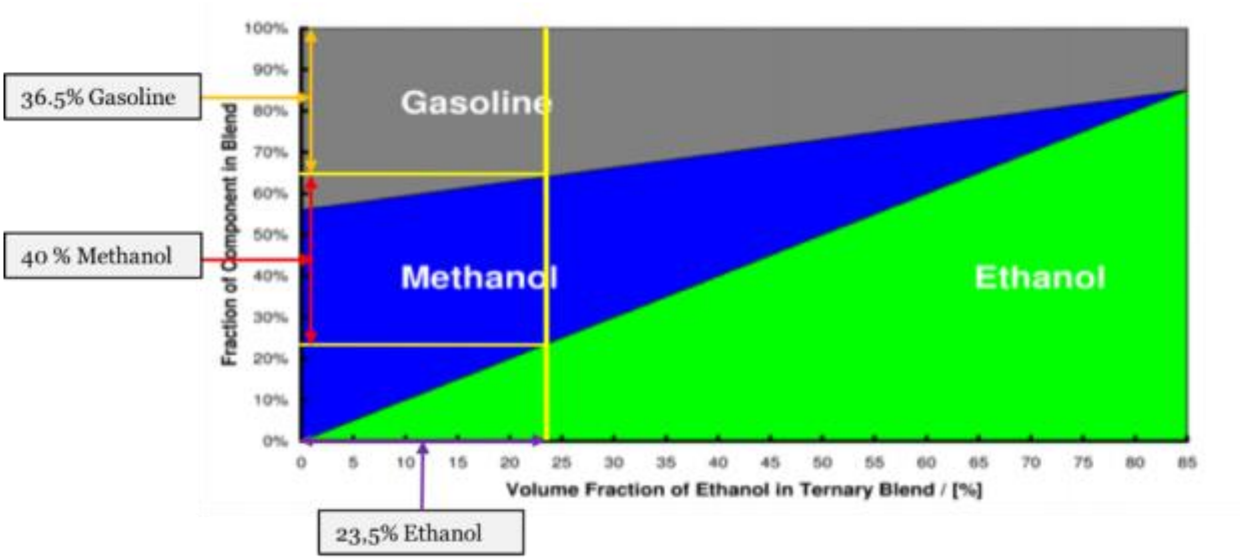
12.7.2 SEKAB

Questionnaires
1) What is the capacity of an average E85 pump in Sweden? (volume of storage at retail station and how many times refilled usually)? 2) How does the ethanol fuel station look like? Are there two different tanks for ethanol and gasoline? 3) Where are large scale ethanol storages in Sweden? 4) How and where is are the ethanol, additives and gasoline blended? 5) Are there special trucks and ships that are used for ethanol? Or can the same transport be used as in gasoline transport? 6) What is the capacity of the current E85 distribution network in Sweden? 7) What are the current cost-prices for 1st and 2nd generation ethanol (Agroethanol)? 8) The current E85 pumps in Sweden, were that gasoline pumps before or that newly build E85 pumps? What are the costs of either building or transforming? 9) What are the average distribution costs of gasoline and ethanol (in €/km*L)?

12.8 Verification of the GEM fuel Blends in the Scenarios

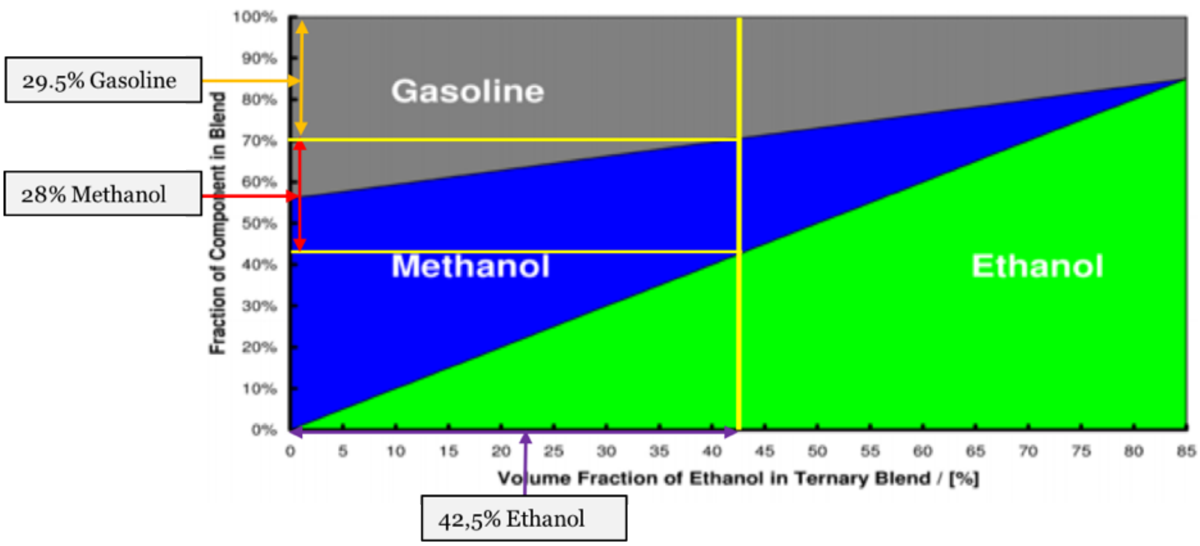
- **Blend HM**

In Blend HM, one GEM fuel blend with a high methanol content is analysed, consisting of 36.5, 23.5 and 40 volume percent of respectively gasoline, ethanol and methanol. percent of respectively gasoline, ethanol and methanol.



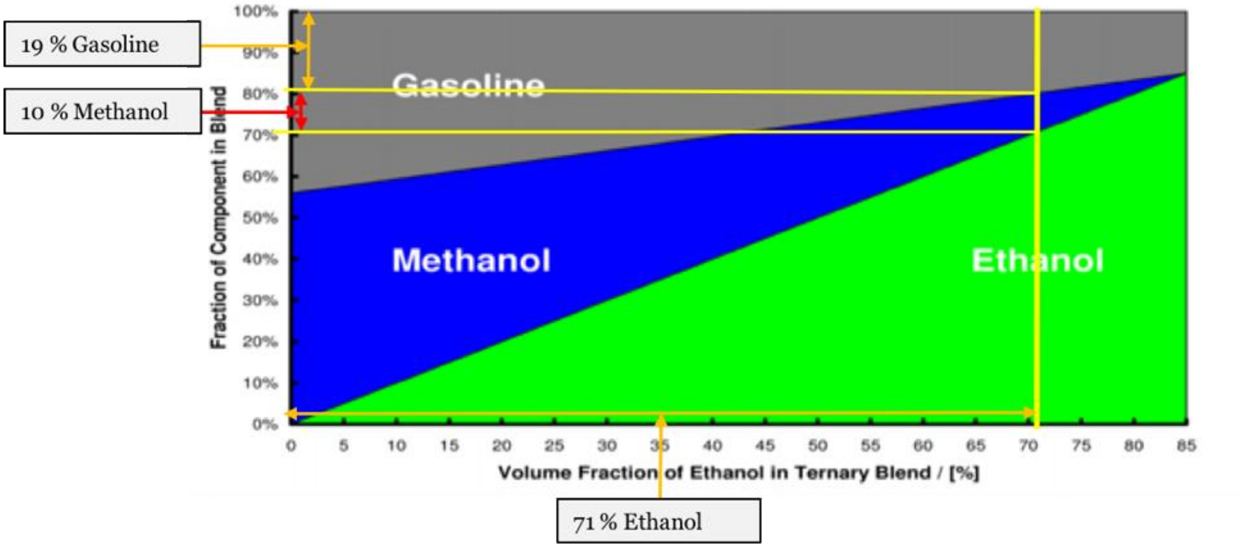
❖ Blend ME

In Blend-ME one GEM fuel blend with a high ethanol content is analysed, consisting of 29.5, 42.5 and 28 volume percent of respectively gasoline, ethanol and methanol. percent of respectively gasoline, ethanol and methanol.



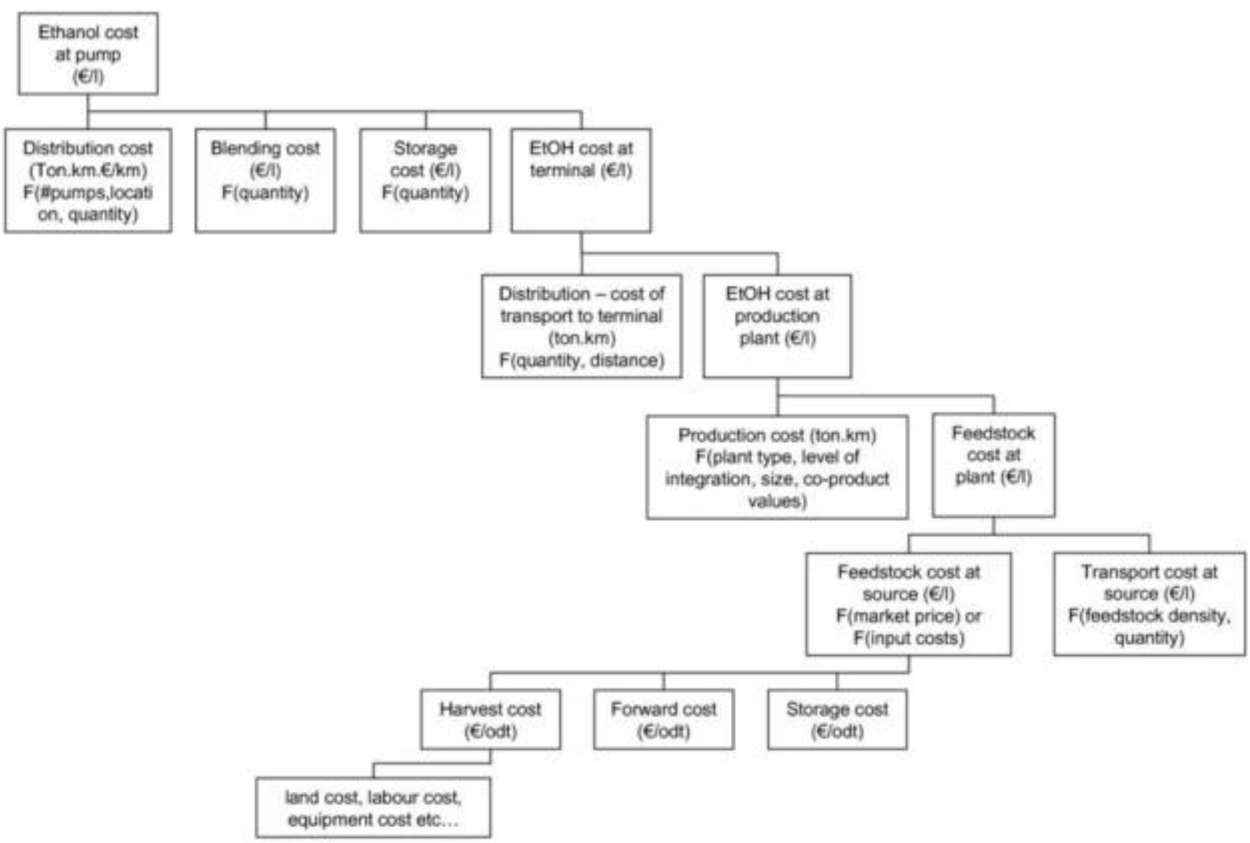
❖ Blend HE

In Blend-HE one GEM fuel blend with a high ethanol content is analysed, consisting of 19, 71 and 10 volume percent of respectively gasoline, ethanol and methanol. percent of respectively gasoline, ethanol and methanol.



12.9 Pricing of Ethanol

Slade et al., has developed a supply-chain cost model in order to determine the pump price of ethanol(excluding tax). The model is depicted in the figure below. In the figure it is illustrated that, at each stage in the supply-chain, the cost is the sum of the previous stages plus the cost of conversion from one product to another. [60]



12.10 Blending of GEM fuel

Since GEM fuel can be utilized in varying compositions in E85 flexible fuel vehicles, it is important that varying compositions can be blended by the blending machines. The following blending techniques can be implemented for the blending of GEM fuel.

- *Splash blending*

Splash blending is when the components are blended by adding the individual components simultaneously together in either a vessel or a truck.

- *Blender pump*

Blending of a fuel can also be done by a blender dispensing pump. With this technology, the different components are stored separately underground at the retail station. The pump blends the pump in various compositions, dependent of the composition needed. The pump can therefore account for variation in the supply of the components of the fuel.

- *Storage tank blending*

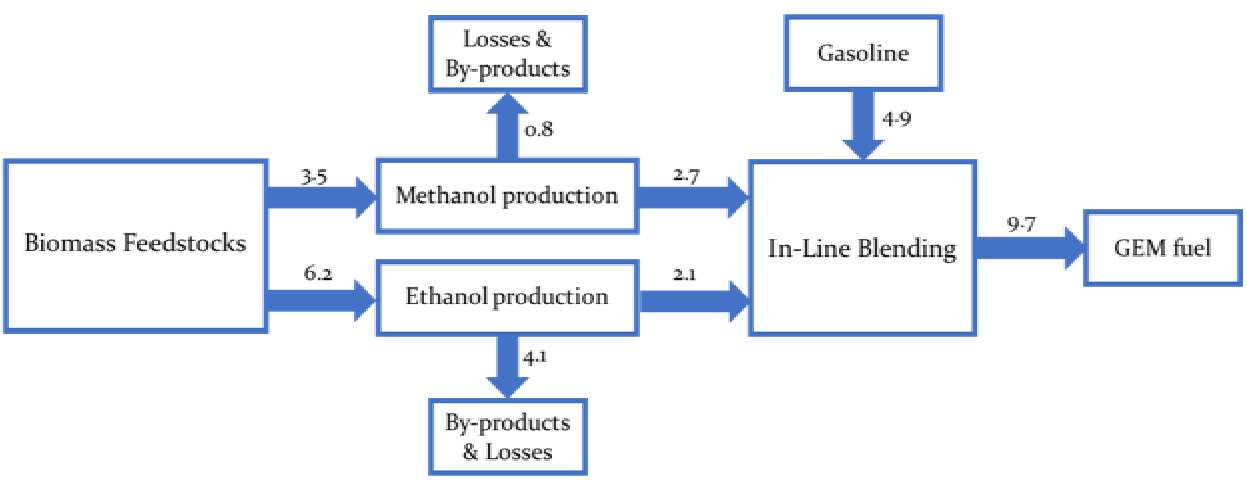
Another technology to blend alcohols and gasoline is by blending the components in the storage tank. The components are added to the storage tank and blended by a pumping system.

- *In-Line blending*

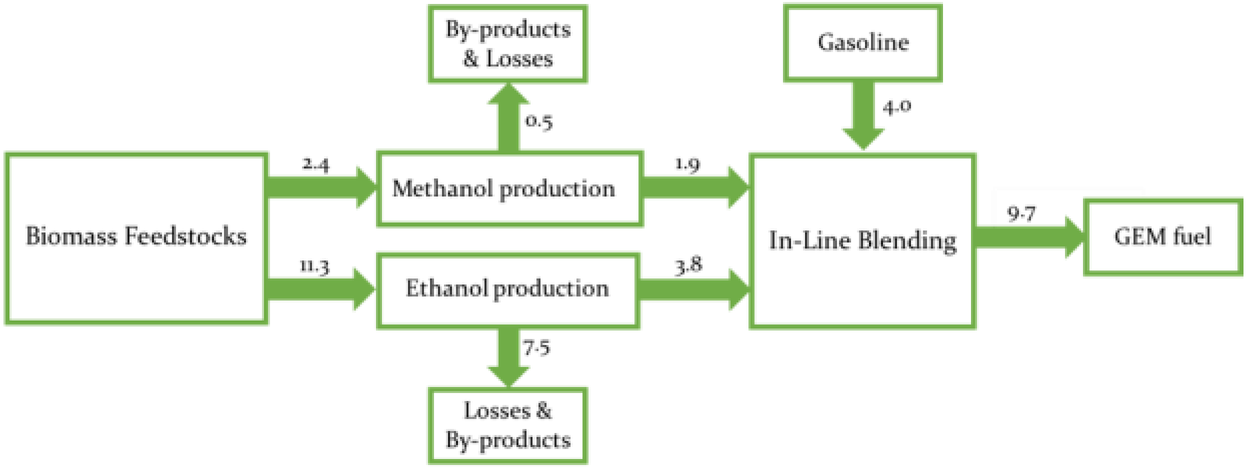
In-line blending is a technology in which the rest of the components are added to the main stream of component. In-line truck blending is globally the most commonly used method of blending alcohols and additives with gasoline. [25] The components are mixed in a pipeline and afterwards added to transporting carrier. As mentioned previously, the In-line truck blending is the technology that is used currently in the Swedish E85 distribution network.

12.11 Energy Flow Diagrams

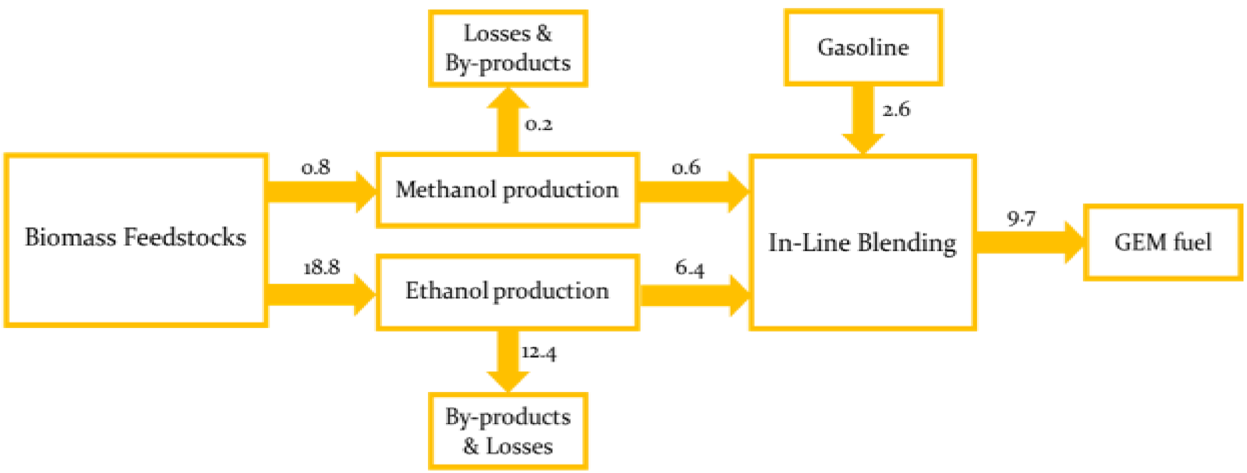
Scenario 1-HM, Energy Flow Diagram(TWh)



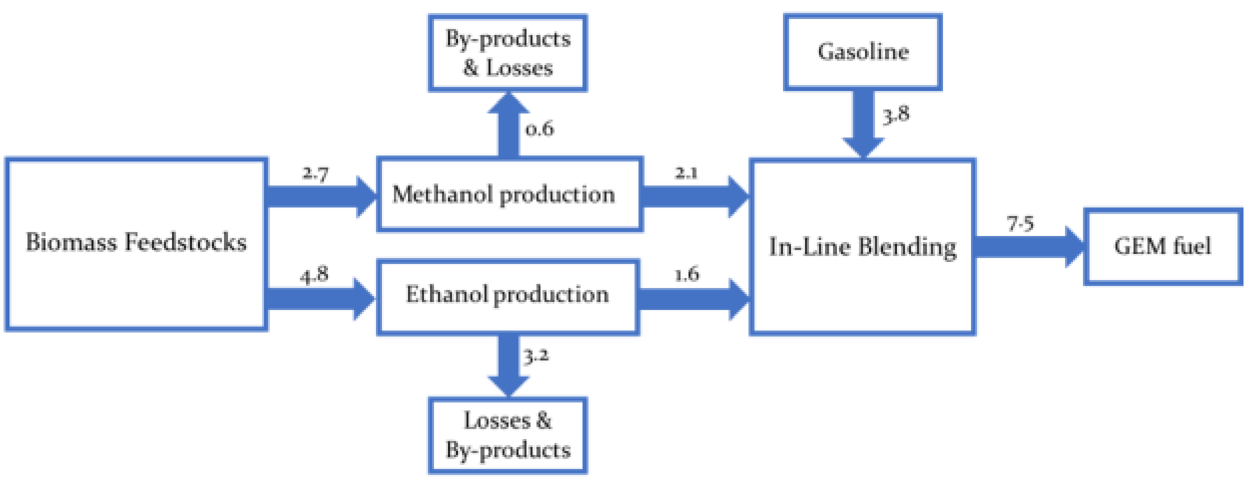
Scenario 1-ME, Energy Flow Diagram(TWh)



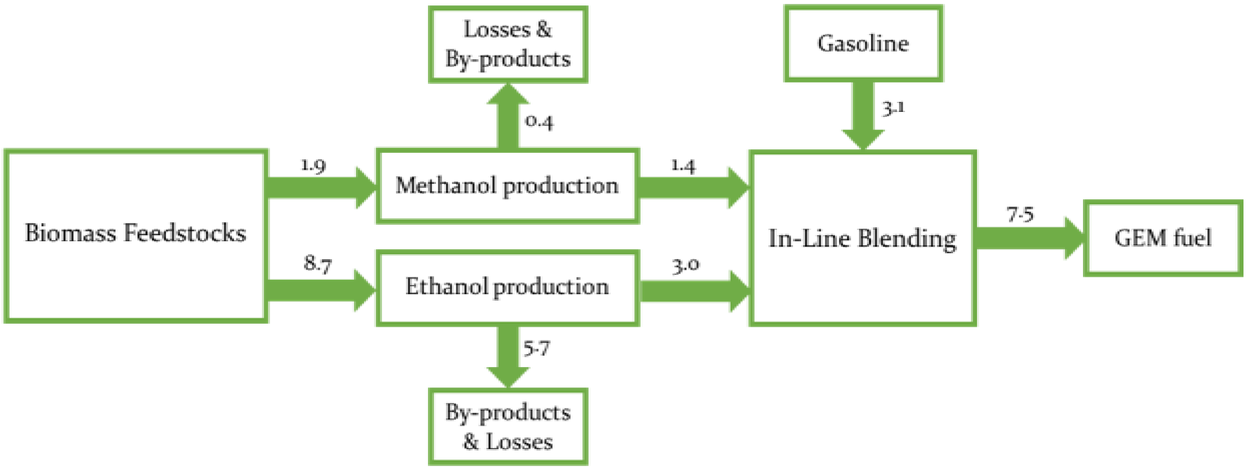
Scenario 1-HE, Energy Flow Diagram(TWh)



Scenario 2-HM, Energy Flow Diagram(TWh)



Scenario 2-ME, Energy Flow Diagram(TWh)



Scenario 2-HE, Energy Flow Diagram(TWh)