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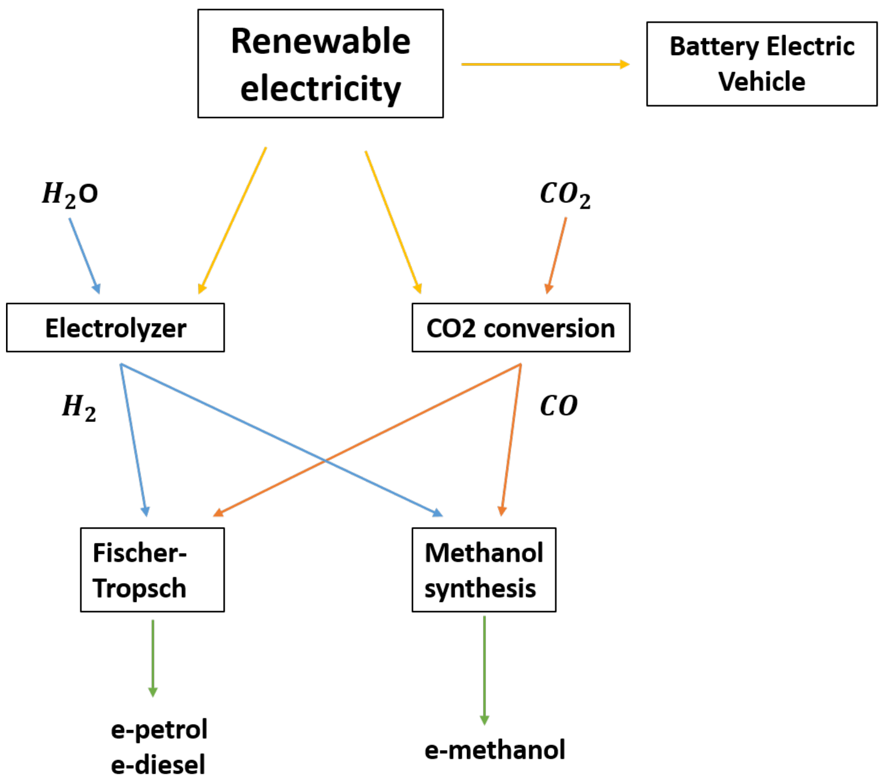

Comparison between Battery Electric Vehicles and Internal Combustion Engine Vehicles fueled by Electrofuels

From an energy efficiency and cost perspective

Master's Thesis in Sustainable Energy Systems

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Cover: Schematic pathway for renewable electricity to electrofuels or Battery Electric Vehicles
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Abstract

Increasing the share of renewable energy used in the transport sector is seen as an important step to globally reduce greenhouse gas emissions. Battery electric vehicles have for a long time been seen as a solution if the electricity is produced by renewable sources, but still suffers from high battery costs and short range issues. As a way to overcome these issues and at the same time keep current car infrastructure, renewable electricity can be used to create synthetic fuels, denoted electrofuels, that are usable in already existing internal combustion engines. This study have investigated which of the two alternatives that would be preferable in different scenarios where both car size and driving pattern is compared. Individual car models have been created and used in different driving cycles to find the specific energy use. Investment and production costs related to electrofuel manufacturing have been estimated to find total cost and energy use. The results show that the BEV is more energy efficient in all investigated scenarios while, however, using electrofuels can in most driving conditions be a more economic solution. A large scale implementation of electrofuels indicate a tremendous increase in electricity demand, where for example 30-93% (depending on fuel type, car size and driving cycle) of the Swedish power production would be needed to be able to produce electrofuels for the entire Swedish passenger car fleet.

Keywords: electrofuels, BEV, e-methanol, e-diesel, e-petrol, driving cycles.

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Tobias Gustafsson & Anders Johansson, Gothenburg, June, 2015

Contents

1
Introduction

The ambitions of the Swedish Government are zero net emissions of greenhouse gases (GHG) for Sweden in 2050 [1]. The vehicle fleet for road based transport should be independent of fossil fuels by 2030 [2], which in the Swedish governmental investigation (FFF-utredningen) was defined as that road based transport should reduce their emissions of GHG by 80% [3]. Increased integration of renewable energy sources is seen as the important step to reach these lower targets on GHG emissions in the future.

Passenger and freight transports contributes to 19% of the energy use and 23% of energy related CO_2 emissions globally [4]. With the global growth of population and economy there are many projections on a great increase of energy use and CO_2 emissions from the transport sector in the future [5]. This is a global challenge and the EU states that all transport related GHG emissions must be reduced by 60% in 2050 compared to 1990 [6]. In directive 2009/28/EC the European Parliament and council demand all member states to have a minimum of 10% renewable energy in the transport sector by 2020 [7].

The transport sector and its actors are highly dependent on a reliable infrastructure to be able to fuel the vehicles whenever the demand arise. But as the majority of the renewable energy production is intermittent and hence, unreliable, integrating the two systems requires a way to balance supply and demand i.e. a way to store the energy at times of overproduction to later be used at times when the demand is higher. One way to solve this is to charge Battery Electric Vehicles (BEV) to let each vehicle operate as a storage unit [8]. This would supply BEV's with cheap electricity that would be used in electrical motors with high efficiency and would decrease the dependency of fossil fuels in the transportation sector. However, BEV's struggle with short driving range problems as well as a lacking infrastructure and expensive batteries and have not yet proven to be the easy solution as many has hoped for [9].

The main propulsion system in vehicles has since the beginning of the 20th century been Internal Combustion Engines (ICE), and being the main powertrain technology of transportation all over the world it has an extensive infrastructure build up around it. However, with the main fuel source originating from fossil resources, large quantities of emissions combined with a low fuel conversion factor of approximately 20% have forced various measures to reduce the contribution to both global warming and local pollution.

Several options to fossil fuels already exists today where biomass-based alternatives are available for both gasoline and diesel. However, the major sources of available and usable biomass compete with food production and have problems to supply the vast amounts needed to replace fossil fuels. To be able to combine current infrastructure with an environmentally friendly energy source, increasing attention is now turned to carbon-based synthetic fuels, known as electrofuels.

Industrial processes to convert electric energy to gaseous and liquid fuels have been known since the 1920s from the Fischer-Tropsch process. Other attempts to produce synthetic fuels occurred during World War II, both with coal and with biomass as feedstock. Since then, several attempts to largely implement for example methanol on the market have been made throughout the years, for example during the oil crisis in the 70's, but have ultimately failed due to the low prices of fossil fuels. With an expected increase in fossil fuel prices, as well as the implementation of a carbon tax, electrofuels may still become a viable solution as a transportation fuel.

When carbon emissions and fuel economy is measured in cars, an industry standard driving cycle is used to simulate a normal driving pattern. This cycle however, does very seldom resemble the actual driving pattern driven by a normal person in an every day situation. Additionally, the different advantages and disadvantages of BEV's and ICE cars are not captured and thus these standard cycles may be a poor method of comparison. Where BEV's, with their regeneration abilities while braking and limited battery size are having an advantage in city traffic, fuels with higher energy density are better utilized during long distance trips with a high power output.

Therefore three different cycles with data collected from urban, rural and motorway driving of a large set of European cars will be examined. This is combined with different car sizes, which driven in a more realistic way will be used to determine the compatibility of electrofuels in the transport sector. These conventional cars will be compared to BEV's to find key factors for implementing renewable energy into the transport sector.

1.1 Aim of the project

This study should compare and evaluate two ways of implementing renewable electric energy in the transport sector. It will investigate what impact BEV's and electrofuels will have on the amount of electricity needed to run cars of different sizes in different environments. The total energy consumption from grid-to-wheel will be analysed and used to discuss the cost and environmental impact of each case. The results will also be compared to conventional petrol and diesel propulsion to further determine advantages and disadvantages of the different alternatives.

1.2 Restrictions

This study should only include modern cars propelled by conventional fuels, electrofuels and/or batteries. The environmental analysis and comparison will cover GHG CO_2 equivalents emissions and will not be a full Life Cycle Assessment (LCA). No attempts to predict the social cost will be made in the report. Only renewable production of electricity and renewable elements needed to form electrofuels are considered. A reference case with the Swedish market will be used as a frame for the results.

1.3 Research questions

- How does the actual total energy use from grid-to-wheel differ for different types of vehicle propulsion systems?
    1. By using more real life driving patterns provided by Volvo Car Corporation instead of the European standard cycle the study will pin point which propulsion alternative that real life driving benefits from.
- What impact does the different propulsion systems have when focusing on environmental, economic and energy efficiency perspectives?
    1. By modelling vehicle characteristics for different car sizes and propulsion systems one can determine how much energy each car consume at specific points and overall in the drive cycles. Focus lies on evaluate how to best use electricity in future passenger cars.
- What benefits/downsides come with using electrofuels in the ICE?
    1. How much can engine efficiency be improved by increased octane number in the electrofuels (e.g. methanol and synthetic petrol)?
    2. What downsides are there (life time of seals, reducing specific energy content etc...)?
    3. Can increased engine efficiency outweigh the extra production energy needed to increase the octane number of synthetic fuels?
- Under what circumstances (car size and driving pattern) can electrofuels be a more attractive fuel option for cars compared to electrified cars, measured from CO2-emission, energy and cost per km?

1.4 Report layout

Following report layout will be used to guide the reader. Chapter 2 gives a background to the topic and the different subjects crucial for the study. Thereafter Chapter 3 explains the methodology used, both in terms of calculations and models but also assumptions made to be able to achieve results. Results and discussion can be found in Chapter 4 and 5 and is followed by the conclusions in Chapter 6. Some extra information about the engine models as well as results from the sensitivity analysis can be found in the Appendices A and B.

2
Background

Following sections will describe the different types of electrofuels, investigated in this report, and the corresponding production methods. The alternative, using electricity to propel a BEV and how that works will thereafter be explained. The sections will also present the different driving cycles that are commonly used to compare different cars regarding performance and emissions as well as to give a background to uncertainties and implications of using them as they are used today. The final section will present the different cars that will be used for comparison.

2.1 Electrofuels

Ever since the industrial revolution fossil fuels have been used as the worlds main energy source as they have proven to being a relatively cheap fuel with a high energy density. They have especially been important in the transport sector where the amount of fuel that is possible to carry is limited. For heavy-duty, aviation and commercial ocean applications there are today few alternatives while light-duty vehicles, however, have the possibility to be electrified. Even so, as more than 90% of the worlds vehicle fleet is dependent on liquid hydrocarbon fuels, these will remain a major part of the fuel infrastructure in the foreseeable future[10].

Fossil fuels are the result of organic matter being put under high pressures and temperatures millions of years ago [11]. All fossil fuels are made up by hydrocarbon chains of different length and composition [12], from the simplest molecule methane to petrol, which can consist of up to 250 different hydrocarbons species [13]. When a hydrocarbon fuel is fully oxidized the exothermic reaction converts the carbon in the fuel to carbon dioxide CO_2 and the hydrogen to water H_2O. The result is a large heat release that can be used to produce work while the products are emitted as exhaust gases [14]. As CO_2 is also a Greenhouse Gas (GHG) the large use of fossil fuels over the years has lead to a global temperature increase, with negative impact on the environment[15].

In the beginning of the twentieth century the invention of the Sabatier reactor made it possible to reverse the combustion reaction by re-energizing H_2O and CO_2 to form CH_4, and the Fischer-Tropsch reactor a few years later made it possible to produce hydrocarbons of any size and composition. The combination of a large energy input required in the process together with the low prices of regular fuels however, lead to a limited use. Due to worries of climate change the process have in the recent years once again received increased attention. Electrofuels is the common name given to hydrocarbon fuels produced from carbon dioxide and water using electricity as the main source, which actually is a reversed process to the combustion reaction.

2.1.1 Production overview

To produce renewable electrofuels both the energy input and the elements to form the molecules have to come from non-fossil sources. Today a lot of the commercial H_2 production is made by reforming CH_4 from natural gas [16], a method that for electrofuel production only would be contra productive regarding emissions. H_2 produced by using electricity to split the H_2O molecule into its elements is called electrolysis.

In Figure 2.1 an overview of the common production steps to produce electrofuels can be seen. H_2 fed from the electrolyzer are put into a reactor together with CO_2 or CO, and depending on which end-product that are requested different types of reactors are used.

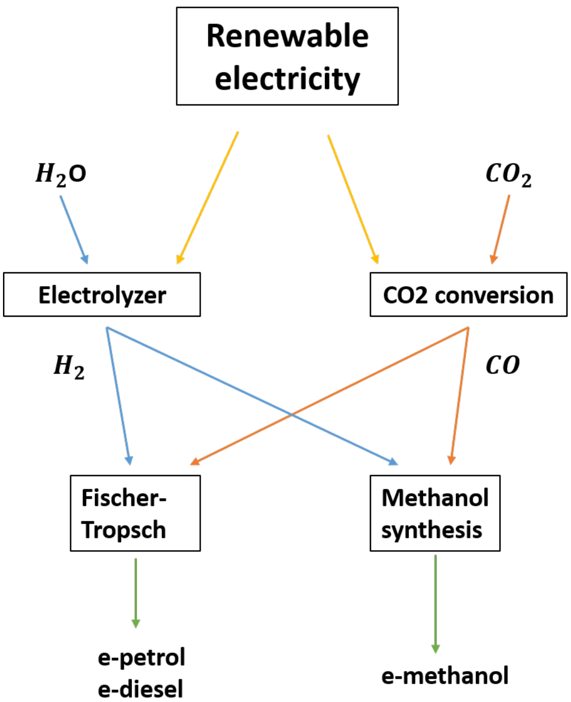

Figure 2.1: The figure shows a schematic view of electrofuel production, with the two pathways of the three different fuels investigated in this study.

Two common types of electrolyzers are currently used: alkaline and Polymer Electrolyte Membrane (PEM)[17]. Both operates in the range of 60-80°C, the alkaline using an alkaline solution (potassium hydroxide) to separate anode and cathode while the PEM are using a solid membrane electrolyte. Both systems have an efficiency from electricity to chemically stored energy of 50-70% [18]. The electricity demanded by the process is preferably supplied from renewable energy production.

The main feedstock for carbon atoms is CO_2, which can be collected in several different ways. Common sources include extraction from air or water or separation of flue gases from industrial processes, power production or biofuel production. To maximize the process efficiency and minimize the cost the CO_2 source should be as pure as possible. As the CO_2 concentration in air and water is very low and no commercial technologies are currently available, this technique will not be included in the study.

Carbon Capture and Storage (CCS) is a collective name for techniques that can be used to avoid CO_2 emissions from power production and industrial processes. Instead of storing the CO_2 it could be used as a feedstock for electrofuels, such processes are expected to be commercial within some years. In biogas production a syngas is created through gasification of biomass and then upgraded to have the sufficient level of CH_4. Left in flue gas is mainly CO and H_2 which instead of being emitted to the atmosphere, could instead be supplied to an electrofuel process. This would ensure that almost all products from the gasification process is used.

As mentioned earlier the H_2 and CO_2 or CO are supplied to a process where they are converted to hydrocarbons. The Fischer-Tropsch process is commonly used when more advanced hydrocarbons are requested. It is possible to create a large set of different hydrocarbons by polymerization reactions, where the requested product is achieved by either extraction or further upgrading [19].

As a large variety of electrofuels can be created and this study will mainly focus on three different types: methanol, synthetic petrol and synthetic diesel, which hereafter will be denoted e-methanol, e-petrol and e-diesel. E-petrol and e-diesel, which can be blended with conventional fuels in all concentrations and thus utilize today's fuel infrastructure, are attractive options and can easily be implemented. E-methanol is the simplest liquid hydrocarbon and is therefore evaluated under the assumption of having the lowest production cost. As a neat fuel for combustion engines, it is currently used in some racing sports and is also possible to blend in petrol where European fuel standard allow 3% methanol in conventional petrol. Higher blends and even pure e-methanol are possible to implement if minor changes to vehicles and infrastructure are made. The following sections will give a background to each fuel and their applications.

2.1.2 Methanol

Containing only one carbon atom, methanol (CH_3OH) is simplest of the alcohol molecules, belonging in the group of oxygenated hydrocarbons. It has been known since the 17th century and was produced by distilling wood material, why it is also known as wood alcohol [20]. The French chemist Paul Sabatier was in 1905 the first to suggested a synthetic pathway to methanol production, which with further development made it possible to produce the liquid in the large quantities needed for the chemical industry. Today methanol can be produced in various ways where the raw material H_2 combined with CO are fed into a process, most commonly a methanol synthesis process or a Fischer-Tropsch process. The carbon source can include gasification of wood, agricultural by-products and municipal waste, however, the current main source is from fossil natural gas, mainly consisting of CH_4.

The use of methanol, as well as ethanol, as a transportation fuel is as old as the ICE itself but have due to low oil prices and being heavy opposed by the oil companies never been a true competitor to fossil fuels[20]. Methanol have been seen with increased attention during times of short supply, as World War II or the oil crisis in the 70s, but have not managed to remain an alternative to fossils afterwards. As an attempt do decrease emissions the state of California have in the last decades been trying to promote the use of methanol cars, with a peak in 1997 with 20 000 units used. Nowadays the methanol cars have mostly been replaced by ethanol, fuel cells and BEV's as the main environmentally friendly car.

Methanol have several properties which makes it suitable to use in an ICE. Pure methanol has an Research Octane Number of 108.7[21], considerably higher than petrol, and can therefore be used under higher compression ratios which result in higher theoretical thermal efficiency. It also has a high flame speed and allows a faster and cleaner combustion, which result in very low emissions from air pollutants as NOx, particulates and hydrocarbons. It can also be used as a drop-in fuel in petrol to increase efficiency as well as decrease both global and local emissions and the share of fossil fuel used when produced in a sustainable way. Another possible area where methanol can be used in the future is as an on board source of hydrogen to fuel cell vehicles which then allows for a higher energy density of the fuel than storing pure H_2 would offer [20].

To be able to use pure methanol in an ICE a few modifications have to made to the engine. These changes includes adjusting or switching pipes and plastic materials as methanol can corrode metals like aluminium and zinc (however, not steel and cast iron) and react with plastics. Cold-start problems that might arise from the low volatility compared to petrol can be solved by adding small quantities of more-volatile components such as butane and pentane to ensure ignition [20]. The main downside is however, the Lower Heating Value (LHV), about half of the petrol and diesel properties, which can be seen in Table 3.3. To ensure the same driving range as its competitors a larger fuel tank has to be added.

Theoretically, methanol ca be used in both Spark Ignition (SI) and Compression Ignition (CI) engines. However, due to methanol being substantially immiscible with diesel due to the different structures of the molecules[20], methanol is often used in an SI engine as this allows the engine to run on methanol, petrol or a mix of them. Adding large amount of methanol to diesel also forces use of additives to compensate for the low cetane number of methanol.

Methanol has been seen as a possible replacement to fossil fuels for a long time and attempts are continuously made to set up large scale production to be able to meet the demand at a competitive cost. As the shipping industry are facing large restrictions regarding emissions and where no other options currently exists, methanol propulsion is already in use in a Stena Lines ship running in Kattegatt and the Baltic sea which will be implemented in 24 more ships if proven to be a satisfying solution [22]. Even though the majority of the methanol production originates from natural gas, production from sustainable sources is emerging around the world. On Iceland, Carbon Recycling International have been producing e-methanol since 2006 completely based on sustainable sources with a current production capacity of 4000 tons of methanol per year [23]. The electricity used to split the water is produced from a mix of hydro, geothermal, wind and solar while the CO_2 is captured as a waste stream from a geothermal power plant. As part of the Icelandic governmental policy to use the large and cheap amounts of electricity available for domestic production, the produced e-methanol is then sold to other countries as a high density energy source and chemical feedstock. Hence, a commercial and sustainable production method of e-methanol is available today.

To summarize, methanol is a mature and well-known alternative fuel that however, never been able to compete with the prices of fossil fuels. With increasing legislation on fossil emissions and pollutants, methanol is more and more seen as a future complement or replacement to fossil fuels.

2.1.3 e-petrol and e-diesel

Petrol has since the beginning of the 20th century been the main fuel used in cars all over the world. Ever since the invention of the Fischer-Tropsch synthesis the possibility to produce gasoline and diesel in a synthetic way have been available, but due to low oil prices it has very seldom been profitable. However, during times of low supply, which took place in Germany during World War II or in South Africa during the boycott years of the Apartheid era [20], the method has been used by reforming syngas to liquid fuels.

Recently, Audi launched the opening of a pilot factory located in Dresden where e-diesel is produced [24]. Using ambient air as CO_2 source and sustainable energy as energy input the test plant will be able to produce approximately 130 litres of synthetic diesel per day, stated to have a high cetane number and being able to blend in any ratio with fossil diesel. The factory use a reversible electrolyzer with the efficiency estimated to 90% and a power to liquid stated efficiency of 70%. With plans to soon launch a full-scale factory, this proves the increasing interest for electrofuels in the automotive industry as a way to cope with increasing emission legislation's. Both e-diesel and e-gasoline will therefore be a part of this study.[25]

2.2 Battery Electric Vehicles

Battery electric cars are propelled by an electric motor which uses electric energy stored on board in batteries. In some cases the car is equipped with a so called range extender to charge the batteries on road. The range extender can be a small ICE or some other machine that converts another energy form to electric energy while driving.

The electric engine does not resemble the characteristics of the conventional ICE, which efficiency is dependent on load and engine speed in a much greater extent then the electric motor. Overall the electric motor has very high efficiency on all loads and engine speeds compared to the ICE i.e much greater efficiency span. One more advantage for the electric motor is the instant torque delivery right after the first start of engine revolution. This means that an electric motor can utilize only one gear instead of a complete gearbox and that increases efficiency and lowers the complexity of the drivetrain. [26]

Electric cars have the advantage of utilizing the electric motors as brakes and generate electricity to charge the batteries instead of dissolving that energy to heat through the friction brakes. This is called regenerative braking and only possible to do within certain brake powers before the conventional friction brakes have to take over the deceleration process. The driving style of people using BEV's therefore have a great impact of the car's total energy demand and possible range. This is also true for ICE driven cars but will make a substantially larger impact on BEV's due to the regenerative braking.

The drawback for BEV's is the significantly lower energy density in batteries compared to petrol and diesel. To reach the same energy density carried by a conventional petrol or diesel tank a very large battery pack is required. The battery pack is both large in volume and mass compared to the conventional petrol or diesel tank carrying the equal amount of energy.

2.3 Driving cycles

To be able to independently compare performance, emission certifications and fuel labeling of car models from different manufacturers driving cycles have for a long time been used [27] with the idea to standardize how a car is driven. The car investigated is put into rolling road dynamometer where the driver follows the chosen cycle in a controlled way where often clutch engage and gear shift as well as acceleration, speed and deceleration are strictly prescribed [28].

Finding a cycle that can represent both driving patterns in urban areas and on highway, long and short distance travels as well as capturing variations in different countries have proven to be a difficult task [26]. This has lead to a vast number of different cycles used over the years, all with certain pros and cons. Since 1990 the New European Driving Cycle (NEDC) has been used as the standard cycle in Europe. It is divided into two parts, one with low speed and one with high speed with several start and stops, as can be seen in Figure 2.2. However, NEDC has been criticized for only covering a small area of engine operation range and therefore allowing car manufacturers to optimize the emission performance and fuel consumption which does not resemble the real-life emissions [29].

As a way to better represent European driving patterns the ARTEMIS driving cycles were launched in 2004 [30]. By collecting detailed data (e.g. speed and acceleration) from 77 private cars in France, UK, Greece and Germany driving, in total, 88 000 km, three sets of real-world driving cycles were created: urban, rural road and motorway. These can be seen in Figure 2.3.

The urban cycle represent driving in a city and are therefore mainly consisting of low velocities and start-stop driving. In the rural cycle velocities are increased and the number of start-stops are decreased while the motorway cycle only contain one stop where the rest of the cycle consist of constant high velocities. The different implications this have on cars and fuel consumption will be further discussed in section 3.1. Due to the nature of the data collected, the cycles vary in length.

As this study aim to investigate the real-life implications of using electrofuels or BEV's in passenger cars the three ARTEMIS cycles were chosen to represent common driving patterns where the different advantages and disadvantages of the fuels can be investigated.

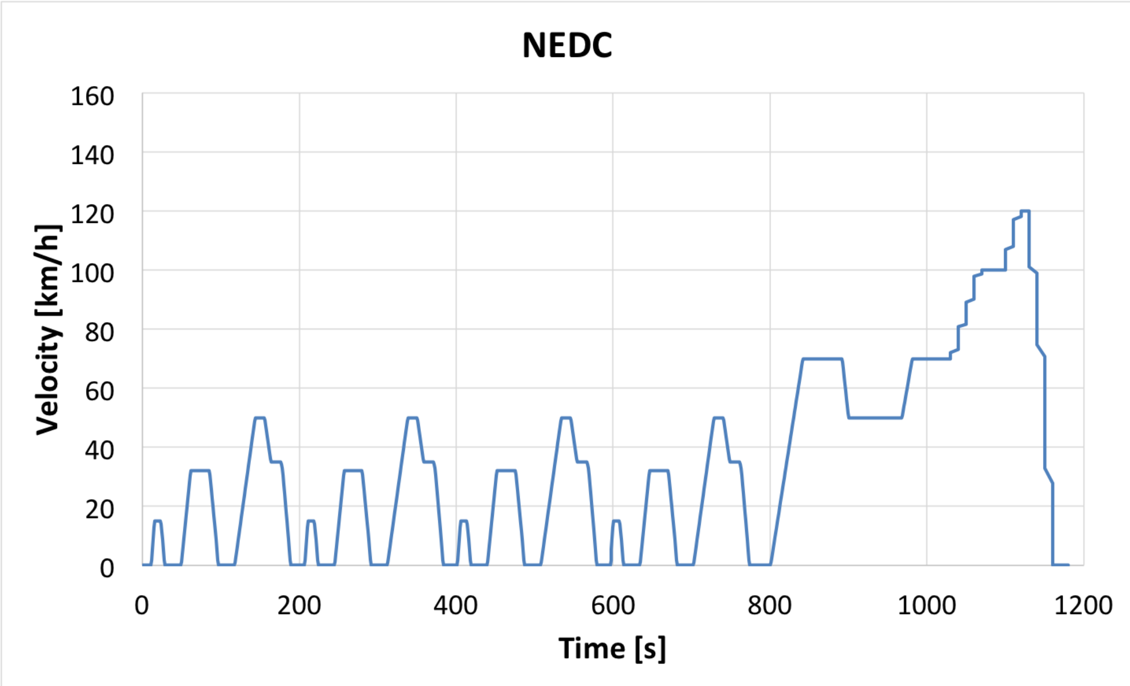

Figure 2.2: The NEDC-cycle is as a standardized driving cycle which is used to determine emission certification and fuel sampling of passenger cars in Europe. However, the cycle is often accused of not representing a normal driving pattern.

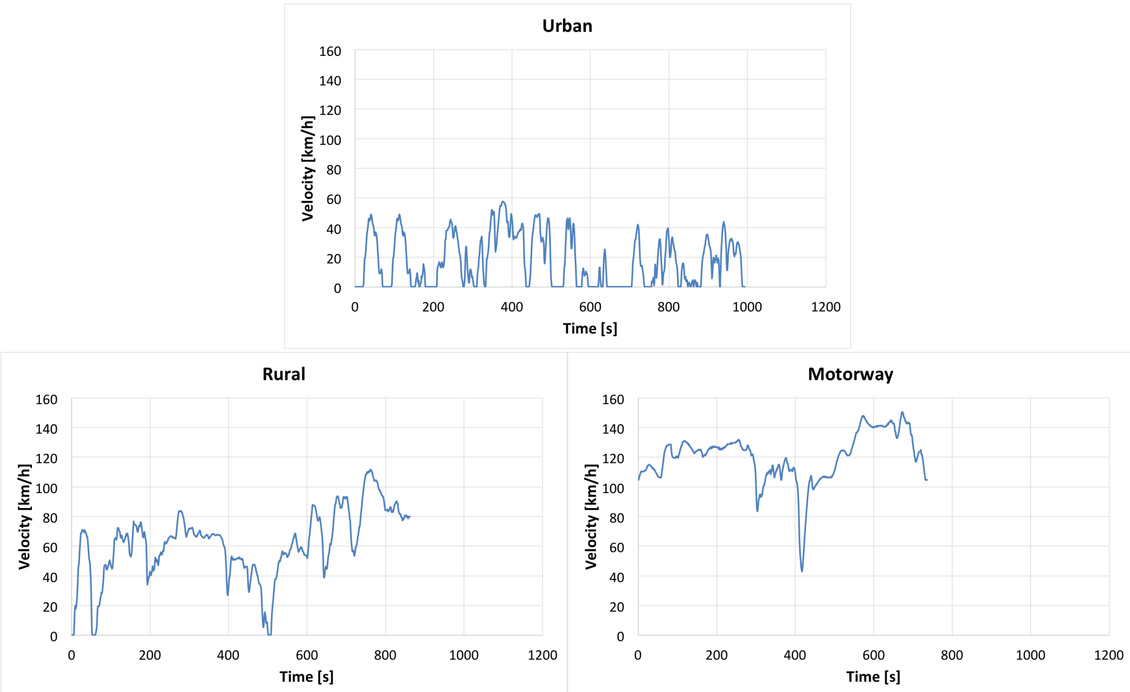

Figure 2.3: The figure shows the velocity profile of three driving cycles used in the study: urban, rural and motorway. The city cycle is dominated by low velocities and many start-stops, while high constant speed is significant for motorway.

2.4 Volvo vehicles

The study compares three different car sizes with official data provided by Volvo Car Corporation. They are defined as size small, medium and large with model details specified in Table 2.1. These specifications are considered base case for petrol and diesel driven cars in the study. Three sizes are used to accentuate the variation and the impact of car size with the chosen driving pattern. All ICE's have four cylinders, 2 litre engine displacement and are turbocharged.

Table 2.1: The table shows specifications used for modelling of the three Volvo cars.

Properties	Small	Medium	Large
Model name	V40	S80	XC90
Mass [kg]	1572	1726	2137
CxA[a] [m^2]	0.63	0.68	0.92
Tire circumference [m]	1.93	1.99	2.31
Tank volume [l]	60	70	71

The chosen car models are displayed in Figure 2.4, all models are or were recently available with the chosen engine, gearbox and wheel setup in both the petrol and diesel application [31]. The sizes represent common car sizes in Sweden and the smallest have the national average weight. It is also noticeable that large cars are more frequently sold in both Sweden and all over the European market than the rest of the world [32] which means that the cars weight do not represent average cars from a global perspective but are a good estimate for the Swedish market.

Figure 2.4: The figure shows the three Volvo cars chosen in the study, V40, S80 and XC90 from left to right.

[a]Cx is the drag coefficient while A is the car frontal area. Together they determine the air resistance of the vehicle.

3
Methods

This study is focused on comparing and evaluating electrofuels on the passenger car market and investigate under what circumstances electrofuels could be the favorable choice of fuel. To create leveled circumstances for cars of three sizes and four different propulsion technologies, a simplified car model, here after denoted VC-model[1] in MATLAB was developed. This model is the first part of the comparison and provides the study with fuel consumption and energy demand figures. The second part consist of a model concerning the economical and environmental effects for each chosen combination of size, driving pattern and propulsion system. Together the two models will provide the study with Grid-To-Wheel (GTW) information for each case.

3.1 VC-model tank-to-wheel

The first part of the comparison estimates the tank-to-wheel (TTW) energy demand of each chosen car size and drive cycle in the MATLAB calculation VC-model. The models are all able to follow the different driving cycles and hence be able to use velocity and acceleration at any given point to calculate energy use and emissions from the car.

3.1.1 Internal combustion driven cars

To model the ICE cars dynamic models of each Volvo car were created which the respective fuel dependent engine models were fitted to. One conventional petrol engine and one conventional diesel engine were provided by Volvo Car Corporation. The diesel engine were adjusted to resemble a methanol fueled engine. A detailed description can be found later in this section.

The petrol engine model took its start by determining the energy needed to propel the car for the different acceleration and velocity demands given by the driving cycles. The least amount of energy needed is found by calculating the forces that affects the car: aerodynamic resistance, acceleration, roll resistance and gradient resistance. The minimum effect that have to be delivered at a specific moment is found by adding the forces together and multiplying with the velocities from the driving cycle. The formulas can be seen in Equation 3.1 through 3.5.

$$F_{aero}(t) = 0.5 * m * \rho_{air} * C_x * A * v(t)^2 \tag{3.1}$$

[1] VC=Vehicle Characteristics

$$F_{acc}(t) = m * a(t) \tag{3.2}$$

$$F_{roll}(t) = m * g * c_r * cos(\alpha(t)) \tag{3.3}$$

$$F_{grade}(t) = m * g * sin(\alpha(t)) \tag{3.4}$$

$$P_{tot}(t) = (F_{aero} + F_{acc} + F_{roll} + F_{grade}) * v(t) \tag{3.5}$$

The total mass that has to be transported is denoted m, the current velocity and acceleration are denoted v and a respectively. In Equation 3.1 the air density ρ_{air}, drag coefficient C_x and frontal area A all effect the aerodynamic resistance. The rolling friction coefficient c_r is dependent of the surface and tyre deformation which are not completely elastic. For all investigated driving cycles the data has been collected on a flat road and the road gradient α is therefore set to zero. Hence, Equation 3.4 can be neglected. An example of the different share of forces can be seen in Appendix A where the forces of a large car driving in the motorway cycle have been calculated and plotted.

Unfortunately, not all fuel that is put into the car is converted into useful energy. The biggest loss takes place in the combustion process where a large portion of the fuel is turned into waste heat instead of mechanical work. The transmission system as well as choice of gear also affects the amount of power that have to be supplied by the engine to the transmission. The transmission efficiency, where losses occurs from mechanical conversion in axis movement and gear connections, is here assumed to be 95%, see Figure 3.1.

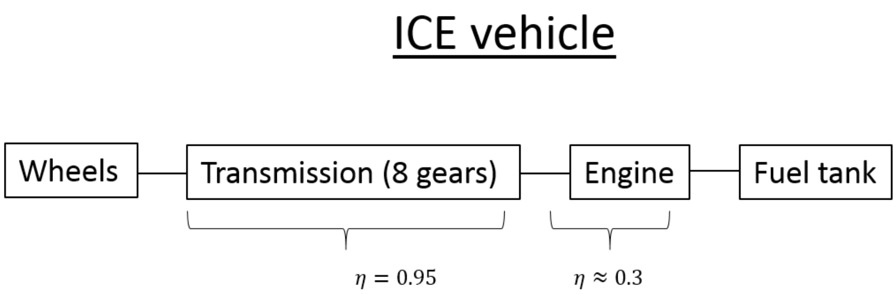

Figure 3.1: A schematic view of the ICE model. All variations are using eight gears with the transmission efficiency set to 0.95. The engine efficiency is dependent on both fuel and load and is determined from the brake specific fuel consumption map.

The power developed by the engine is a combination of torque and Rotations Per Second (RPS). The engine RPS is determined from the RPS of the wheels, which are connected through the transmission system. By using different gears this relation can be changed and allows the engine to work within a more narrow span of RPM and torque than otherwise could be achieved. This makes it possible to keep the engine within a specific working range where it can be adjusted to be more efficient.The gear ratios used in the VC-model are based on the car data explained in Chapter 2.4. A suitable gear is chosen for each measurement point by determining velocity spans combined with the acceleration needed. During which conditions a certain gear is chosen can be seen in Table 3.1 and 3.2

Table 3.1: Gear choice for low acceleration levels

Gear	**Car speed** $[km/h]$	**Car acceleration** $[m/s^2]$
1st	0<15	-
2nd	15<25	-
3rd	25<35	-
4th	35<45	-
5th	45<60	<0.5
6th	60<70	<0.5
7th	70<85	<0.5
8th	>85	<0.5

Table 3.2: Gear choice for high acceleration levels

Gear	**Car speed** $[km/h]$	**Car acceleration** $[m/s^2]$
3rd	25<40	>0.5
4th	40<70	>0.5
5th	70<85	>0.5
6th	85<100	>0.4
7th	>100	>0.3

By determining the engine speed needed at a certain car velocity, the resulting torque demand can be calculated. With the help of a Brake Specific Fuel Consumption (BSFC) map, a matrix where the specific fuel consumption have been measured for a large set of combinations of engine RPM and engine torque loads, the specific fuel consumption can be found for all possible car velocities in the drive cycle. An example of a BSFC map can be seen in Figure 3.2, where the diesel map used in this study is shown.

For petrol and diesel, BSFC maps for the chosen engines were used. However, one did not exist for the methanol engine and was created under following assumptions. As explained in section 2.1.2 methanol is most commonly used in a SI engine, however, the higher resistance to auto-ignition allows methanol SI engine to use almost diesel-like compression ratios. Therefore a diesel BSFC map is used to find the fuel consumption while compensations are made for pump losses that arise from using a SI engine. The lower LHV of methanol is also compensated by multiplying the diesel fuel flow with the LHV ratio to get the true methanol fuel flow.

Apart from fuel consumption at different speeds several functions is added to simulate a more realistic driving pattern and to include real car functions to the VC-model. An electric load of 1 $[kW]$ is used at all speeds to simulate the use of auxiliary equipment such as radio and air condition powered by the alternator. A start and stop function where the engine is turned off if the car stands still for more

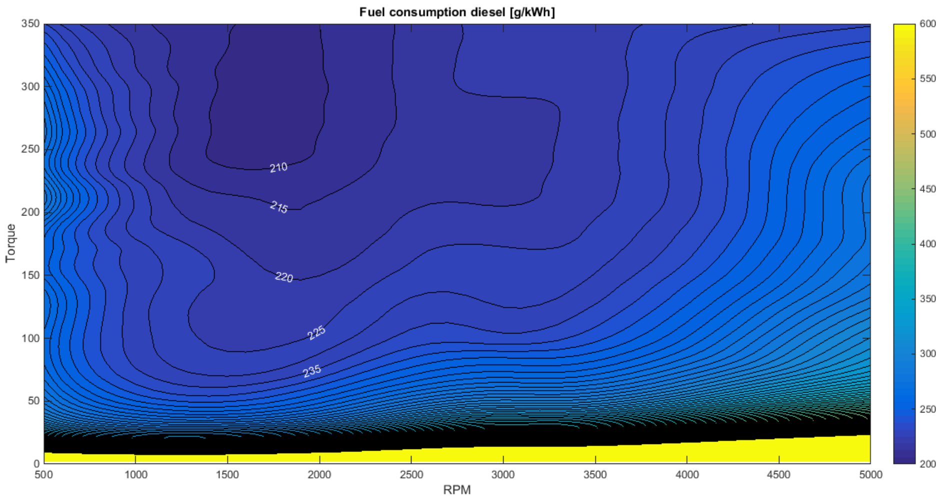

Figure 3.2: The figure shows the brake specific fuel consumption map used for the diesel engine in the study. Each combination of RPM and torque will end up in an area where the fuel consumption in $[g/kWh]$ can be found.

than two seconds and started one second before the car runs again, is also used to reduce the fuel consumption. To further implement the functionality of normal car behaviour, a clutch function is added to ensure torque limiting slip and free rolling at slow velocities during start and stop of the car.

3.1.2 Battery electric vehicle model

The configuration of a BEV is slightly different compared to a conventional car: due to the use of an electric motor the energy supply have to be exchanged from a fuel tank to a battery while the transmission system and gear box can be simplified. A schematic view of the BEV part of the VC-model can be seen in Figure 3.3.

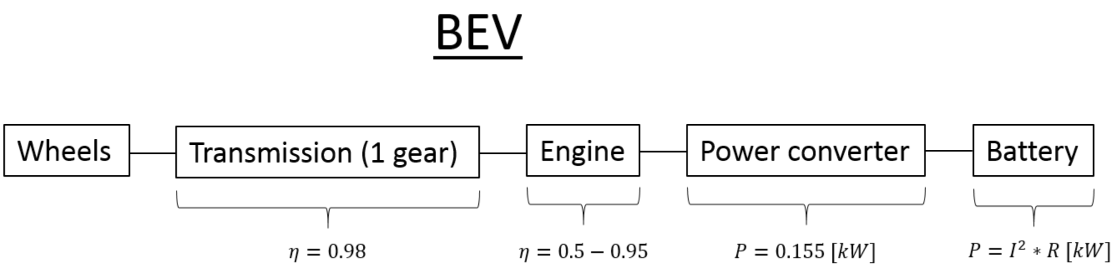

Figure 3.3: A schematic view of the BEV part of the VC-model which unlike the ICE car only uses one gear for all loads. The power converter losses are assumed constant for all loads while the internal losses in the battery are dependent on the current.

The BEV have a different type of powertrain compared to the conventional ICE vehicle, however, the two systems are assumed to have the same weight. The calculations to determine the least amount of force needed to propel the car are therefore the same as for the ICE model except for the extra weight added by the batteries. The BEV transmission system only consist of one gear since an electric motor has full torque capacity from first start of engine revolution. One gear reduces the transmission losses which is constantly set to 0.98 throughout all conditions.

The electric motor used is a 350 $[V]$ interior permanent magnet synchronous motor using alternating current. A power converter is used as a link between the battery and the motor to both shift the power from AC to DC and regulate the power output. Losses from the conversion are set to 0.15 $[W]$ when torque is applied, as shown in Formula 3.6. A similar map as the BSFC is used to calculate the efficiency and current demand based on torque and rpm. The internal losses in the battery are dependent on the current and are calculated using Formula 3.7 where the resistance is set to $R = 0.088[\Omega]$ per 12 $[kWh]$ of installed battery capacity. As for the ICE model, the auxiliary loads are assumed to be 1 $[kW]$.

$$P_{loss_{converter}} = 0.15\,[W] \tag{3.6}$$

$$P_{loss_{internal}}(t) = I(t)^2 * R\,[W] \tag{3.7}$$

One of the main benefits of using an electric motor is that it also can be used as a generator when run on negative load. When this is done the kinetic energy of the vehicle is transformed to electrical energy. This reduces the vehicle speed and the generator can therefore be used when braking is wanted. This method can, however, only be used to a certain braking power level to avoid overheating the battery. In this case the regular brakes are used. From a rule of thumb, a maximum regeneration limit in $[kW]$ is set to 2.5 times the battery capacity in $[kWh]$, which means with a battery size of 24 $[kWh]$, the maximum charge and discharge level is 60 $[kW]$. The amount of regenerated power is calculated as the brake power available at the wheels multiplied with the Battery-To-Wheel (BTW) efficiency twice, as the power has to travel from the wheel to the battery and back again to be utilized.

3.1.3 Efficiency calculations

As the different test cycles all vary in length and duration energy and fuel consumption are based on a mean value calculated per driven kilometer. For the ICE the energy input is determined from the fuel flow, the density and the LHV of the fuel. The properties of the synthetic e-petrol and e-diesel are assumed to be the same as the for the conventional products, these values can be seen in Table 3.3.

Table 3.3: The table shows the fuel properties used in the study. Most notable is the low LHV of methanol which is less than half of petrol and diesel.

Fuel	**Density** $[kg/m^3]$	**LHV** $[MJ/kg]$	$\mathbf{CO_2}$ **emissions**[a] $[g\,CO_2/l_{fuel}]$
Petrol	735	44.4	2337
Diesel	835	43.4	2684
Methanol	791	19.9	1083

[a]Tail pipe emissions.

From the table a major disadvantage of methanol compared to petrol and diesel can be seen, the LHV is less than half of petrol and diesel which means that twice the amount of fuel would have to be fed to the engine to achieve the same heat release. However, the higher resistance to self ignition allows for higher compression ratios and thereby a higher thermal efficiency which despite the low LHV still makes it a valid fuel option.

The TTW efficiency is found by comparing the energy needed at the wheels to propel the car to the engine energy input, which comes from either a battery or fuel tank. This shows how efficient the energy put into the car is used by the car, it is an important way to express how to best utilise the produced electricity in the transport sector.

3.1.4 VC-model fuel adaptions

In the customers eyes, fuel and car prices are usually the most important factors of choice. Other important measurements for customers are range capacity and refueling options. To compensate for the LHV value of methanol the fuel tanks on the base models are enlarged when converted to methanol propulsion. This is assumed to be a possible solution but will result in much more difficult packaging of the larger tank volume. The assumed changes of tank volume is presented in Table 3.4.

Table 3.4: The table shows the methanol converted car's new tank size.

Car size	**Tank volume** $[l]$
Small	90
Medium	100
Large	100

In the assumption of converting ICE to BEV of the base models battery sizes are chosen to represent equivalent available BEV on the market. The battery weight which is added to the base car models mass is assumed to be 7.5 $[kg/kWh]$, sizes and added mass are presented in Table 3.5. These battery packages are assumed to be possible to fit in the cars and will result in packaging challenges. The other equipment required for BEV conversion is assumed to be cancelled out by the complete drivetrain change.

Table 3.5: The table shows the BEV conversion battery size and corresponding mass added to the base case car model.

Car size	**Battery size** $[kWh]$	**Battery mass** $[kg]$
Small	24	180
Medium	60	450
Large	85	637.5

With the new fuel tank and batteries sizes it is possible to calculate available range for each car model and fuel type in all driving cycles, this is dependent on either fuel or electricity consumption. The range is found as the possible driving length for corresponding fuel or electric consumption with the carried energy amount.

3.2 Economic and energy use model GTT

The Grid-To-Tank (GTT) model investigates both economic aspects and energy consumption. The economic evaluation considers investment cost and running costs of the car from a production point of view. The running cost is based on the fuel price and is estimated to cover the investment and running cost of the fuel manufacturing plant. Based on the car energy use given from the VC-model the energy input needed to the system is calculated. Finally, the cost and environmental impact per unit can be found. The study uses a base case to find all efficiencies and prices before analyzing how the results would be affected from making different assumptions on the most uncertain parameters in a sensitivity analysis.

3.2.1 Car cost

The investment cost of buying a car is dependent on a large variety of options, spanning from brand and comfort level to performance and style. When modeling the different car sizes and propulsion system, a standardized car was chosen where the different powertrain packages were fitted. The petrol driven car is the cheapest alternative from a manufacturing point of view and is set as the level zero. To this, the extra costs associated with the alternatives is added. This is done to get a good comparison of where the other options differs from today's conventional technologies in price independently on customer choices.

In collaboration with Volvo Car Corporation prices have been estimated on batteries including their accessories as well as on the additional cost for the more expensive diesel after treatment system needed to manage emission legislation. The petrol and the electric drivetrain is considered to have the same cost, however, battery prices is estimated to 140 € per installed $[kWh]$ where an additional cost of 50% of the battery price is added for battery package. The prices are summarized in Table 3.6. Due to the small adjustments that have to be done in order to make a gasoline drivetrain compatible with methanol, this cost is set to zero.

Table 3.6: The table shows the fuel specific incremental cost compared to the petrol powered car, the battery management and packaging is a battery size dependent constant cost.

Propulsion system	**Incremental cost**	**Unit**
Diesel	2000	[€$/car$]
BEV battery cost	140	[€$/kWh$]
Battery management, packaging	Total battery cost * 1.5	[€$/kWh$]

In order to get a fair comparison between different techniques an annuity cost model, shown in Equation 3.8,

$$A = I * \frac{r}{1 - (1 + r)^{-n}} \tag{3.8}$$

is used to spread out the first large cost penalty over the cars economic life time. The economic life time n of a car is estimated to ten years and the average driving length is estimated to 12000 $[km/year]$ according to data from SCB [33]. The interest rate r is set to 5% and the investment cost displayed in Table 3.6 is denoted I in the equation. The annuity cost denoted A divided by estimated driving length over the cars life time form the extra cost for each non petrol propulsion system per kilometer. This is represented as the fixed car cost in the study. The resulting costs for the different car sizes and propulsion systems can be seen in Appendix A.

3.2.2 Grid-to-wheel efficiency

In order to compare using the plug at home to charge a BEV with fueling electrofuels at a tank station, the efficiency of producing electrofuels and their corresponding manufacturing efficiency becomes vital. To find the overall efficiency from grid to wheel the path is divided into four main steps: production, distribution, fueling and TTW.

E-methanol, e-diesel and e-petrol both have the same first step in the production, the electrolyzer. In the base case it is assumed that the electrolyzer have an efficiency of 70% as explained in section 2.1.1. The next step is processing H_2 and CO_2 into a liquid fuel. This is done by either Fischer-Tropsch or methanol synthesis with an efficiency assumed to be 60% and 79% respectively [34]. These steps result in a total production efficiency of 42% and 55% for e-diesel and e-methanol. As the BEV have the advantage of using electricity from the grid as fuel, the production efficiency is assumed to 100% in this study.

The next main step is distribution of fuel. As conventional petrol and diesel already have an existing infrastructure for transport and storage, e-diesel, e-petrol and e-methanol have the advantage of by small means being fitted to the current system. It is assumed that the losses associated with transport and storage for chosen electrofuels is 0.5%. The electricity used for charging the BEV have to be distributed over the electric power system from the origin to the charging point, which is assumed to be at home, and therefore assumed to have 10% distribution losses.

The third main step is fueling the car and in the liquid fuel case there are almost no losses from pump to tank and the assumption is zero losses for this step. In the BEV case charging a battery is associated with some transfer losses from plug to battery, resulting in emitted heat from the device. The losses is assumed to be 10% for charging the BEV.

The last main step is TTW, explained in section 3.1, which is used as input for the GTT model to calculate the GTW efficiency for each case.

3.2.3 Fuel cost model

This study focuses on the production cost without any profit added to the end price to perform the comparison in an objective way. Due to great uncertainties and business secrets, the cost of producing the different e-fuels is based on estimations of investment costs of electrolyzers as well other reactors or processes needed for production. The investment cost for electrolyzers is estimated to 600 [$€/kW$] where the stack needs replacement every 7th year at one third of the original investment cost [35]. The Fischer-Tropsch synthesis and the CO_2 to CO process combined with storage and other accessories are estimated to 200 [$€/kW$], based on already existing facilities that converts gas to liquids [36]. The electrolyzer and Fischer-Tropsch with accessories represent the total investment cost of the factory.

To find the fuel price an annuity cost for the factory is calculated with Equation 3.8 where the estimated life time n is set to 25 years. The fuel cost can then be calculated with equation 3.9 in the unit [$€/GJ$] with electricity prices estimated to 25 [$€/MWh$] for industry users and 75 [$€/MWh$] for domestic users. This equation takes all production related costs in to account, and all variables it contains is explained in Table 3.7.

$$C_{fuel} = \frac{A_{fuel} * f_1}{CF} + OM + D + \frac{E * f_2}{\eta} \tag{3.9}$$

Table 3.7: The table shows explanations of variables used in Equation 3.9.

Variable	Explanation
A_{fuel}	Investment annuity cost
f_1	Conversion factor from [kW] to [GJ]
CF	Capacity factor of the factory
OM	Operations and maintenance cost 4% of the total investment cost
D	Distribution cost, assumed zero in base case
E	Energy input cost, electricity or oil for conventional production
f_2	Conversion factor from [MWh] to [GJ]
η	Energy conversion efficiency

As a result of the output from the VC-model TTW in [l/km] the price in [$€/GJ$] requires to be converted in to [$€/l$], Table 3.3 contains the fuel information used in the conversion. The sum of the fixed costs explained in Section 3.2.1 and the variable fuel costs represents the propulsion system's total car cost per kilometer.

3.2.4 Grid-to-wheel electricity consumption

The idea of electrofuels is to utilize electricity, preferable renewable, to produce fuels. To find out how much electricity that is required to provide cars with electrofuels, the study calculates the corresponding GTW electricity consumption for each case. With the help of the TTW energy use together with electrofuel production efficiencies the study can derive the GTW electricity consumption. The results are, as stated, dependent on the car's fuel or electricity consumption of each case and is thereafter compared with the BEV's total electricity consumption.

4
Results

This chapter presents the results completed by this study and the content is divided into three main parts. A sensitivity analysis in the end is conducted to understand and see the dependency of significant variables.

4.1 Tank-to-wheel

This section present results concerning TTW for all cases. Findings are conceived to get a greater understanding of the different car sizes and driving cycles dependency on energy use. It also gives the foundation for the GTW analysis presented in section 4.2, which gives the overall energy use and costs related to each combination of car and driving cycle.

4.1.1 Energy use

To determine the overall fuel energy input needed to provide a car with enough energy for propulsion the energy use within the car, i.e. BTW and TTW [Wh/km], first have to be determined. In Figure 4.1 the energy use for BEV's and ICEV cars

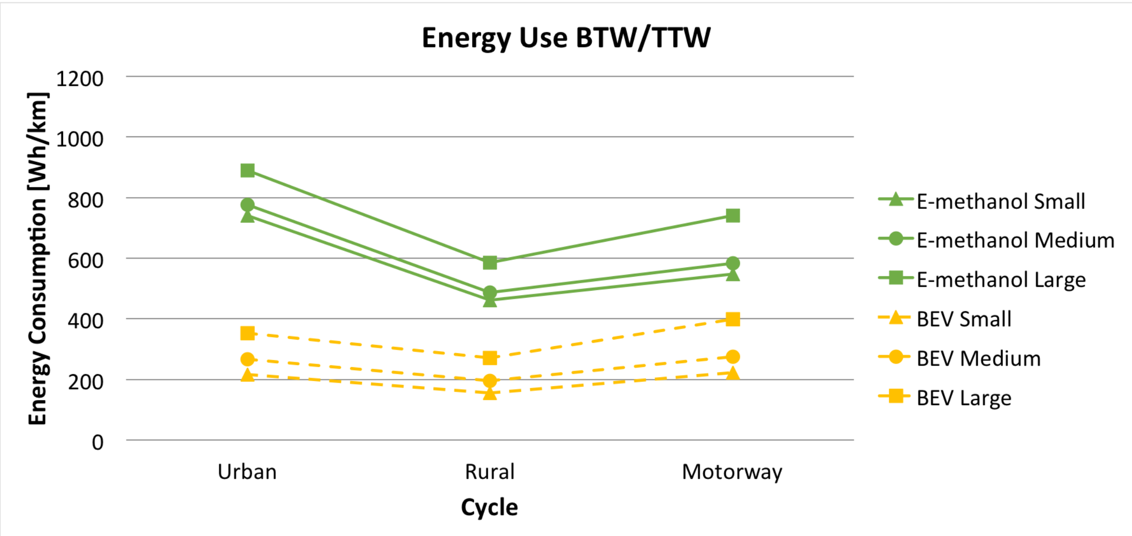

Figure 4.1: The figure shows the energy use BTW/TTW of BEV and e-methanol for all sizes and cycles, the energy use is constantly higher for e-methanol than the BEV cars regardless of size and cycle.

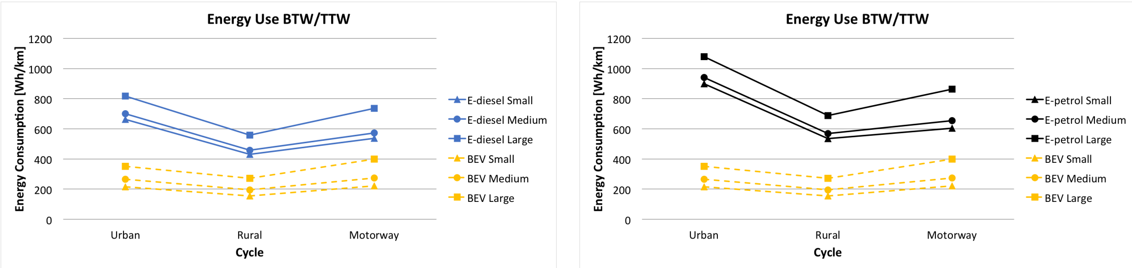

Figure 4.2: The figure shows the energy use BTW/TTW of BEV, e-diesel and e-petrol for all sizes and cycles, the energy use is constantly higher for these two electrofuels than the BEV cars regardless of size and cycle.

run on e-methanol can be seen for the three different driving cycles. The energy use has the dimension $[Wh/km]$ and is a mean value of the the total amount of energy drawn from the tank or battery over the driving cycle, divided by the cycle length. This gives a good estimation of how energy intense a certain driving pattern is.

Two general trends can be seen in the figure: the e-methanol car uses more energy than the BEV and the higher the vehicle weight the more energy is needed. As explained in section 2.3 the urban cycle is dominated by start-and-stop and low velocities This can especially be seen in the urban cycle where the BEV can benefit from the possibility of regenerating a lot of the brake power back to the battery. Therefore only a small difference between urban and rural cycle can be seen, unlike the e-methanol ICE which benefits much more from higher and more constant speeds where the conditions are more suitable for the ICE characteristic.

Since the air resistance is dependent on the velocity squared, the large cars have an extra disadvantage in the highway cycle, dominated by high velocities where both the extra weight as well as the bigger frontal area contributes to a high energy use. All car types have the lowest energy use in the rural cycle where few accelerations are needed and the mean power demand is low. When looking at the e-petrol and e-diesel they follow the same trend as the e-methanol, as can be seen in Figure 4.2.

As explained in the section 3.1.1 the methanol engine is a modified diesel engine with added pump losses when the throttle is not fully open. At high loads, which typically is the case in the highway cycle, only insignificant pump losses occurs in the methanol engine and therefore it has almost the same energy use as the e-diesel. In the urban and rural cycle, on the other hand, throttling occurs and differences can therefore be seen between the two fuels. The petrol engine generally work at lower compression ratios leading to a lower fuel efficiency. Therefore the petrol engine has the highest energy use of the investigated alternatives, almost five times higher than the BEV in the city cycle.

4.1.2 Efficiency

To further explain the big differences in energy use between ICEV's and BEV's the TTW efficiencies are shown in Figure 4.3. The e-methanol cars' efficiencies are in all cycles increased with increased weight. As extra weight means a higher torque demand, this makes the chosen engine work at a more optimal load. When looking at the BSFC map in section 3.2 this can be understood by the engine working point moving into a new area with a lower fuel consumption as a result. However, even though a higher efficiency is achieved with increased weight, a heavier car still consumes more energy, as earlier explained.

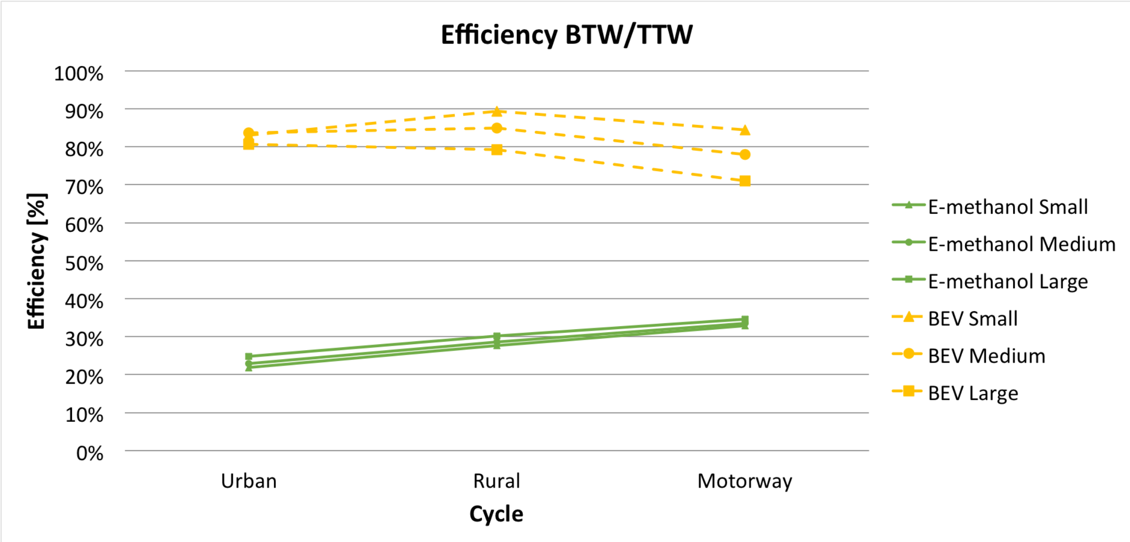

Figure 4.3: The figure shows BTW and TTW efficiency for all sizes of BEV and e-methanol in all cycles.

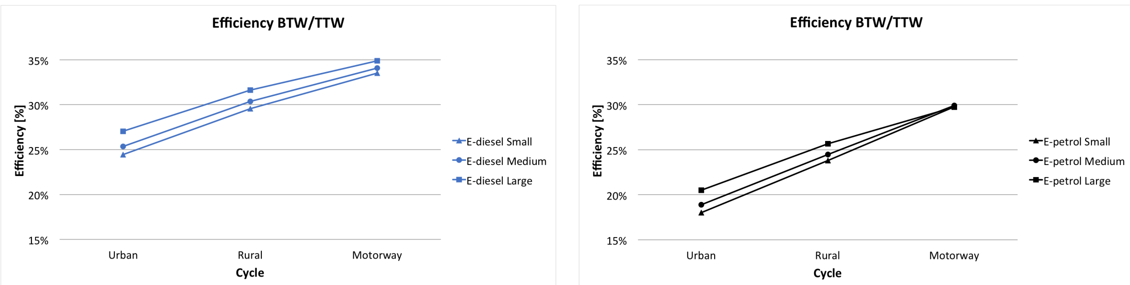

Figure 4.4: The figure shows TTW efficiency for all sizes of e-diesel and e-petrol in all cycles.

The BEV's shows a very high BTW efficiency spanning from maximum 89% to minimum of 71%. The high BTW efficiencies are possible due to very high engine efficiency through out the electric engine's whole working area. The three BEV sizes have similar efficiency in the urban cycle while the difference increase with rural and motorway cycles due to the internal losses dependency on current and hence higher loads results in bigger losses. This also explains why the efficiency of the small BEV is higher than the others, unlike the trends of ICE vehicles. Converting electric energy into mechanical energy is not an exothermic reaction like in the ICE. The converting of energy do dissolve heat but through friction and is much lower than in the combustion process. The BEV's also have a higher efficiency on the transmission with the possibility to utilize only one gear instead of several to fit the ICE's more narrow optimal working point.

The small BEV's efficiency is noticeably lower in the city cycle than the medium sized but responds predictable in the other two cycles in line with the larger cars. This rather strange behaviour is connected to the regenerative braking which is dependent on available wheel power and mass. Larger mass results in both a higher accelerating kinetic energy and thus carries more energy which is available during braking. A larger battery also increases mass but with the downside of more losses internally of the battery because of size dependent losses.

When looking at the other two ICE driven cars, e-petrol and e-diesel shown in Figure 4.4, they follow the same trend as e-methanol but with some exceptions. The e-diesel have a slightly higher efficiency on all cycles than the e-methanol and they are close to the same in the motorway cycle. As explained in Chapter 3.1.1 the e-methanol engine is in this study based on the conventional diesel engine. The e-petrol driven car have a lower efficiency then e-methanol on all cycles and follow the trend explained above with one exception. The motorway cycle on the large car deviates from this predicted trend due to tire choice with standard gearbox ratio, this combination moves the cycle used working point slightly outside the optimal range.

4.1.3 Fuel consumption

To understand and get a feeling of the energy use presented in section 4.1.1 the corresponding fuel consumption is presented in Table 4.1. It shows large differences in volume between e-diesel and e-methanol which is expected considering the fuels different LHV. The e-petrol have a higher LHV and lower density than e-diesel and still consumes a larger volume of fuel per kilometer which again shows how much more fuel efficient the e-diesel engine is compared to e-petrol engine. It also shows the importance of changing tank volume of e-methanol driven cars to compensate for the higher fuel consumption.

Table 4.1: The table shows average fuel consumption for all ICE driven cars in all driving cycles. Sizes denoted S, M and L are short for small, medium and large.

Size & Fuel	**Urban** $[l/100km]$	**Rural** $[l/100km]$	**Motorway** $[l/100km]$
S e-methanol	16.9	10.5	12.5
M e-methanol	17.7	11.1	13.3
L e-methanol	20.4	13.4	16.9
S e-diesel	6.6	4.3	5.3
M e-diesel	6.7	4.6	5.7
L e-diesel	8.1	5.6	7.3
S e-petrol	9.9	5.9	6.7
M e-petrol	10.4	6.3	7.2
L e-petrol	11.9	7.6	9.5

4.1.4 Range

To highlight the difference between the amount of energy carried and the consumption of each case in the three driving cycles the possible driving range were calculated. The driving range for e-methanol and BEV as well as e-petrol and e-diesel is shown in Figure 4.5. It is noticeable that the e-methanol can drive much longer compared to the BEV even with the considerably lower energy use of the BEV. Given the 50% tank size increase the methanol vehicles are able to drive 500-900 km between fueling occasions, a reasonable range for most users.

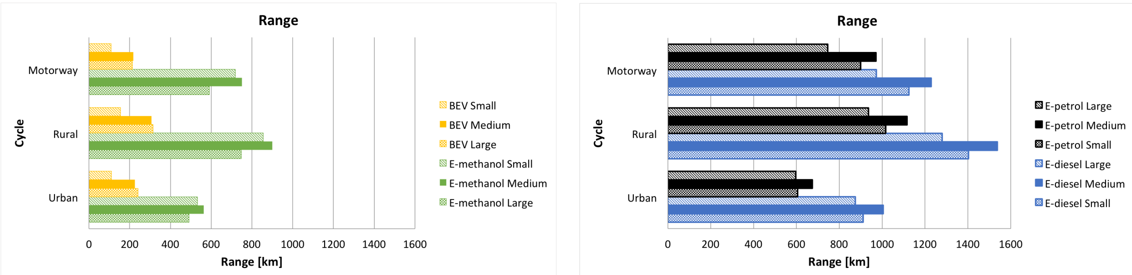

Figure 4.5: The figure shows available driving range for all sizes of BEV, e-methanol, e-diesel and e-petrol in each cycle. With the increased e-methanol tank size, all ICE vehicles have considerably longer range than the BEV's.

When looking at the e-diesel, e-petrol in Figure 4.5 and comparing them to the driving range of BEV's the gap between them is even larger. These findings stresses the fact of batteries low energy density and that very high BTW efficiencies are not enough to by fair means compare BEV's to ICEV's driving range. The reason for the rather similar driving range between the medium and large sizes of BEV's, as well as that the driving range are shortest for the small BEV, is that in this analysis it is assumed that the battery package increases with the size of BEV and is thus much larger in the largest car which increases the driving range

4.2 Grid-to-wheel

When all car parameters have been determined the fuel demand and the costs connected to each car type can be investigated. The costs connected to the production of the e-fuels in the base case can be seen in Table 4.2.

As the factories producing the different e-fuels are assumed have the same investment costs, Operations and Maintenance (O&M) cost, and capacity factors. Due to the different reactor efficiencies, the electricity demand varies for producing e-methanol compared to e-diesel and e-petrol. Therefore, electricity demand and thus the total cost of electricity is higher for the two latter. This ends up with an e-fuel production cost approximately two times higher than the price for conventional petrol.

Table 4.2: The table shows production costs connected to the different electrofuels where regular petrol is added for comparison, all prices without tax or profit added. As can be seen the price per GJ for the electrofuels is approximately double the price of conventional petrol.

Cost centre	e-methanol	e-diesel/e-petrol	Conv. petrol
Total investment [€/GJ]	6.34	6.34	-
O&M [€/GJ]	3.55	3.55	-
Electricity [€/GJ]	12.56	16.53	-
Total fuel cost [€/GJ]	22.45	26.42	10.04
Total fuel cost [€/l]	0.35	0.96/0.86	0.33

4.2.1 Car cost

To determine the total cost per kilometer for the car during its life time, investment costs are added to the running costs, as explained in section 3.2.1. The result for e-methanol and BEV can be seen in Figure 4.6.

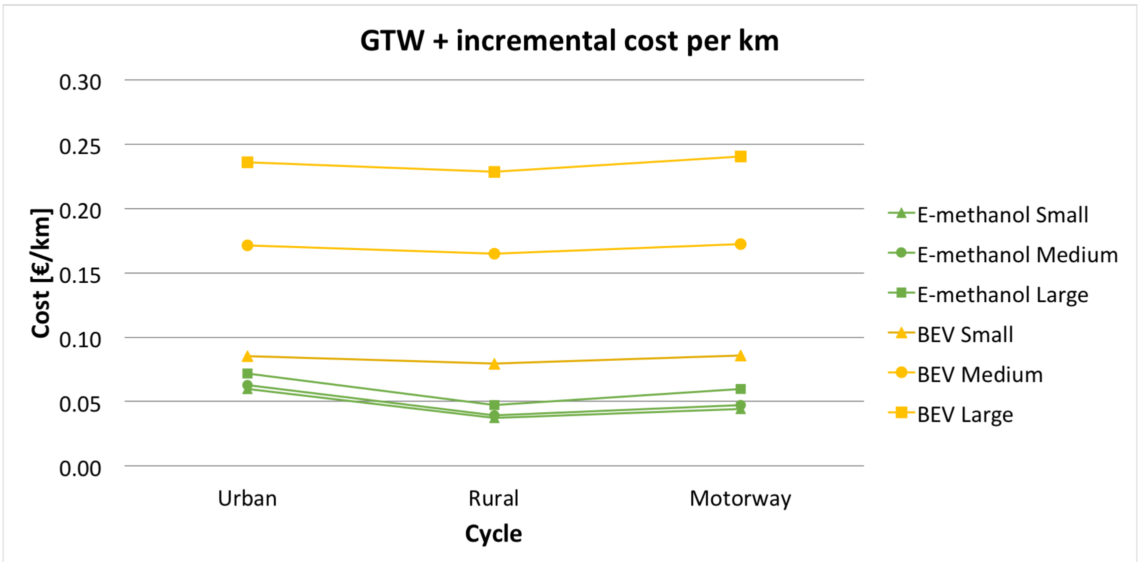

Figure 4.6: The figure shows the differences in GTW cost with incremental cost included per kilometer for BEV's and e-methanol in the base case.

The e-methanol cars have only a running cost, as the car itself do not have to be adjusted. Therefore the cost is only a function of the fuel consumption and all three car sizes is within a narrow span. The BEV on the other hand have large investment costs from the battery but small running costs as they all have a high efficiency combined with low "fuel" price. This also means that the BEV's are almost independent on driving cycle with the exception of the large car on the motorway. With the large batteries that is needed for the medium and large car, the share of the investment cost outweigh the low running costs and the price of using a BEV end up being approximately three times the cost of an e-methanol car in the same size. The small car with a much smaller battery, however, is able to compete with the e-methanol cars. Once again these prices are based solely on production cost and not what the consumers pay in the end.

Although the cars run on e-diesel have a much lower fuel consumption compared to e-methanol, the cost is higher and closer to the small BEV. The e-diesel cars have a higher cost per kilometer compared to e-methanol because of the incremental cost added as a fixed price per kilometer and the higher fuel price, which can be seen in Figure 4.7. The e-diesel cars are considerably cheaper than the medium and large BEV, also seen is that all sizes of e-diesel is cheaper than the small BEV in rural due to the low "fuel" consumption in that driving cycle.

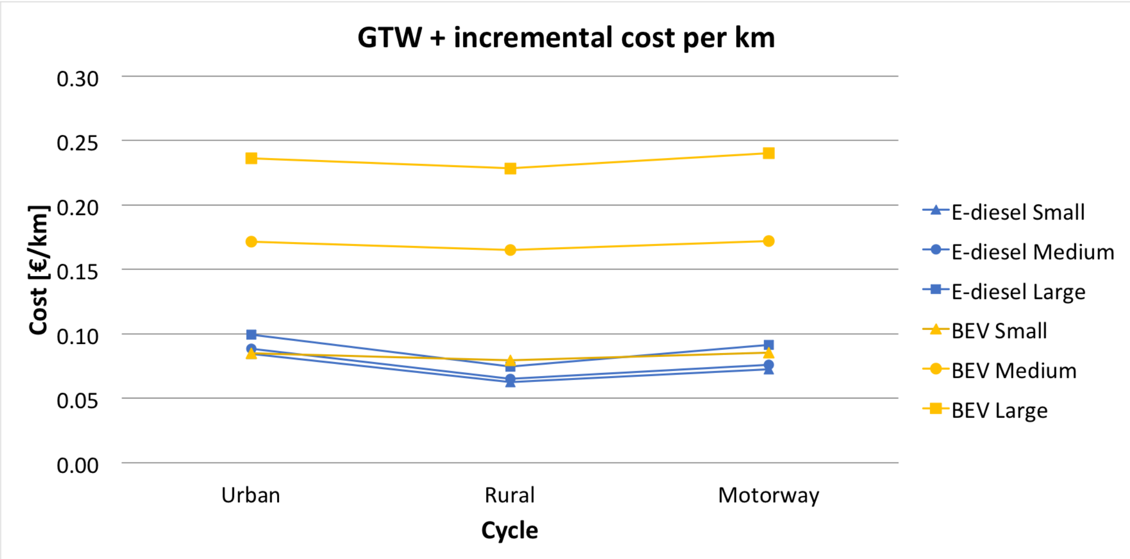

Figure 4.7: The figure shows the differences in GTW cost with incremental cost included per kilometer for BEV's and e-diesel in the base case.

As can be seen in Figure 4.8 all cars exceed the small BEV's cost per kilometer in the urban driving cycle, whereas the three e-petrol cars have lower cost per km in the rural and the motorway cycles, although similar to the small BEV.

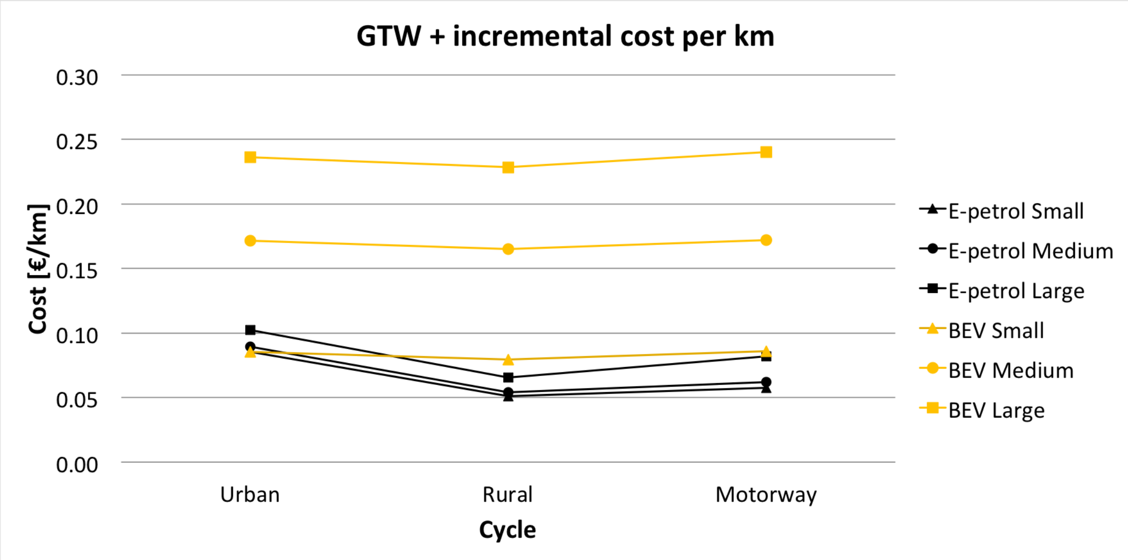

Figure 4.8: The figure shows the differences in GTW cost with incremental cost included per kilometer for BEV's and e-petrol in the base case.

4.2.2 Electricity consumption

Combining production efficiency (GTT) with the cars TTW efficiency the study calculated the amount of electric power input needed to propel each car per kilometer. These findings result in big differences between BEV and ICE powered cars, the result of BEV and e-methanol required electric consumption per kilometer is shown in Figure 4.9.

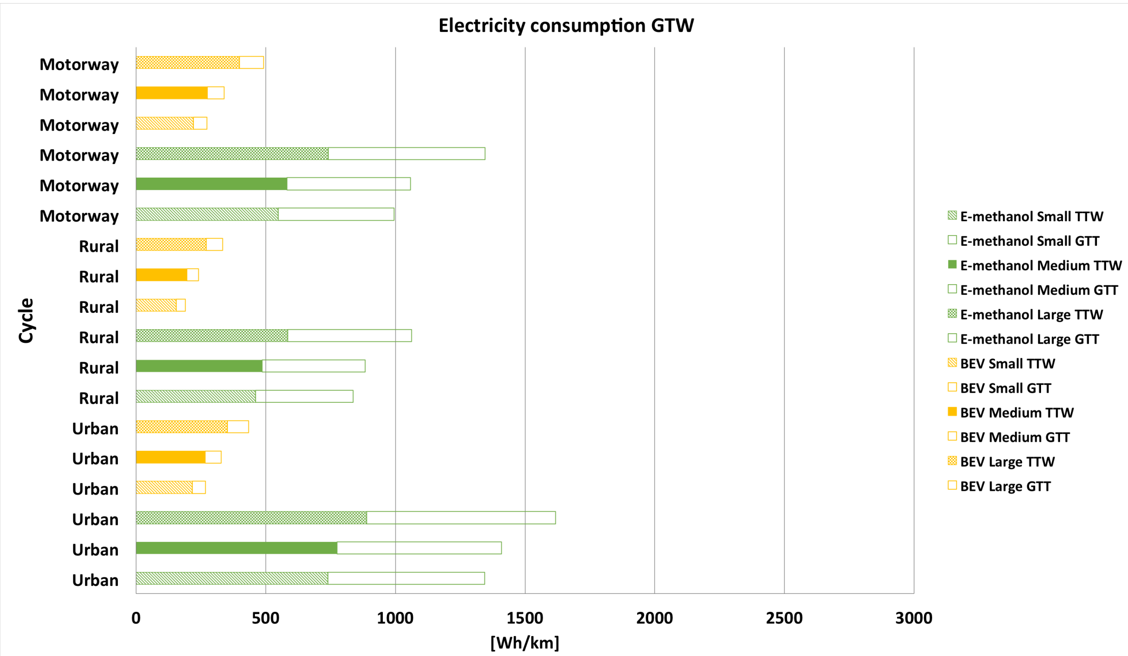

Figure 4.9: The figure shows the electricity demand GTW per kilometer to propel BEV and e-methanol cars in each driving cycle.

To produce and drive on e-methanol requires up to four times the electricity from GTW compared to driving BEV. The biggest loss occurs inside the engine due to the low efficiency of ICE. Production of e-methanol is considerable less efficient compared to using the electricity to charge batteries at home. In the e-diesel case the engine itself have a better TTW efficiency but as the production of e-diesel is less efficient than e-methanol the total energy input needed is larger. Electricity consumption GTW for e-diesel and e-petrol is shown in Figure 4.10.

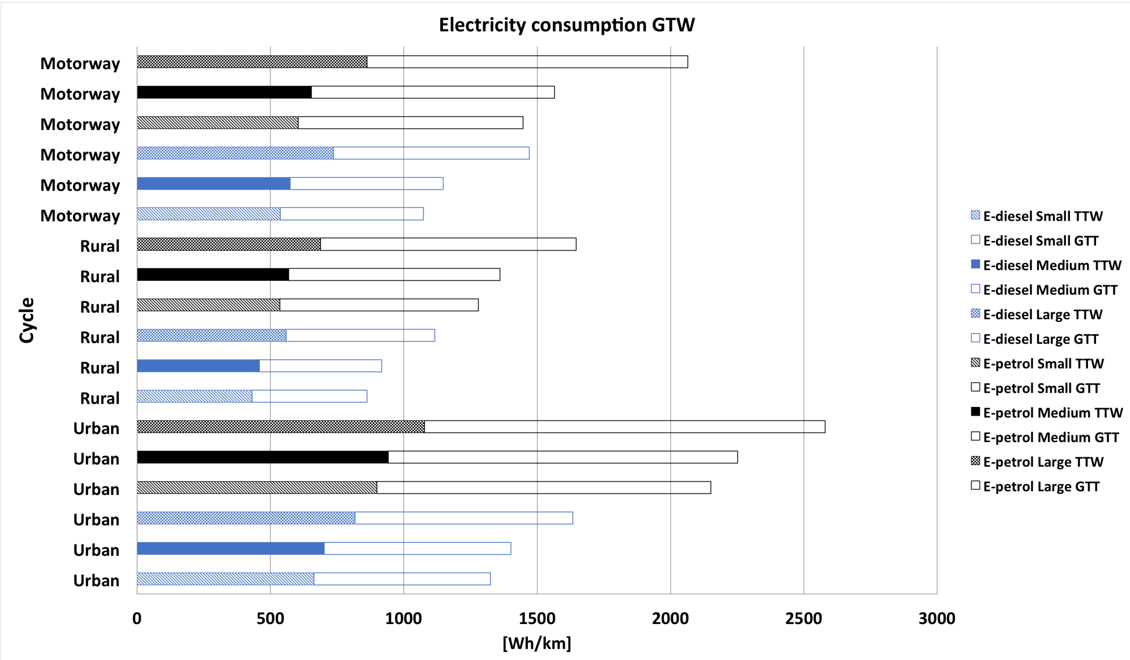

Figure 4.10: The figure shows the electricity demand GTW per kilometer to propel e-diesel and e-petrol cars in each driving cycle.

The electricity required to drive the small e-petrol car is more than seven times the amount of driving the small BEV in the urban cycle. It can also be seen that e-diesel is a bit more electricity intense than e-methanol overall due to lower production efficiencies mentioned earlier. In the urban cycle e-diesel consumes less electricity than e-petrol, the much lower TTW efficiency of e-petrol creates this big difference between them.

4.3 Resources and cost perspectives

This section investigates the resource and cost perspective for large scale implementation of electrofuels in Sweden. By scaling up the electrofuel demand to all of Sweden's passenger cars it is possible to interpret probability of future electrofuel production.

4.3.1 How much electricity is required to provide Sweden with electrofuels?

To give the results some perspective and to fully grasp the GTW electricity consumption of electrofuels a comparison is made with Sweden's annual electricity production. Assuming the annual electricity production to 150 [$TWh/year$], estimating the average driving length to 12000 [$km/year$] and the fact that Sweden have about 4.5 million cars registered [33]. If all these cars were to be driven by electrofuels the resulting electricity demand would be as presented in Table 4.3. The following numbers are based on the small car in the rural cycle to show the minimum electricity required to provide all cars in Sweden with electrofuels.

Table 4.3: The table shows how much electricity each fuel would require to provide all of Sweden's cars on average per year, calculated with the electricity consumption of a small car in rural cycle. Sweden's annual production of 150 [$TWh/year$] represent 100% in the right hand side column.

Fuel	**Electricity demand** [$TWh/year$]	**Share of production**
BEV	10.3	7%
e-methanol	45.2	30%
e-diesel	55.7	37%
e-petrol	69.1	46%

When looking at the extreme case of a large e-petrol car driven in urban environment the demand rise to 93% of the annual Swedish electricity production. Regardless of cycle, size and type of electrofuel, a large scale implementation of electrofuels as a base fuel would not be possible in Sweden's current electric power system. Except from a major change in the electricity production, securing a large enough CO_2 feedstock would also be required, which is presented in section 4.3.3.

4.3.2 How many BEV's could one e-methanol factory represent?

To give this study more perspective on the financial part of electrofuels and BEV's, a comparison between building one e-methanol factory and how many BEV's that the factory represents is conducted. All e-methanol car sizes and driving cycles are tested and as in the electricity investigation above it is assumed that the cars are driven 12000 [$km/year$].

One e-methanol factory of the size 110 [MW], which with the base case assumptions made in this study corresponds to a fuel production of 482 [$GWh/year$]. This factory size would have an investment cost of 278 million €. The battery pack in the small BEV with the base case assumption have a cost of 5040 € per car, which means that one factory investment cost would represent 55254 small BEV battery packs in cost. All the 482 [$GWh/year$] of e-methanol produced in the factory would for example be enough to fuel 87211 small cars, 1.6 times more e-methanol driven cars than small BEV's for the same investment cost. When looking at the large cars it is 4.5 times more e-methanol driven cars than BEV's, which is a considerably higher higher amount of vehicles replaced with this investment cost. If the investment cost instead would pay for medium BEV battery packs it covers 22102 cars and in the large car case it would cover 15601 large BEV's. The number of e-methanol cars in their respective size and cycle that the fuel produced per year in the factory could cover is presented in Table 4.4.

Table 4.4: This table shows the number of e-methanol cars that the 110 $[MW]$ factory could fuel per year for each size and driving cycle, with average driving length of 12000 $[km/year]$. The right column shows the number of BEV cars of each size that could instead be bought for the factory investment cost.

Car size	Urban	Rural	Motorway	BEV per factory
Small	54273	87211	73313	55254
Medium	51788	82658	68963	22102
Large	45125	68715	54203	15601

4.3.3 What is the water and carbon dioxide demand for e-methanol?

The water and CO_2 demand for producing e-methanol is estimated and compared to give the calculated production values some perception of reality. This investigation is divided into two parts, first estimating demand of the 110 $[MW]$ factory described in section 4.3.2 and second scaled to the entire Sweden's electrofuel demand.

By looking at the overall chemical balance for producing e-methanol in Equation 4.1, it is possible to estimate the demand of water and CO_2 per liter of e-methanol with knowledge of molar mass and other properties of the compounds included.

$$4\,H_2O + 2\,CO_2 \rightleftharpoons 2\,CH_3OH + 3\,O_2 \tag{4.1}$$

From this balance and with above described knowledge the investigation approximates water demand to 2 $[l]$ and the CO_2 demand to 3.6 $[kg]$ per liter of e-methanol produced. In Table 4.5 results of the investigation is presented for the 110 $[MW]$ factory and in Table 4.6 the upscale to Sweden's minimum and maximum electrofuel demand is presented. The average water flow in Göta älv is 570 $[m^3/s]$ [37] and in 2013 Sweden emitted 55.8 $[Mton]$ [38] of CO_2.

The results of the investigation pin points that water supply should not be a problem for either the factory or the scale up in Sweden. From Table 4.6 it can also be seen that if all cars in Sweden were in the category large the demand for CO_2 would be higher than Sweden's total CO_2 emissions. This is of course an enormous amount of CO_2 and sets the electrofuel production in perspectives. It should, however, be noted that Sweden also have large amounts of non-fossil CO_2 emission indicating that the electrofuel production, in this maximum assumption, still would be theoretically possible from a CO_2 perspective. It should also be noted that this exercise is a theoretical calculation to elaborate around perspectives but in reality it is not likely that 100% electrofuels would be demanded for the car fleet.

Table 4.5: The table shows water and CO_2 demand for the 110 $[MW]$ e-methanol factory, it is compared with the annual water flow in Göta älv and Sweden's total CO_2 emissions from 2013.

Factory	**Amount**	**Unit**
e-methanol produced	0.1	$[Mm^3/year]$
Water demand	0.2	$[Mm^3/year]$
Part of Göta älv	12	$[ppm]$
CO_2 demand	0.4	$[Mton/year]$
Part of Sweden's CO_2 emissions	0.7	[%]

Table 4.6: The table shows the water and CO_2 demand for e-methanol if all cars in Sweden where run on electrofuels, it is compared with the annual water flow in Göta älv and Sweden's total CO_2 emissions from 2013. Min represents small cars driven in rural cycle and max represents large cars driven in urban cycle.

Sweden	**Amount**	**Unit**
e-methanol demand min	10	$[Mm^3/year]$
Water demand min	21	$[Mm^3/year]$
Part of Göta älv min	0.1	[%]
CO_2 demand min	37	$[Mton/year]$
Part of Sweden's CO_2 emissions	67	[%]
e-methanol demand max	20	$[Mm^3/year]$
Water demand max	40	$[Mm^3/year]$
Part of Göta älv max	0.2	[%]
CO_2 demand max	72	$[Mton/year]$
Part of Sweden's CO_2 emissions	129	[%]

4.4 Sensitivity analysis

To get a deeper understanding of dependency on the assumptions made in this study this section will present the results of the sensitivity analysis. Figures made to illustrate how the results are affected from changing parameter values are presented in Appendix A & B and only explained in following sections. Each section presents only one parameter change from the base case to decrease complexity of the analysis.

4.4.1 Electricity price

The main cost for producing electrofuels except of the factory investment is the running cost of electricity, which means that naturally the production price of the fuel is highly dependent on this expense. To see the actual dependency of electricity price two different cases were chosen, the first one lower the private price to 25 $[€/MWh]$. This is the assumed price of industry use and gives an indication of the dependency of BEV's electricity demand. The change of price resulted in a slightly lower cost per kilometer for the BEV's but not down to the e-methanol level in rural and motorway. The e-petrol cars are only lower in the rural cycle for all cases except for the large which is marginally higher than the small BEV. The e-diesel cars have higher cost than the small BEV in both urban and motorway while the small and medium stays marginally lower in rural. The medium and large sized BEV are still in a higher range of cost than the cars driven by electrofuels. Results are presented in Figures A.3 to A.5.

The second electricity price change is in the other direction, a higher price for the industry is set to 75 [$€/MWh$], which is the price estimated for private use. As described before this makes a large impact on electrofuels due to the greater amount of electricity required to produce electrofuels compared to charge and drive BEV's. The price increase results in e-methanol for all cycles and sizes to raise above or stay just the same as the small BEV cost per kilometer. The e-methanol still stays below the medium and large BEV for all cycles, which indicates the high incremental cost for BEV's. The e-diesel trend shows that all cases but the large in urban and motorway have a lower cost than medium BEV but higher than the small BEV. The e-petrol's high fuel consumption in urban result in a higher cost than medium BEV for all sizes. In the other cycles the cost is lower than medium BEV and higher than small BEV except for the large car in the motorway cycle. Results are presented in Figures A.6 to A.8.

4.4.2 Battery price

The incremental cost of the BEV's are based on the battery cost which is a rough estimation that currently is rather uncertain. Therefore the study investigates two battery cost levels, one which is double the original estimated cost and one which is half of the estimated cost.

The lower battery cost makes the small BEV somewhat competitive with the e-methanol but the medium and large BEV's still have a higher cost for all cycles. In the e-diesel case the small BEV have a lower cost overall and the medium and large BEV are still at a higher level. For the e-petrol case the urban cycle costs are higher than the small BEV and lower or close to the medium BEV. In both rural and motorway the small and medium e-petrol stays in the competitive range around the small BEV. The large e-petrol car have a higher cost but still remains lower than the medium BEV. Results are presented in Figures A.9 to A.11.

With the higher battery cost all cases with electrofuels have a lower cost than the small BEV. The medium and large BEV have costs at a factor three or higher than electrofuels in all cases. This indicates once again the dependency of battery cost as the most important one for BEV's. Results are presented in Figures A.12 to A.14.

4.4.3 Electrolyzer efficiency

The Audi e-diesel factory claims to have reversible electrolyzers with the efficiency 90% which is mentioned in section 2.1.3. Therefore the study will investigate the affect of changing the electrolyzer efficiency from 70% to 90%.

This will affect the total electricity consumption and the production efficiency for all electrofuels, which also changes the fuel price. Regarding the cost per kilometer all electrofuel cases drops down under or stays very close to the small BEV cost with this change. The fuel price per liter decreases by 10-14 %, the e-methanol changes the least because of the higher production efficiency in methanol synthesis. Results are presented in Figures B.1 to B.3. The electricity consumption for all electrofuels decreases by approximately 14-16%, with the e-methanol again in the lower end of the range because of above stated. The lower electricity consumption are still hard to implement in the power system if scaled up to all Swedish cars fueled by electrofuels. Results are presented in Figures B.4 to B.5.

4.4.4 Capacity factor

With increasing intermittent electricity production the possibilities of over production occurs from time to time. If instead of exporting the electricity or in worst case disconnect it from the grid, producing electrofuels could be a good way to store the electricity. If assumed that electrofuels only is produced when over production occurs and assuming this is only 10% of the year, the study investigates the change of capacity factor from the conservative base case of 50% to the estimated 10%. With the estimated over production it is assumed that the electricity price do not change from the usual price level. There could occur some special cases when the price level decreases but it is not concerned in this analysis. A change from the base case 50% to the more normal wanted production level of 90% is also investigated.

When assuming a capacity factor of 10% the price per liter changes by almost a factor three for all electrofuels, all the e-methanol cars except for the large car in urban have a higher price than the small BEV and lower than the medium BEV. The large cars cost per kilometer in urban is higher than the medium BEV but still lower than the large BEV.

As the e-methanol car cost per kilometer increases so does also the cost for e-diesel and e-petrol. In the rural cycle all sizes for both e-diesel and e-petrol have a lower cost than medium BEV, the two smaller e-diesel cars cost levels is similar to the medium BEV for the other cycles. The e-petrol driven cars high fuel consumption in urban makes the cost higher than the medium BEV and the large e-petrol car are the only case that exceeds the large BEV cost. The other two cycles and sizes follow the e-diesel trend, which overall makes the e-diesel a more promising fuel than e-petrol. Results are presented in Figures B.6 to B.8.

If the capacity factor is set to 90%, the cost for all electrofuel driven cars drops below or stays the same as the small BEV in all cases. This capacity factor could be possible to reach in the future when the production of electrofuels might be a mature process. Results are presented in Figures B.9 to B.11.

5
Discussion

When this study started the main question that was to be solved were how to find the best way of integrating renewable electricity into the transport sector. This turned out to be a very complex matter where the answers is highly dependent on what point of view that are important. As can be seen in the results, the GTW energy use highly differs between electrofuels and BEV's, so if the target is to reduce the energy use, BEV's would seem to be the clear solution. However, without large incentives, the users will most likely buy the cheapest option where only the small BEV can compete with the electrofuel alternatives.

One of the biggest drawbacks of BEV's is the short range that can be driven between charges. This also showed in the results where the range of the BEV's are constantly lower than the electrofuel alternatives. It can, however, be discussed if a range between 100-200 km would be enough for the normal city driver without having to feel the so called range anxiety. Then the small BEV would be affordable compared to electrofuels and with the lower battery price investigated in the sensitivity analysis it would even be cheaper. So in city or urban traffic the small BEV could therefore be a good choice for both the user and especially the energy system.

As the battery price is another disadvantage of the BEV, the cost per $[kWh]$ of battery is key to making the BEV an option for the future. In this study the price was set low compared to today's prices, which however, are expected to decrease over the years. As shown in the sensitivity analysis, lower battery prices would make the BEV option a bit more attractive from a cost perspective, but without batteries with increased energy density it is hard to compete with larger cars. One interesting finding is that the range increase is not linear with battery size of the BEV due to the extra energy consumption that follows with heavier cars. This concludes that there could be a limit where the larger battery does not have any affect on driving range, which could be defined as the largest suitable battery size. Of course improvements can still be made within the battery market itself especially on increasing the energy density and reduction of production costs.

In earlier studies, a standard car is often chosen where only a weight change is applied to see how car size affects the results. This study has instead focused on comparing and evaluating already existing car alternatives, on which modifications has been done to fit the different fuel alternatives. This has increased the complexity of the cars and been done on the expense of seeing exact implications of each variable change. However, in real life parameters like wheel diameter and frontal area are adjusted to fit different car sizes and will therefore in fact have an affect on the results. Another alternative to developing own car models could have been to use already developed models at Volvo Car Corporation, which probably would have given more exact results than what this model produced. This would however, even more reduced the possibility to make personal adjustments and understanding of variable changes.

From the TTW results, the ICE efficiency is increased with increased weight due to using a more optimal RPM and torque demand in the chosen engines. This might look a bit different when using engines optimized to each specific car size and is also something that could improve the accuracy of the results. Using the same engine type in cars of different size is however, a common way to reduce production and development costs for car manufacturers and optimal engines are therefore not always used in reality. As can be seen in Figure 4.3 and 4.4 the differences that would arise from choosing a more optimized engine for each size are not expected to make any major changes to the results.

Finding valid production data proved to be a difficult task as it is often considered business secrets and information from factory and equipment suppliers are therefore hard to verify. The fuel production part of the study is therefore largely based on assumptions from earlier work and could probably be improved if more correct data were available.

As a result of assumptions made and car sizes available, two things have to be mentioned that might somewhat have affected the result. The weight of the chosen small car can be argued to be outside the range of what is normally considered a small car and therefore have a high energy consumption compared to other cars in that segment. One quick calcuation with a weight reduction of 30% only results in 15% lower fuel consumption for ICE and with the chosen engine the TTW efficiency even decreases some. This could imply that engine optimazation is a good way to reduce energy use for ICEV's. We have noticed that driving pattern is more dependable than size of passenger cars regarding the energy use or the fuel consumption. Regarding the e-methanol, the tank size is of crucial importance to be able to make up for the LHV of the fuel. With the tank in the same size as petrol and diesel cars have today e-methanol would still have a range exceeding the BEV, but obviously the incentives to choose a small e-methanol car over the other fuel options, as well as over a small BEV, would be a lot lower.

In this study the results of using electrofuels in passenger cars have been evaluated on the assumption that the only incentive is low price or low energy use. The possibility to produce electrofuels from renewable energy however, contains several advantages that which have been outside the scope of this study but still may largely affect the scale of electrofuel use in the future. When looking at the storage option, converting electricity into a fuel to later use it in an ICE instead of putting it directly into a battery will of course lead to increased losses. The electric power transmission is however, limited by distance where losses and expenses gets bigger and bigger with greater distance. This causes problems as a lot of the renewable energy production potential lies in distant areas with transmission problems as a result. This goes for solar panels in the great deserts, possible hydro production in remote mountain parts and thermal heat on remote islands. Transporting liquids in either pipelines or boats have lower losses connected to it, hence using the remote electricity production to produce electrofuels that can be transported to habitat areas without big losses could be an alternative. This idea is already in place on Iceland where the cheap electricity, based on thermal heat, is converted to a transportable liquid, and offers an interesting possibility for the future.

Electrofuels also offers a great variety of usage, e-methanol have the possibility of being used both as a drop-in fuel as well as on its own. Therefore it exists a great potential of replacing parts of fossil use both today and in the future, and may ease the transition from a fossil based transport sector to sustainable alternatives. Apart from producing methanol, the possibility to produce fuel via the Fischer-Tropsch reactor also offers the option of designing and improving the fuel. They can be produced without toxins, carcinogens and sulphur which means a fuel better for engines, humans and the environment. They can also be designed to produce jet fuels for aviation as well as to have improved octane number compared to regular fuels which could increase the efficiency even more of the engines and reduce the amount of energy losses. The use of electrofuels as drop in also offers possibilities to integrate the renewable energy into the current fossil fuel infrastructure. From the investigation of investing in one e-methanol factory it was found that one factory is equivalent to 55,254 packs of 24 $[kWh]$ batteries, an unlikely increase of vehicles compared to the 2100 BEV's[33] currently used in Sweden. If the investment instead payed for the e-methanol factory it could fuel 1.7 million small cars in rural with 5% drop-in of e-methanol, which lower the CO_2 share from all these cars by 5%. This implies that if the target is to decrease emissions at the lowest possible cost, using electrofuels as drop in is probably a better solution since incentives for customers and infrastructure investments have to be made to increase the share of BEV's. The factory could supply up to 68,715 large cars with pure e-methanol and by that replace 4.5 times more fossil fueled cars than investing in battery packs for large BEV's. Additionally choosing electrofuels would take away the uncertainty of whether customers in the end will buy BEV's or not and hence increasing the probability that the money invested will have an effect.

Compared to first generation biofuels such as ethanol or biodiesel, the electrofuel production does not compete with food production or other arable land which is already scarce. Electrofuels are instead in need of water, CO_2 and renewable electricity, in the e-methanol factory investigation the findings on water use stresses the fact of water not to be a problem in Sweden. Even when scaled up to provide e-methanol to fuel for all cars in Sweden the water demand is only 0.2% of Göta älv's water flow. When looking at the CO_2 demand to fuel 1.7 million cars with drop-in from one 110 $[MW]$ factory it needs quite a small part of Sweden's CO_2 emissions but the scale up to fuel all cars with only e-methanol the demand rises to above Sweden's emission levels, which makes the assumption hard to implement without importing CO_2 or CO to Sweden. The most difficult problem is, however, to deliver the amount of renewable electricity needed to provide all of Sweden with e-methanol, increasing the electricity production by 30% or more is hard enough for today's electric power system already running near the limit of production.

Even with the complexity and low energy efficiency of producing electrofuels the cost per kilometer is still lower than for BEV's, especially the two larger cars which are much more expensive than the smaller one. In our study we have chosen a bit conservative capacity factor on the production, with the more optimistic capacity factor of 90%, which may have been a better choice, the cost for electrofuels decreases even more below the BEV's cost levels and is presented in the sensitivity analysis. This emphasis's the possibility of implementing electrofuels to the passenger car market, and most certainly as a drop-in fuel option.

A possibility that has not been investigated in this study is a combination of BEV and electrofuels in a hybrid car. A hybrid car has an ICE in combination with a battery and electric motor which allows for electric drive during shorter distances, normally up to 50 kilometers and the possibility of regenerative braking to charge the battery. If longer distance or more power is needed, the ICE is used alone or in combination with the electric motor. The downside compared to a normal ICEV is the extra cost and weight for the battery pack. Using electrofuels in hybrid cars could also be a good way to phase out fossil fuels from the passenger car market. Further studies on implementing electrofuels could be done with hybrid cars included to find other possible conclusions.

In this study no consideration has been made regarding the outdoor temperature. Doing so would likely be a disadvantage for the BEV since heating up the cabin have to use battery capacity rather than using waste heat, as done in ICEV's. Additionally, batteries are temperature dependent wherefore determining the impact of outdoor temperature could be an interesting target for further studies.

As mentioned in the introduction, the car industry is under less pressure of a fuel transition than the shipping and aviation sector. In these sectors there are currently few options to fossil fuels due to prices, energy density matters and emission legislation's, which by a large probability will be forced to other alternatives. As the demand for alternatives increases, development and production costs can be expected to decreased and make electrofuels an even more valid solution. But that is only if the electric power system converts to only non fossil fuels, which also is the main problem and requirement for BEV's to truly be environmentally friendly.

When evaluating the research questions some conclusions can be drawn while others remains unanswered. For each driving cycle and car size, the BEV's have a lower specific energy consumption, however, at a higher cost. The small BEV is able to compete with the cost of electrofuels with the assumptions made in the base case, and could be an equally good option when a long driving range is not important. Answering what is the best way to use renewable electricity the obvious answer is in BEV's when looking at the total energy demand per driven kilometer. This solution is, however, dependent on customers buying more expensive cars and is therefore connected to bigger uncertainties whether the proposed decrease in global emissions from the transport sector is connected to a higher cost for both customers and governments. Using the different electrofuels all comes with specific upsides and downsides but the main benefit of using synthetic fuels compared to their respectively commercial alternatives is that electrofuels are free of toxins and pollutants. Due to uncertainties regarding the electrofuel production no connection between octane number and production energy use and cost was found. The choice of propulsion system is highly dependent on who is asking the question and what the target is, it is clear that choosing between low energy consumption or low cost is more important than to base the choice on how the car is driven.

6
Conclusion

The following conclusions can be drawn from the analyses made in this study.

- To minimize the amount of energy use, BEV's is the preferred choice regardless of cycle and size compared to electrofuels.
- Electrofuels outperforms BEV's when it comes to range and even though much more energy inefficient, e-methanol can be a more cost-efficient option in all investigated driving cycles.
- The choice of driving cycle is more decisive than car size for electrofuels regarding energy use and cost. BEV's incremental cost are dominated by battery size and therefore almost independent on driving cycle. Even though a less expensive "fuel" cost BEV's will be more expensive than electrofuels.
- A large scale implementation of electrofuels would put an unrealistic demand on the electric power system. In Sweden water supply would not be an issue, however, CO_2 feedstock could be an issue. A realistic alternative to reduce the fossil fuel use in the near future could be to implement electrofuels as drop-in fuel.
- Using electrofuels as drop in offers the easiest solution for governments to integrate renewable electricity into the transport sector as it is not dependent on customers buying BEV's or car manufacturers adapting vehicles to new fuels.

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A
Appendix 1

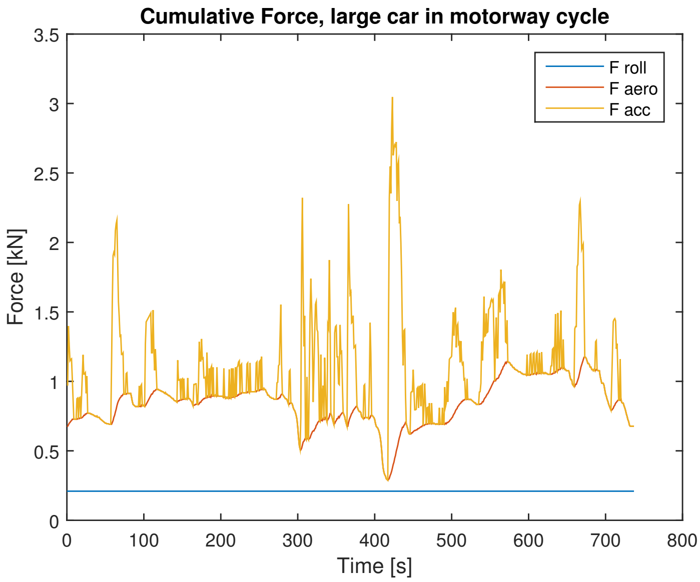

Figure A.1: Share of forces for a large car in highway cycle. As can be seen, the biggest share is made up of air resistance due to the high velocities.

Table A.1: The table shows the incremental costs for the different vehicle sizes and propulsion sytems [€/km]

Car size	e-petrol	e-methanol	e-diesel	BEV
Small	0	0	0.022	0.065
Medium	0	0	0.022	0.147
Large	0	0	0.022	0.203

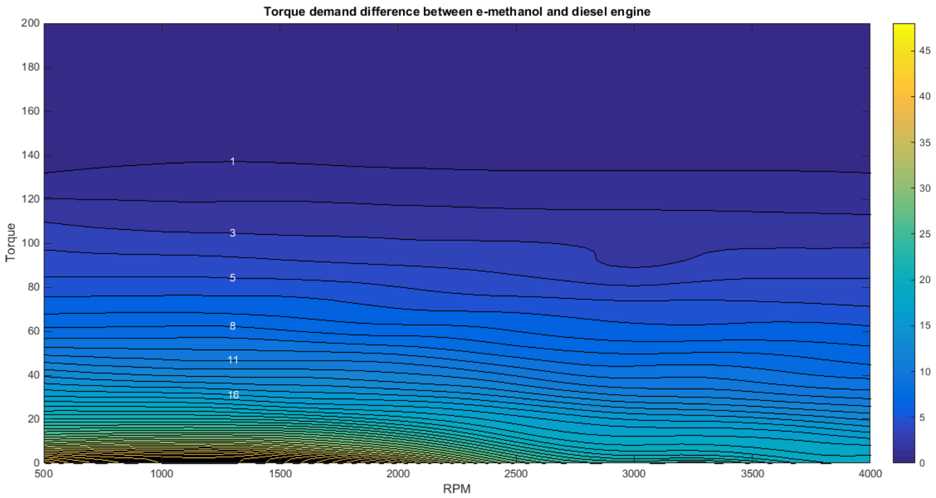

Figure A.2: The figure shows the percentage difference between the torque needed for a diesel and methanol engine. Since pump losses only occurs until full throttle is used, the difference are bigger the lower load that is applied.

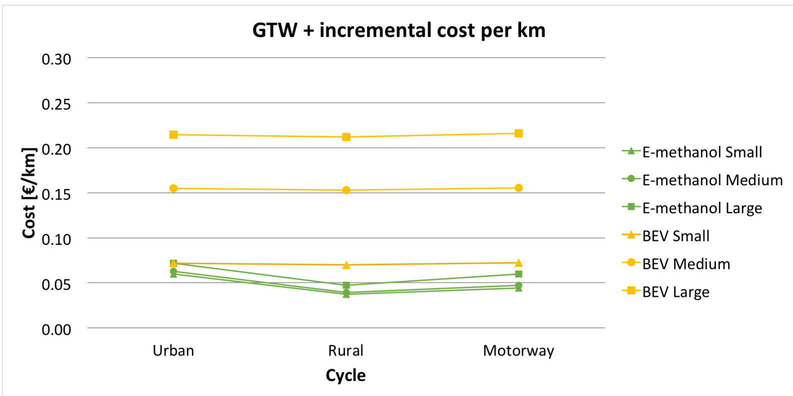

Figure A.3: The figure shows cost per kilometer for BEV and e-methanol cars if private electricity price would be 25 [$€/MWh$].

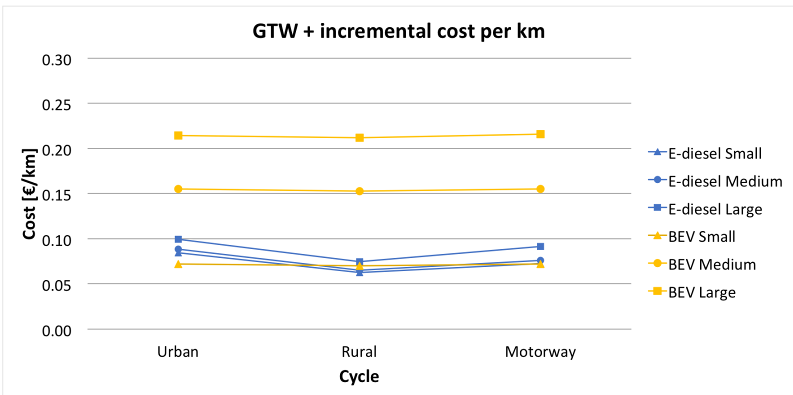

Figure A.4: The figure shows cost per kilometer for BEV and e-diesel cars if private electricity price would be 25 [$€/MWh$].

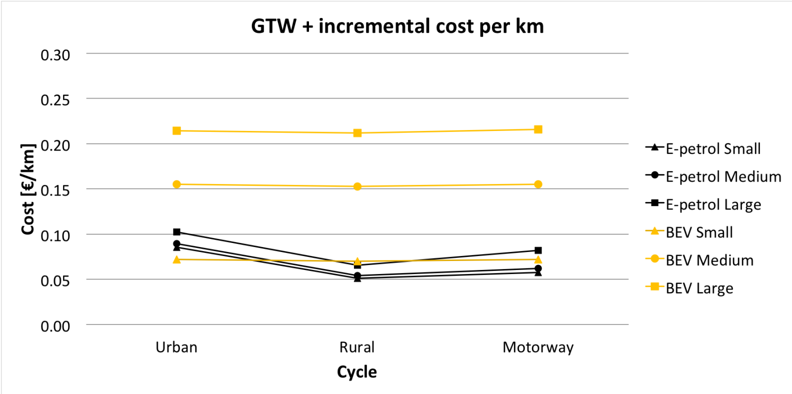

Figure A.5: The figure shows cost per kilometer for BEV and e-petrol cars if private electricity price would be 25 [€/MWh].

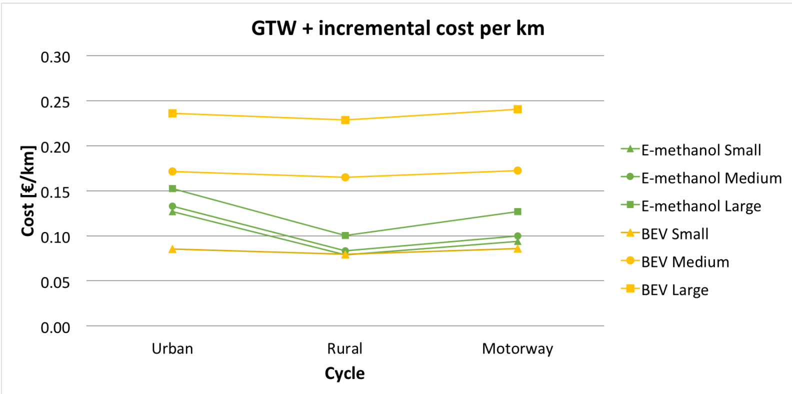

Figure A.6: The figure shows cost per kilometer for BEV and e-methanol cars if industry electricity price would be 75 [€/MWh].

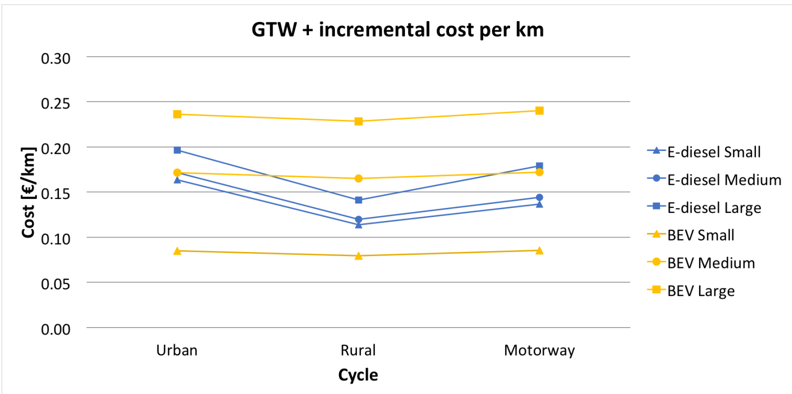

Figure A.7: The figure shows cost per kilometer for BEV and e-diesel cars if industry electricity price would be 75 [€/MWh].

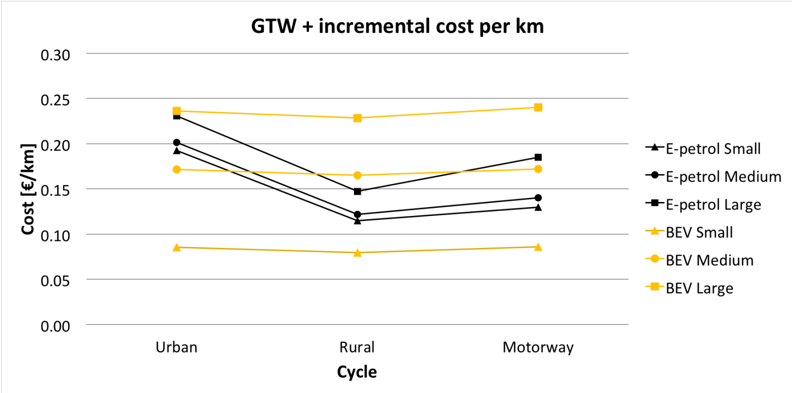

Figure A.8: The figure shows cost per kilometer for BEV and e-petrol cars if industry electricity price would be 75 [$€/MWh$].

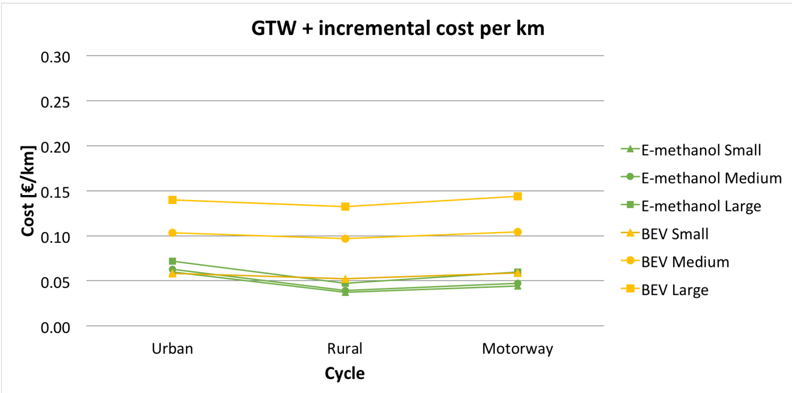

Figure A.9: The figure shows cost per kilometer for BEV and e-methanol cars if battery cost would be 70 [$€/kWh$].

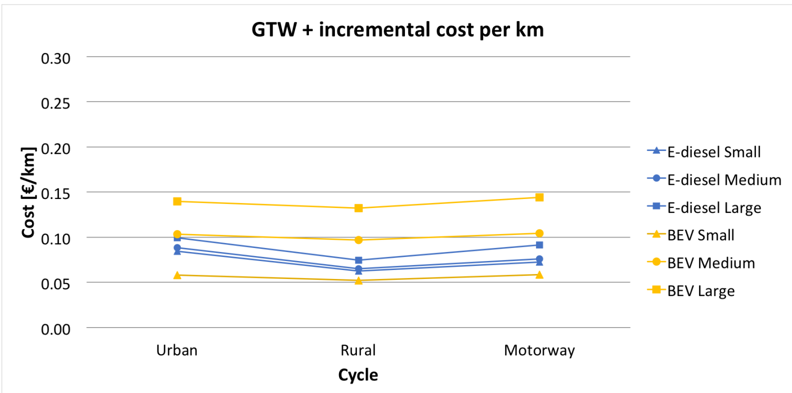

Figure A.10: The figure shows cost per kilometer for BEV and e-diesel cars if battery cost would be 70 [$€/kWh$].

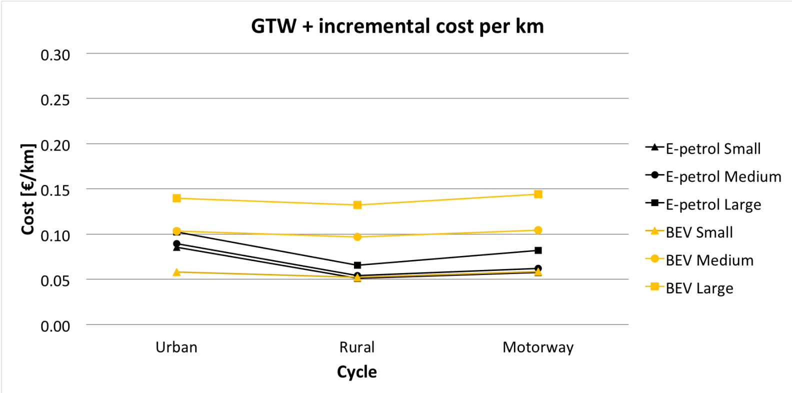

Figure A.11: The figure shows cost per kilometer for BEV and e-petrol cars if battery cost would be 70 [$€/kWh$].

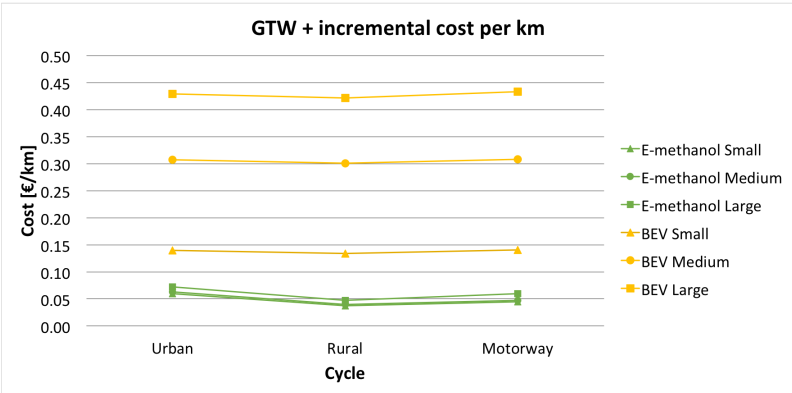

Figure A.12: The figure shows cost per kilometer for BEV and e-methanol cars if battery cost would be 280 [$€/kWh$].

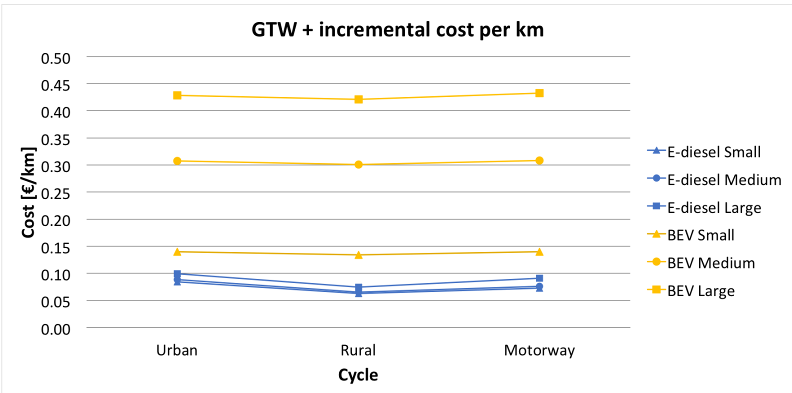

Figure A.13: The figure shows cost per kilometer for BEV and e-diesel cars if battery cost would be 280 [$€/kWh$].

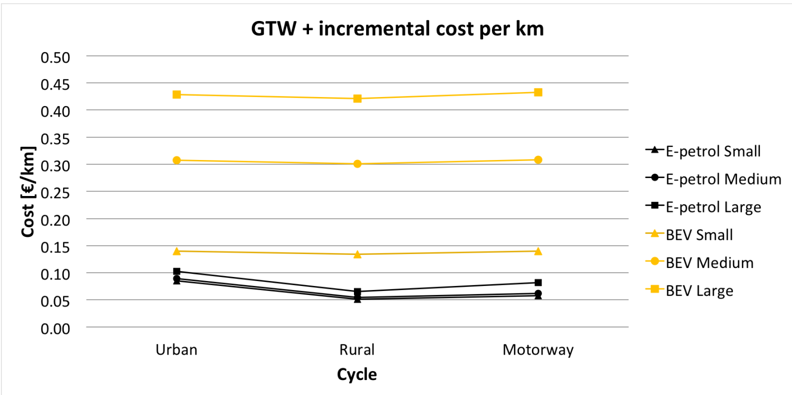

Figure A.14: The figure shows cost per kilometer for BEV and e-petrol cars if battery cost would be 280 [€/kWh].

B

Appendix 2

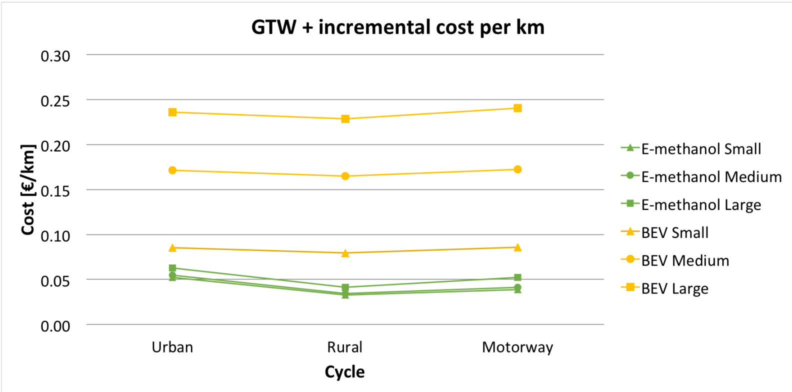

Figure B.1: The figure shows cost per kilometer for BEV and e-methanol cars if the electrolyzer had 90% efficiency.

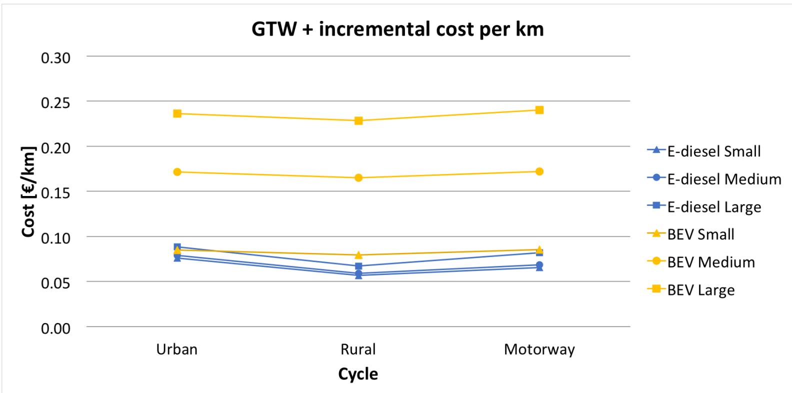

Figure B.2: The figure shows cost per kilometer for BEV and e-diesel cars if the electrolyzer had 90% efficiency.

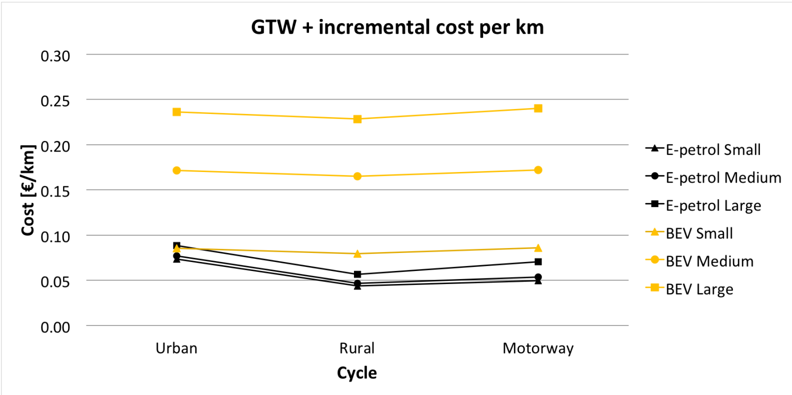

Figure B.3: The figure shows cost per kilometer for BEV and e-petrol cars if the electrolyzer had 90% efficiency.

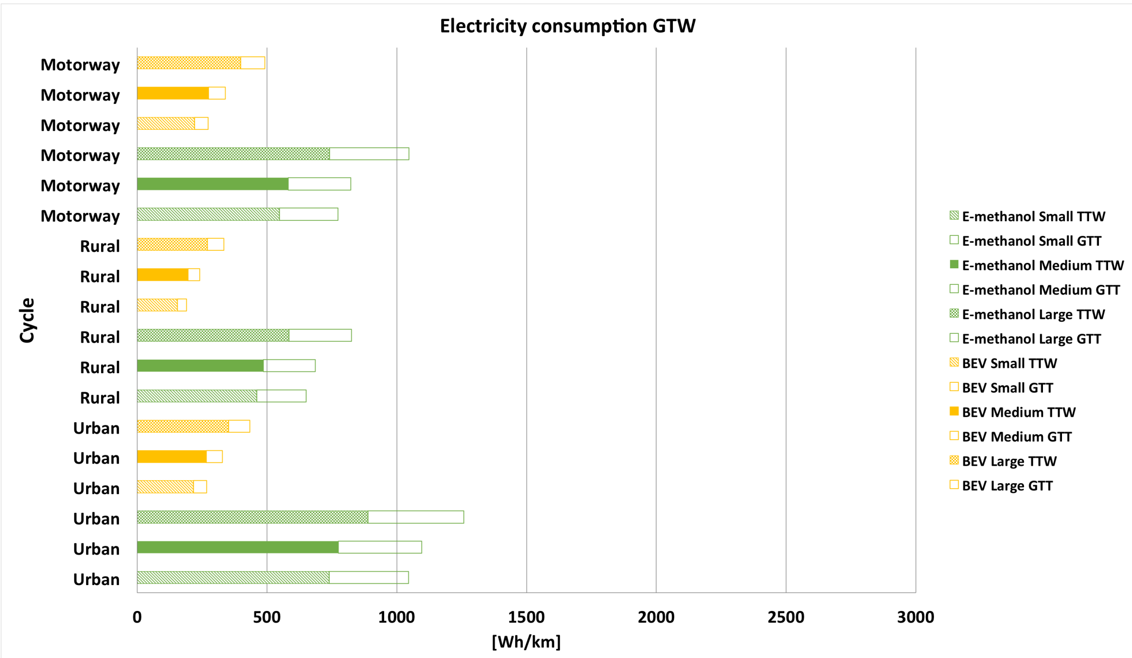

Figure B.4: The figure shows the electricity demand GTW per kilometer to propel BEV and e-methanol driven cars in each cycle if the electrolyzer had 90% efficiency.

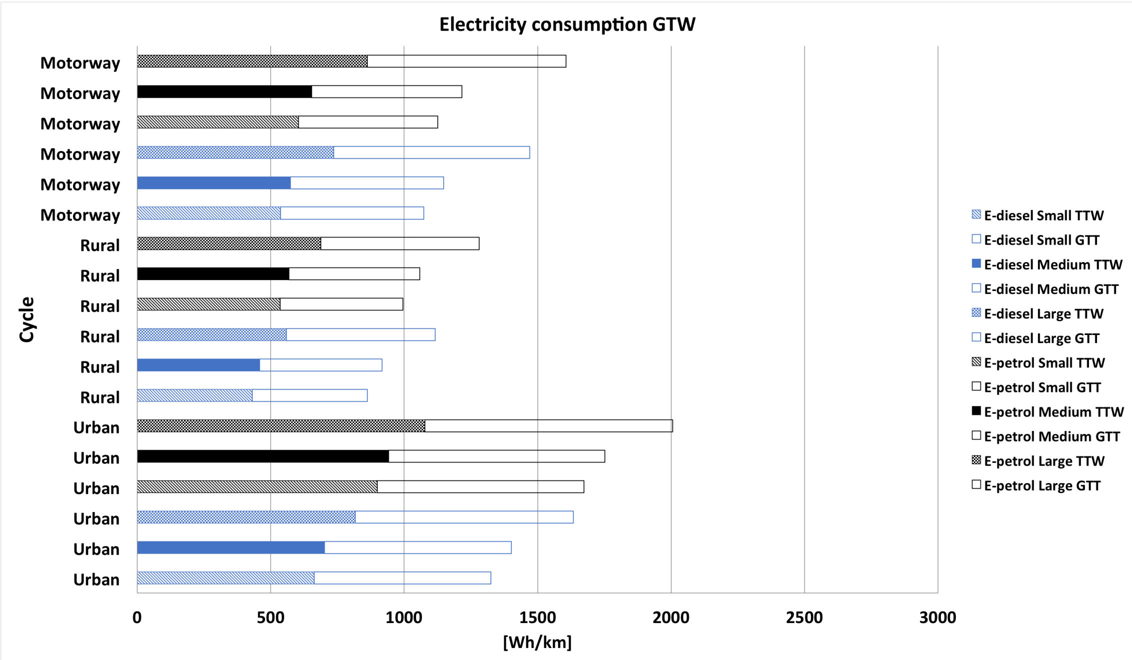

Figure B.5: The figure shows the electricity demand GTW per kilometer to propel e-diesel and e-petrol driven cars in each cycle if the electrolyzer had 90% efficiency.

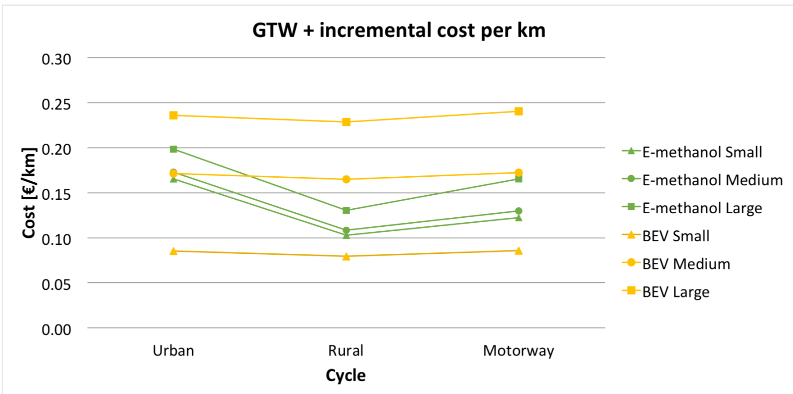

Figure B.6: The figure shows cost per kilometer for BEV and e-methanol cars if the capacity factor of the e-methanol factory would be 10%.

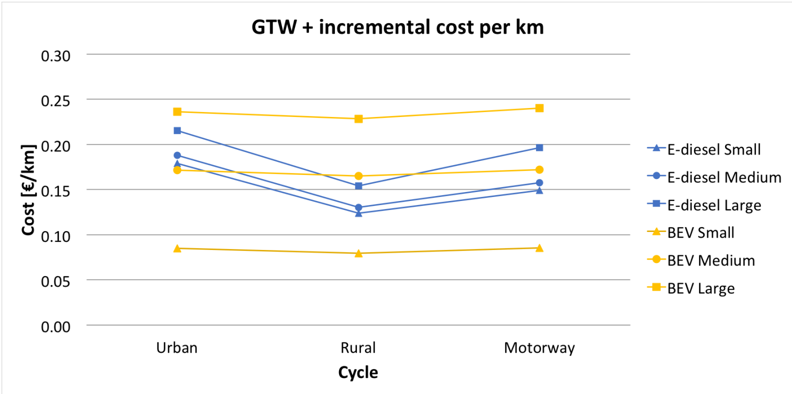

Figure B.7: The figure shows cost per kilometer for BEV and e-diesel cars if the capacity factor of the e-diesel factory would be 10%.

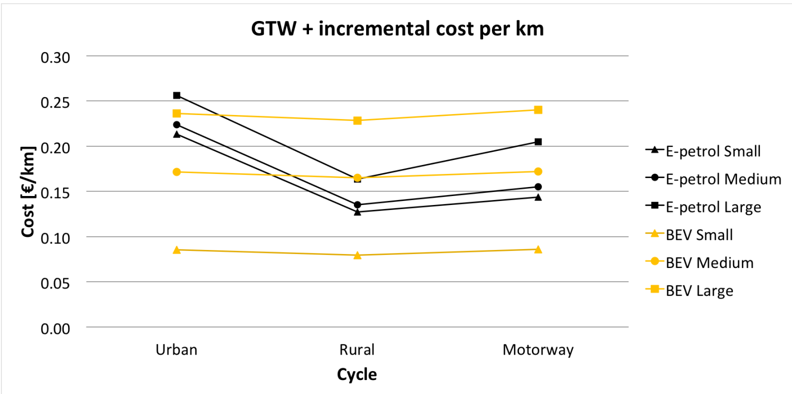

Figure B.8: The figure shows cost per kilometer for BEV and e-petrol cars if the capacity factor of the e-petrol factory would be 10%.

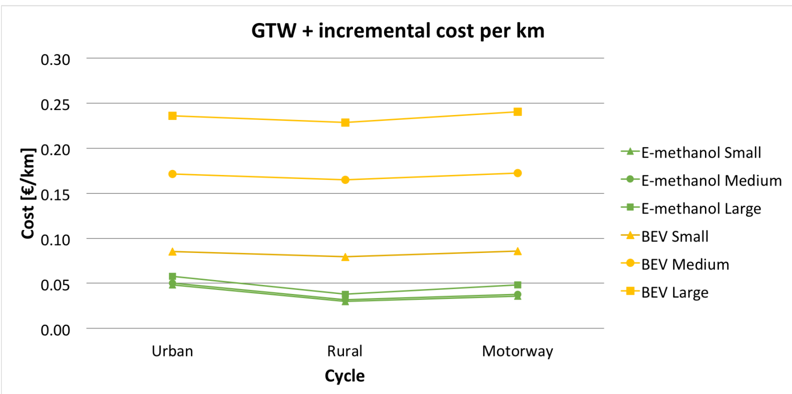

Figure B.9: The figure shows cost per kilometer for BEV and e-methanol cars if the capacity factor of the e-methanol factory would be 90%.

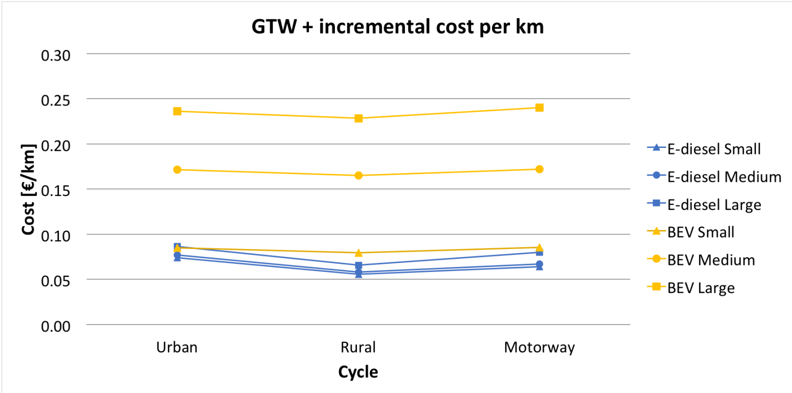

Figure B.10: The figure shows cost per kilometer for BEV and e-diesel cars if the capacity factor of the e-diesel factory would be 90%.

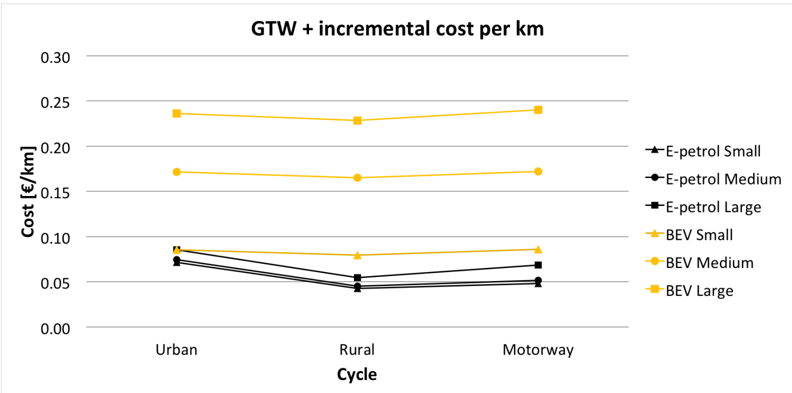

Figure B.11: The figure shows cost per kilometer for BEV and e-petrol cars if the capacity factor of the e-petrol factory would be 90%.