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Battery Electric Vehicles

Performance, CO_2 emissions, lifecycle costs and advanced battery technology development

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Summary

The coming years a few electric vehicles will emerge on the market that are powered by a rechargeable battery. The success of the battery electric vehicle (BEV) is very dependent on the battery technology. This study tries to gain insight in the battery types suitable for electric vehicles and the development of advanced batteries the coming decade. Also a comparison is made between passenger vehicles powered by petrol or diesel and a few battery electric vehicles that will be introduced the coming years.

A consortium of car manufacturers, the USABC, set up the goals that advanced batteries should have in order for the battery electric vehicle to become a commercial success. The specifications of a number of battery types are compared with the USABC goals.
None of the commercially available batteries suitable for electric vehicles can meet the minimum goals from the USABC, required for successful commercialisation. Especially the price of a battery pack is a large burden for successful commercialisation. The lithium-ion battery is the best candidate that can meet the required goals within years, except for the price goal. Another type of battery that will meet the required specifications the next decade is the zebra battery. After 2020 the metal air batteries can be possible candidates for electric vehicles. A large drawback of metal air batteries is their low specific power, needed to give enough power to drive the electric vehicle.

The first battery electric vehicles that will appear on the market are passenger cars in the lower car segments. Petrol and diesel powered passenger vehicles in the sub-mini class, mini class and the compact class are compared with battery electric vehicles from the same classes.
The comparison between the vehicles is done based on a well-to-wheel analysis on emissions of CO_2, primary energy consumption, efficiency and the total lifecycle costs.

The efficiency and energy use of a battery electric vehicle are very dependent on the source of the electricity. In this research the average electricity mix in Europe is used. The best efficiency is achieved by the Nissan Leaf with a W-T-W efficiency of 27.1%. The Toyota Yaris has a W-T-W efficiency of 16.5%, the lowest efficiency of all the vehicles researched in this thesis. The primary energy consumption of a battery electric vehicle compared to an internal combustion engine vehicle does not differ significantly. The Smart Fortwo diesel has a primary energy consumption of 1.40 MJ/km, the lowest of all the vehicles researched. The Smart Fortwo is followed by the Smart Fortwo electric, the Mitsubishi iMiev and the Nissan Leaf with a primary energy consumption of 1.48, 1.55 and 1.64 MJ/km respectively. The highest primary energy consumption is achieved by the Ford Focus petrol with 2.59MJ/km.
The dependence on fossil fuels can not simply be reduced by the introduction of the battery electric vehicle. Increasing the amount of renewable energy in the European electricity mix is utmost important for reducing the total use of fossil energy.

The emissions of CO_2 caused by the transport sector can be reduced by the battery electric vehicle. The well-to-wheel CO_2 emissions are reduced by approximately 50% compared to a similar internal combustion engine vehicle. All the BEVs researched in this thesis have lower CO_2 emissions than the ICE vehicles when the electricity comes from the European mix. The Smart Fortwo emits 62 g/km, where the Smart ForTwo petrol emits 121 g/km. The Ford Focus petrol emits 187 g/km, the highest of all the vehicles researched in this thesis.

When only using state-of-the-art coal fired power plants for the electricity to power an electric vehicle the reduction is very small. Using gas fired power plants will lower the emissions even further compared to the European electricity mix.

The lifecycle costs of a battery electric vehicle in the A class are much higher than a similar internal combustion engine vehicle. The Peugeot 107 will cost €0.20/km during the lifetime of the vehicle. The lowest costs of an A class BEV are €0.38/km for the Smart Fortwo electric. The high retail price is the cause of the high lifecycle costs. The only BEV that can compete with the ICE vehicles is the Nissan Leaf. The lifecycle costs of the BEV are €0.37/km, the same as the lifecycle costs of the VW Golf petrol.

Successful introduction of the battery electric vehicles for individual consumers is going to be slowed down by the high retail price of the vehicle. The next decade the number of electric passenger vehicles sold to consumers will increase but not on a large scale. The market for battery vehicles will most likely remain a niche market the next decade. Only a drastic retail price drop, partly by reducing the battery pack price, can change this.

1. Introduction

To reduce greenhouse gas emissions and improve security of energy supply the European Union aimed at a substitution of 10% of the conventional fuels (conventional diesel and gasoline) in the road transport sector before the year 2020 (VROM, 2007).
Also a reduction of 20% greenhouse gasses in 2020 compared to the levels of 1990 was proposed by the European Union in 2007.
The transport sector accounts for about 31% of European energy use (EEA, 2008) and 25% of the European CO_2 emissions. A large part of the CO_2 emission reduction can be achieved by introducing alternative fuels and drive trains, like hydrogen, fuel cell technology and electric powered vehicles. These alternatives also can help reduce the dependence on oil from unstable regions in the Middle-East.

The problems alternative drive trains and fuels are facing right now are the high costs and the lack of a good infrastructure for alternative fuels. Also in the case of battery powered vehicles a problem is the range of the car. The current batteries are not capable yet to power a light duty vehicle for more than two or three hundred kilometers (Van Mierlo, 2006). However the future of battery powered vehicles can be bright. The battery technology has improved significantly the last decades mainly through the development of mobile phones and laptops. Lithium-ion batteries are the standard batteries in mobile phones and laptops right now. Those batteries are also being used in the new battery electric vehicles coming on the market the next few years and are likely to be the standard for electric vehicles the next decade (Kennedy et al. 2000).

The main problems electric vehicles are facing are the batteries, costs and charging facilities. Because of the limit in range of BEVs the cars that going to be introduced into the market most likely will be small city cars. Nissan, Mitsubishi and Smart are examples of car manufacturers who are going to introduce the electric city car the coming years.
In this research a chain analysis is performed for battery powered city vehicles on costs, efficiency, fuel economy and emissions. Those results will be compared with conventional internal combustion engine vehicles powered by fossil fuels.
The research also focuses on the development of the battery technology. As the battery is a crucial part in the electric vehicle the success of the car is mainly dependent on the battery development. This research tries to map whether the battery can meet the required targets for the usage in electric vehicles considering costs, lifetime, specific energy and specific power.

1.1 Problem definition

This research focuses on the W-T-W efficiency, primary energy consumption, lifecycle cost and CO_2 emissions involved with driving a BEV in the Netherlands. Only light duty vehicles are being researched as they are most likely to be the main BEV introduced into the market.
The BEV seems to be a relatively clean and efficient way of using energy in comparison with other fuels (Mierlo et al. 2006). Therefore there is a great potential of saving energy and reduce emissions when the BEV is being introduced on a large scale.
The efficiency as well as the emissions of the BEV already have been subject of research and numerous can be found in literature. The development of battery technology and the future costs of advanced batteries are uncertain but are utmost important for the success of the BEV. The battery technology is considered to be the most critical factor in the commercialization of the BEV. Delucchi et al. (Delucchi et al. 1989) already researched the lifecycle costs, performance and battery technology of EVs in 1989. The research predicted a large technology improvement of the battery and a commercial breakthrough of the EV at the turn of the century. The battery technology has made considerable progress since then as a result of the success of the mobile phone and notebook technology. The improvement of the technology is still going on but the battery price remains a big obstacle. Therefore predictions on the price and performance of the battery are important for the commercialization of the BEV. EPRI (EPRI 2004) and also Anderman et al (Anderman et al. 2000) made an assessment on advanced batteries for electric vehicles. At the time of their research lithium batteries for electric vehicles where not commercial available and improvements has been made since. An overview of available and future batteries is not up-to-date. This research gives an overview of the advanced batteries for electric vehicles of today and tomorrow.

The electric car has been subject of research, for instance by Eaves and Eaves (Eaves and Eaves 2004), Campanari et al (Campanari et al. 2009), Mierlo et al (Mierlo et al. 2006), Granovskii et al (Granovskii et al. 2006) and Ahman (Ahman 2001). These researches all focus on the theoretical efficiency of a BEV. The real efficiencies and fuel consumption of BEVs coming on the market the next years are not part of the research. They also do not make a distinction between different vehicle classes. From these researches it is known that BEVs can be very efficient and have low CO_2 emissions. The emissions and efficiency from real BEVs using electricity from the grid are not compared with conventional ICE vehicles from the same classes. The cost of driving a BEV is part of research by Delucchi and Lipman (Delucchi and Lipman 2001). The results of this research are based on larger vehicles in the higher classes and do not focus on the lower classes.
This thesis is trying to give an overview of available data in the public domain on the performance, lifecycle costs and development of advanced batteries for Battery Electric Vehicles.

1.2 Research question

1.2.1 Central research questions

In this research a chain analysis is performed on primary energy consumption, efficiency, emissions of CO_2 and the lifecycle costs of a BEV. For the calculations cars are divided into different classes based on there size and power. The classes are based on those used by the ANWB (ANWB, 2008). The calculations are only made for the three smallest segments which represents the largest share of all the passenger cars in the Netherlands (BOVAG-RAI 2008). Also the first BEVs coming on the market will be cars in the lower segments. The results are compared with existing data from vehicles running on conventional fuels.

The implementation of electric vehicles does not solely depend on costs, efficiency and emissions. Also the development of the battery technology, charging facilities and grid capacity are critical points in the implementation of electric vehicles of which the battery development is crucial.

In accordance with this two main questions are proposed:

Which batteries, suitable for battery electric vehicles, have the potential to compete with internal combustion engine fuels considering the battery lifetime, specific energy, specific power and costs?

What is the well-to-wheel efficiency, energy consumption, CO_2 *emission and lifecycle cost of a battery electric vehicle in the sub-mini, the mini and the compact class compared with a conventional internal combustion engine vehicle in the same class?*

1.2.2 Sub-questions

To answer the main question also a few sub-questions need to be answered.
The battery technology has to be researched because future developments can be important for the implementation of electric vehicles. The battery capacity, lifetime, charging time and price development is analyzed. Based on data gathered in literature a future price of different battery technologies is estimated. The goals of the USABC are used as a guide for answering the main question.
The well-to-wheel primary energy consumption, CO_2 emissions, efficiency and lifecycle costs of a few reference conventional ICE vehicles are calculated to compare with the results of the battery electric vehicles.

2. Methods

This research tries to map the potential of the BEV on the short term. A chain analysis on efficiency, energy consumption, CO_2 emissions and lifecycle costs of battery electric vehicles is made and compared with conventional fossil fuels used in the Netherlands. For this analysis different reference cars are used derived from the ANWB classes (ANWB, 2009). Four cars from the mini class, the small middle class and middle class are used as reference for the calculations on a battery electric car. Each class will have two diesel and two gasoline powered ICE vehicles.

The potential of the battery electric vehicle depends on more than efficiency and costs alone. The most important are the charging facilities and battery technology. The focus in this research is on battery development as it is considered the most important factor whether the BEV will be a success.

2.1 Battery technology development

Data on emissions, cost and efficiency can be used to make a comparison with conventional vehicles. The battery technology development however determines for a large part the success of the BEV and therefore is researched. The USABC has set a number of goals a battery for an electric vehicle should have. These goals determine the commercial success of the BEV on long term and consist of minimum requirements a battery should have. An assessment is made on car batteries for a number of battery parameters to see which batteries have the potential to reach the long term goals.
The focus in this research is on the development of battery lifetime, energy efficiency, specific power, specific energy and costs.

Battery Lifetime and efficiency
The lifecycle of a battery represents the number of charging and discharging cycles possible before it loses its ability to hold a useful charge (typically when the available capacity drops under 80% of the initial capacity) (Mierlo et al. 2004). The lifecycle of a battery depends on the depth of discharge (DOD). Improvement of the lifecycle is important to extent the calendar life of a battery. Batteries for electric vehicles should last as long as the lifetime of the vehicle. Otherwise replacement of the car battery is necessary within the lifetime of the car. This will increase the price of driving a BEV.
The efficiency of a battery is given by the energy losses that occur when charged and discharged. The amount of energy that is available to power the wheels represents the efficiency of the battery.

Specific energy and power
The specific energy of a battery describes the energy content and determines the vehicle range. This is most important for BEVs where batteries can be optimised to have high energy content. High specific power is especially important for hybrid drive trains. The specific power determines the acceleration performance of a vehicle.
The US Advanced Battery Consortium (USABC) specific power goals for future advanced batteries are 300 W/kg for the midterm and 400 W/kg for the long-term. The specific energy goals are 150 Wh/kg and 200 Wh/kg, respectively, for the midterm and long-term.

The specific energy of a battery researched here is expressed in Wh/kg. However the amount of energy that a battery can hold depends on different factors like the temperature, humidity and the rate at which the battery is discharged.

Costs

The production costs of EV batteries are going down and the specific energy of a battery is still rising. Normally the price of a product will go down when the production goes up. A learning or experience curve describes this production costs decline. The costs of batteries are still going down and a relation between cumulative production and cost per unit is being researched.

The formula for a learning curve is given below (Neij, 1999):

$$\mathrm{C}_{\mathrm{cum}} = C_0 \mathrm{Cum}^{\mathrm{b}}$$

$$\log \mathrm{C}_{\mathrm{cum}} = \log C_0 + \mathrm{b} \log \mathrm{Cum}$$

$$PR = 2^b$$

$$LR = 1 - 2^b$$

in which:

C_{cum} = Cost per unit
C_0 = Cost of the first unit produced
Cum = Cumulative production
b = Experience index
PR = Progress ratio
LR=Learning Rate

The learning rate of the different batteries researched is calculated if possible. For some battery technologies not enough information is at hand to do such a calculation. In this case the data gathered from literature is used to make a price prediction.

2.2 W-T-W chain analysis

Comparison of the lifecycle costs and performance between ICE vehicles and BEVs can only be done properly when the whole well-to-wheel chain of the car fuel is analyzed. The energy losses embodied in plants, buildings and vehicles are not included in this thesis. Embodied energy account for 7-8% of the total lifecycle energy of today (Ahman 2001). As this is a comparative study and the embodied energy for ICE vehicles and BEVs are assumed to be equal this does not have an effect on the results.

2.2.1 Efficiency and primary energy consumption

The W-T-W efficiency is calculated with the formulas given below (*Ahman*, 2001):

$$\eta_{\mathrm{primary}} = \frac{\text{Usefull energy at the wheels}}{\text{Primary energy}}$$

$$\eta_{\text{vehicle}} = \frac{\text{Usefull energy at the wheels}}{\text{Energy supplied to the vehicle}}$$

$$\eta_{\text{powertrain}} = \frac{\text{Usefull energy at the wheels}}{\text{Energy supplied to the powertrain}}$$

Energy losses occur during electricity production, transportation, charging and driving the vehicle. Regenerative braking has a positive effect on the efficiency.
Figure 2.1 gives an overview of the efficiencies.

The useful energy at the wheels is the total tractive effort of the vehicle. The tractive effort consist of the mechanical power required overcoming the drag resistance (F_a), the rolling resistance (F_r) and the acceleration force F_l.

The drag- and roll resistance are given by (in N) (Blok 2006):

$$F_a = 0.5 \cdot C_D \cdot A \cdot \rho \cdot v^2$$

$$F_r = C_R \cdot M \cdot g$$

In which:
C_D = the drag coefficient of the car
C_R = rolling resistance coefficient
A = the frontal area of the car (m2)
ρ = the density of air
M = the car mass (kg)
g = the acceleration of gravity (m/s2)
v = the speed of the car (m/s)

The acceleration force of a vehicle consist of the linear acceleration of the vehicle given by (in N) (Larminie and Lowry 2003)

$$F_l = M \cdot a$$

In which:

F_l = linear acceleration force (Newton)
M = the car mass (kg)
a = acceleration of the vehicle (m/s^2)
v = the speed of the car (m/s)

The acceleration force also consists of a rotational acceleration component. This force makes the rotational parts of the vehicle turn faster. This force can be implemented in the equation above by simply adding 5% to the mass of the car (Larminie and Lowry 2003).

The vehicle efficiency can be calculated as the three forces together are the useful energy at the wheels. The vehicle efficiency then becomes (GM 2002):

$$\eta_{\text{vehicle}} = \frac{(\mathrm{F_a} + F_r + \mathrm{F_l}) * \Delta v * \Delta t}{\text{Energy supplied to the vehicle}}$$

It should be noted that when descending $\mathrm{F_l}$ becomes negative. However this braking power can not be used in a normal ICE vehicle and is turned into heat. In a BEV regenerative braking is possible and it is assumed that 25% of the braking force is regenerated and stored into the battery (Ahman 2001). This regenerative energy is part of the energy supplied to the vehicle. Without regenerative braking the energy use during the driving cycle would be larger.

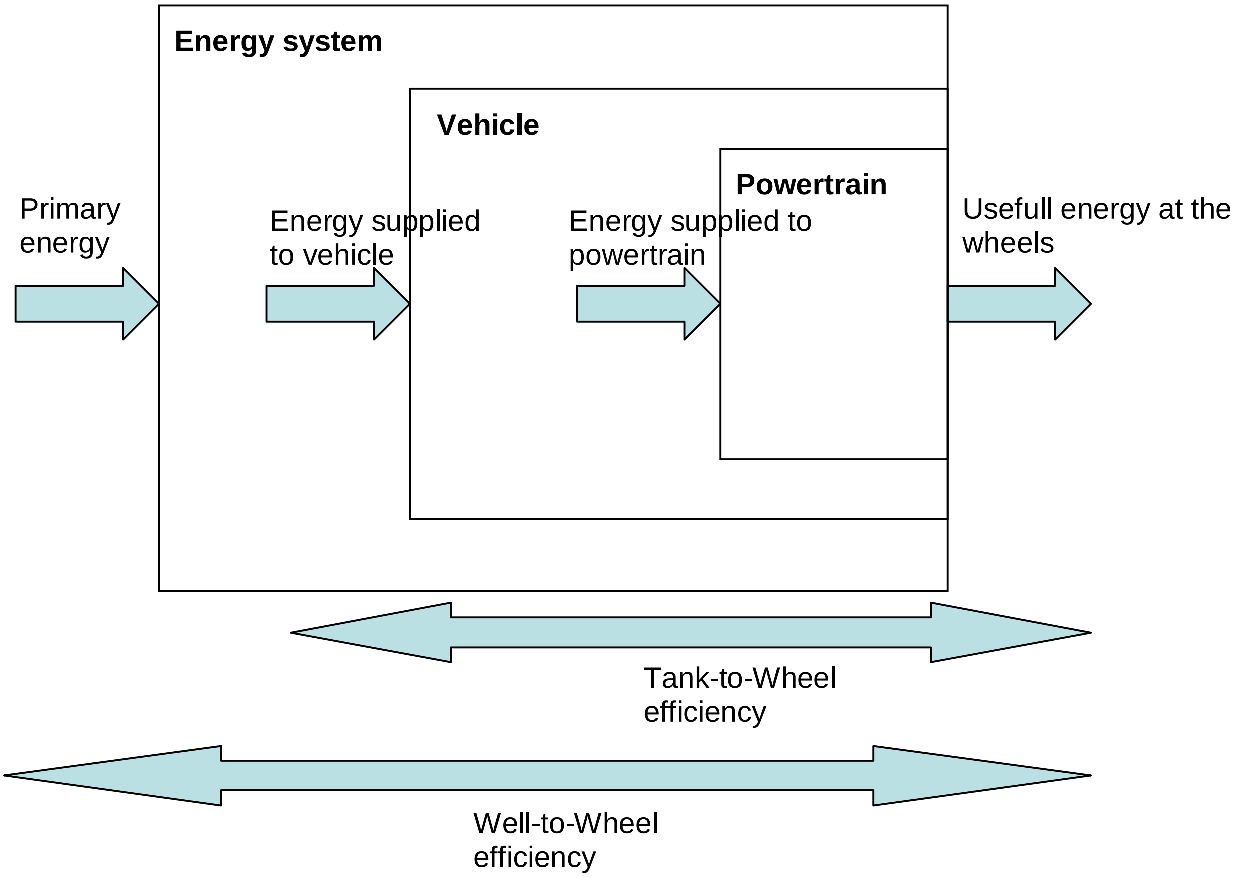

Figure 2.1: The chain efficiency

The vehicles efficiencies are simulated using data from standardized driving cycles and excel. For Europe this is the New European Driving Cycle (NEDC) (EEC Directive 70/220/EEC) and for the USA the UDDS is used (CFR 40, 86, App.I). The driving cycles can be found in appendix A, where the velocity at each second is given. To calculate the vehicle efficiency during the total driving cycle, the useful energy at the wheels is simulated during each second. The average power to overcome the drag- and roll resistance and acceleration force during the cycle represents the useful energy at the wheels.

The vehicle efficiency can now simply be calculated with the fuel consumption during the driving cycle (energy supplied to vehicle) and the power to the wheels (useful energy at the wheels).

2.2.2 CO_2 Emissions

The CO_2 emissions are calculated with the primary energy efficiency and emission data of the European electricity mix. All the emissions occur during the extraction and transport of the primary energy and the production of the electricity used to power the car.
The emission is calculated with the following formula:

$$CO_2 emission = EUmix \times E_{cons} \times \eta_{charge} \times \eta_{transport}$$

in which:

CO_2 emission = W-T-W CO_2 car emission (g/km)
η_{charge} = Electric vehicle charge efficiency
$\eta_{transport}$ = Electricity transport efficiency
EUmix = Average CO_2 electricity mix emission in Europe (g/kWh)
E_{cons} = Fuel consumption based on the NEDC (kWh/km)

2.2.3 Lifecycle Costs

The total costs involved with driving a BEV consist of the depreciating of the investment, variable and fixed costs. The costs of driving a BEV are calculated in €/km.

Depreciating of investment costs

The depreciation of the vehicle is the annual capital costs divided by the number of kilometers driven in which the annual capital costs are:

$$\mathrm{ACC} = \alpha \times \mathrm{I}$$

in which:

α = capital recovery factor
I = Initial investment

$$\alpha = \frac{\mathrm{r}}{1 - (1 + \mathrm{r})^{-\mathrm{L}}}$$

in which:

r = discount rate
L = Lifetime (in years)

The depreciation of the vehicle can not simply be calculated by dividing the retail price by the lifetime of the vehicle. When the investment is not made, interest would be received each year. Or in the case the capital for the investment comes from a loan, interest have to be paid each year. Therefore the discount rate is introduced in the equation.

Variable costs

The variable costs consist are separated into maintenance and repair and fuel costs.
The variable costs depend on the fuel consumption of the BEV and costs for maintenance and repair (M&R). The M&R costs for the petrol and diesel powered vehicles are derived from the ANWB. The M&R costs of the BEVs are based on the numbers given by the ANWB and literature.

Fixed costs

The fixed costs consist of two parts. The first part is the costs for car washes, road services and other costs that are no M&R costs. These are derived from the ANWB and are considered to be equal for all vehicles. The second part of the fixed costs is the road taxes in the Netherlands. These are dependent on the type of vehicle and are usually higher for diesel cars.

Taxes

In this thesis a distinction is made between the taxed and untaxed lifecycle costs. The taxes applied in the Netherlands are used to calculate the taxed lifecycle costs.
First of all the retail price in the Netherlands of a vehicle consists of value added tax (VAT) and a vehicle tax (BPM). For a few low emission vehicles, like the BEVs, the vehicle tax is abolished.
Secondly, the M & R and fixed costs have also VAT included. When calculating the untaxed lifecycle costs the VAT is subtracted from the original values derived from the ANWB.
Thirdly, the battery costs used throughout this thesis are excluding VAT. When replacing the battery during the lifetime of a BEV the VAT should be included when calculating the taxed lifecycle costs.
Fourthly, road taxes are part of the fixed costs. These taxes are applied to all vehicles with the exception of the BEVs and some low emission vehicles.
At last, the fuel prices are including VAT and excise duty. The breakdown of the fuel prices are given in section 2.3.
All prices, taxes and excise duties in this thesis are from the year 2009. Road taxes and excise duties are subject to change and can influence the total lifecycle costs. Therefore a distinction is made between taxed and untaxed lifecycle costs.

2.3 Data collection

The data used in this thesis comes from other public reports and researches on the BEV. The data on advanced batteries is derived from vehicle and battery manufacturers and also from other researchers. Table 2.1 gives an overview of the data assumptions used in this research.

Fuel price

For the cost of driving a BEV the current taxed and untaxed fuel and electricity prices in the Netherlands are used. The current taxed consumer prices are around €1.50 per litre for gasoline and €1.10 litre for diesel. Electricity from the grid cost around €0.24 per kWh.
Taxes and excise duty make up the largest part in the total price of the fuels. The price of electricity in the Netherlands consists of two parts, the price of delivery and the price of transporting the electricity. It is assumed that the BEV is charged at a home charger. The costs for transportation are a fixed price for each household. Charging a BEV will only increase the costs with the price of the electricity delivered. In table 2.2 the difference between the fuel price and fuel costs is given where in figure 2.2 the breakdown of the fuels is given in €/GJ.

Future prices of fuels and electricity can make a difference in the outcome. However an assessment of the price development of fuel prices and electricity is beyond the scope of this thesis. During the lifetime of the vehicle fixed fuel prices are used.

Table 2.1: Data assumptions

Parameter	
Rolling resistance coefficient normal	0.01
Rolling resistance coefficient low	0.07
Density of air at 20°C (kg/m3)	1.205
Gravitational force (m/s2)	9.81
Additional car weight ICE (passenger and fuel) (kg)	100
Additional car weight BEV (passenger) (kg)	70
Lifetime ICE vehicle (yr)	15
Lifetime BEV (yr)	17
Discount rate (%)	5
VAT (%)	19
Energy content diesel (MJ/l)	36
Energy content gasoline (MJ/l)	33
Fuel consumption passenger car	Based on NEDC or UDDS
European electricity mix primary energy efficiency	35%
European electricity mix CO_2 emission (g/Mj)	120.8

Table 2.2: Difference between fuel price and fuel costs

	Fuel costs	Excise duty/energy tax	VAT	Fuel price
Gasoline (litre)	€ 0.55	€ 0.71	€ 0.24	€ 1.50
Diesel (litre)	€ 0.50	€ 0.42	€ 0.18	€ 1.10
Electricity (kWh)	€ 0.09	€ 0.11	€ 0.04	€ 0.24

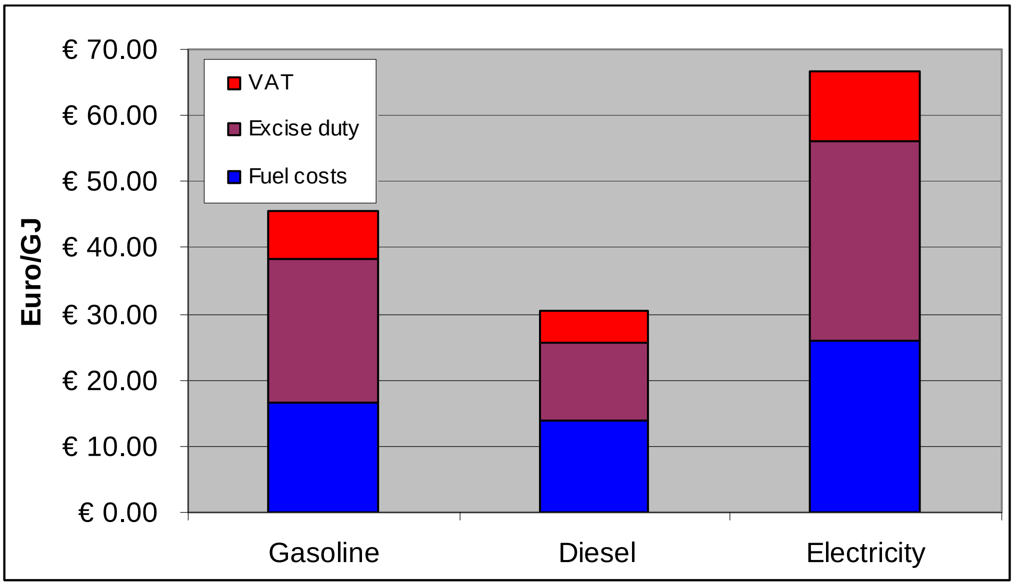

Figure 2.2: Breakdown of fuel prices in taxes and fuel costs

3. Advanced battery technology development

The battery is the most important and crucial part in the design of an EV. In order for the BEV to become a commercial success the batteries should meet certain goals. These goals should accompany enough lifecycles, a certain specific power, specific energy and a price of the battery that can compete with an ICE. Batteries that are used today in BEVs are lead/acid (Pb/A), nickel–metal hydride (NiMH) and lithium batteries (Ahman 2001). Also a few other batteries have emerged for the use in BEVs; the Zinc air and the Zebra battery ($NaNiCl_2$) which is used in the Th!nk electric city vehicle (Th!nk 2009).

3.1 Battery goals

The United States Advanced Battery Consortium (USABC) is part of the United States Council for Automotive Research (USCAR) and promotes long term research on electrochemical energy storage (EES). The consortium has set up the goals that batteries for EVs should meet in order to become commercially successful (table 3.1). In this chapter the batteries suitable for BEVs are described. According to the current and potential specifications of BEV batteries a prediction can be made whether the USABC goals can be met.

Table 3.1: USABC Goals for Advanced Batteries for EVs (USABC 2009)

Parameter(Units) of fully burdened system	Minimum Goals for Long Term Commercialization	Long Term Goal
Power Density (W/L)	460	600
Specific Power – Discharge, 80% DOD/30 sec (W/kg)	300	400
Specific Power - Regen, 20% DOD/10 sec (W/kg)	150	200
Energy Density - C/3 Discharge Rate(Wh/L)	230	300
Specific Energy - C/3 Discharge Rate(Wh/kg)	150	200
Specific Power/Specific Energy Ratio	2:1	2:1
Total Pack Size(kWh)	40	40
Life(Years)	10	10
Cycle Life - 80% DOD (Cycles)	1000	1000
Power & Capacity Degradation(% of rated spec)	20	20
Selling Price - 25,000 units @ 40 kWh($/kWh)	<150	100
Operating Environment(ºC)	-40 to +50 20% Performance Loss (10% Desired)	-40 to +85
Normal Recharge Time	6 hours (4 hours Desired)	3 to 6 hours
High Rate Charge	20-70% SOC in <30 minutes @ 150W/kg	40-80% SOC in 15 minutes
Continuous discharge in 1 hour - No Failure(% of rated energy capacity)	75	75

3.2 Battery types

A typical battery consists of two or more electrochemical cells joined together. The battery converts stored chemical energy into electric energy. A single battery cell is made of a negative electrode and a positive electrode which are connected by an electrolyte. The chemical reaction between the electrodes and electrolyte generates electricity. Rechargeable batteries can reverse the chemical reaction by reversing the current. This way the battery can be recharged. The kind of material used for the electrodes and electrolyte determines the battery specifications. A number of batteries available or under development are suitable for EVs. These batteries are described here.

3.2.1 Lead/acid

Lead/acid (Pb/A) batteries are the oldest type of battery used in vehicles. The battery negative electrodes contain elementary lead (Pb) while the positive plates have lead dioxide (PbO_2) as active material in charged state. The electrodes are immersed in an electrolyte of sulphuric acid (H_2SO_4). When being discharged the lead of the negative electrodes and the lead dioxide of the positive electrode reacts with the sulphuric acid. Lead sulphate is formed on the electrodes and the electrolyte loses its dissolved sulphuric acid and becomes water. Energy is released during the chemical reaction and when energy is added the process will reverse.
The overall reaction is:

$$Pb + PbO_2 + 2H_2SO_4 \longleftrightarrow 2PbSO_4 + 2H_2O$$

Most ICE vehicles use a SLI (start, lightning, and ignition) Pb/A battery. The Pb/A battery is the most mature technology of the EV batteries and the prices are the lowest. However their specific energy also is low compared to the other battery technologies. A typical Pb/A battery for an EV has a specific energy of around 35 Wh/kg and a specific power of 250 W/kg (Burke et al. 2007). The number of lifecycles than can be achieved by a Pb/A battery is 100 cycles for a normal SLI car battery (Ruetschi 2004). The reason for the short lifetime of a car SLI battery is corrosion of the active material on the positive plate (anodic corrosion). Means to reduce corrosion on the battery plates are mechanical compression. The more advanced valve-regulated Pb/A (VRLA) batteries can achieve around 800 cycles, while with compression realised in tubular-plate positive electrodes the Pb/A batteries can achieve around 1500 cycles (80% DOD) (Ruetschi 2004). Charging and discharging SLI batteries goes slow and are not suited for use in a BEV.
The valve-regulated lead-acid nevertheless, are more suitable for rapid recharge. That type of Pb/A batteries are capable of being recharged in a few minutes (Fleming et al. 1999). Prices today of a Pb/A battery pack for EVs are around 90 €/kWh (Ahman 2001;Chan et al. 2007).

3.2.2 Nickel Metal Hydride

There are four types of nickel based batteries that use nickel in the positive electrode of the battery; the nickel iron (Ni-Fe), nickel zinc (Ni-Zn), nickel cadmium (Ni-Ca) and nickel metal hydride (Ni-MH). The Ni-Zn and Ni-Fe batteries are not considered to be an option for EVs because of their short lifecycle and low specific power (Chau et al. 1999). Ni-Ca is the most mature technology of the cadmium based batteries. It has similar specifications compared to the Ni-MH (Larminie and Lowry 2003). The advantage of the Ni-MH battery is that it uses no cadmium and is therefore environmental friendlier. The battery considered to be an option for a BEV in this research is the Ni-MH. The battery uses hydrogen absorbed in a metal hydride at the positive electrode. Nickel oxyhydroxide becomes nickel hydroxide during discharge. At the negative electrode hydrogen is released from the metal producing water and electrons during discharge. The overall reaction is written as:

$MH + NiOOH \longleftrightarrow M + Ni(OH)2$

Nickel-metal hydride batteries have developed rapidly since the introduction in 1991. They are being used in hybrid vehicles like the Honda Civic hybrid and the Toyota Prius because of their high specific power. Power increased from under 200 W/kg in the early 90's to 1200 W/kg commercially and up to 2000 W/kg at a development level (Fetcenko et al. 2007). Specific energy increased from around 50Wh/kg to 75 Wh/kg today (Yinga et al. 2006).
The lifetime of a NIMH battery can be as high as 3000 cycles if the battery operates between 20% and 80% SOC (State of Charge) and could well meet the projected lifetime requirements of full-function battery EVs and plug-in HEVs (EPRI 2004). The number of deep cycles that can be achieved today are already over 1000 cycles (80% DOD).
The technology will be the dominant battery technology in hybrid and electric vehicles the next five to ten years because of their safety and lifecycle advantages over lithium batteries (Kromer and Heywood 2007). Ni-MH does not deteriorate over time, like lithium-ion batteries, and when temperature and usage is being controlled the battery can be designed to last the life of the vehicle.
However, the Ni-MH battery is not expected to improve in specific energy as the 75 Wh/kg is close to its fundamental practical limits. The price of a Ni-MH battery pack is still around 450 €/kWh (Chan et al. 2007) and prices are not expected to drop much the next decade. The price of a Ni-MH battery pack is highly dependent on the price of nickel. Approximately one third of the mass of a Ni-MH battery pack for a BEV consist of nickel (Rade and Andersson 2001). The price of nickel is very volatile with heavy fluctuations in market prices the last decade (metalprices.com, 2010). Therefore it is hard to make future price predictions for NiMH batteries.

3.2.3 Lithium-ion

Lithium-ion batteries have the potential to become the dominant battery technology in BEVs and HEVs. They rapidly developed the last years for the use in small consumer electronics like cell phones and notebooks. Most BEVs that are coming to the market the next years will be equipped with lithium-ion battery packs. Examples of BEVs that use lithium-ion batteries are the Tesla Roadster, the Th!nk City and the Mitsubishi iMiev.
Lithium-ion batteries are very suitable as high performance EV batteries because of the main characteristics of lithium metal. Of all the different metals lithium has the highest standard potential and electrochemical equivalent. This indicates it has the highest specific energy potential (in Wh/kg) of all metals and on a volumetric energy basis (Wh/l) it is only inferior to aluminium and magnesium (Linden and Reddy 2002). Lithium is also very light, the lightest of all metallic materials.
Lithium-ion batteries come in many ways. The specifications of the battery can vary according to the materials that are used on the anode or cathode. The commercially available batteries usually use lithiated carbon as anode, but some companies are experimenting with other materials. Altairnano developed a battery with a nano-structured lithium titanate anode (LiTiO) instead of lithiated carbon. An advantage of this design is the speed at which electrons can leave or fill up the nano-structured grid. The LiTiO battery can be charged rapidly and also has a longer cycle life than most other lithium based batteries (Altairnano 2009).
Currently there are a number of batteries commercially available that uses lithiated carbon as anode. The most common batteries have a cathode consisting of lithium cobalt oxide

(LiCoO), lithium manganese dioxide ($LiMn_2O_4$) or lithium iron phosphate ($LiFePO_4$). The batteries used in mobile phones and notebooks are the lithium cobalt oxide batteries and are less suitable for BEVs than the manganese dioxide or iron phosphate.
More advanced lithium batteries used for military applications are lithium sulphur dioxide ($LiSO_2$) or lithium thionyl chloride ($Li\text{-}SOCl_2$). The specific energy of lithium-ion batteries today ranges from 50 Wh/kg (THUNDERSKY) to 200 Wh/kg (SAFT) for the more advanced batteries. Power density can be as high as 2000 W/kg (electrovaya 2009).
Lithium-ion batteries usually use a liquid non-aqueous organic electrolyte but also solid electrolytes are used for dry lithium-ion batteries. The most common electrolytes solutes are lithium salts such as LiClO4, LiBr, LiCF3SO3, and LiAlCl ((Linden and Reddy 2002).
For years lithium-polymer batteries where seen as a very promising battery technology for the use in EVs (Ahman 2001). Lithium polymer batteries have the same characteristics as lithium-ion batteries but use a polymer gel as electrolyte. The polymer battery is thinner and lighter than a common lithium-ion battery and can be used in applications where thin shaped batteries are required. A drawback of the polymer battery is the short lifetime of 600 deep cycles and a specific power up to 250 W/kg (Hadjipaschalis et al. 2009), lower than a lithium-ion battery.

3.2.4 Metal air

Most metal air batteries can not be recharged by simply reversing the current as can be done with the other batteries mentioned in this chapter. Instead the electrodes of the battery have to be replaced by new ones. Metal air batteries are mechanically rechargeable batteries and are comparable with fuel cells. A mayor advantage of the metal air batteries is that the battery only consists of one reactant. The other reactant is oxygen which does not have to be carried in the battery. The metal air battery therefore has a weight advantage over other types of batteries.
There are a few metal air batteries being developed of which the zinc air battery is the only one that is commercially available. The aluminium air, magnesium air, iron air and lithium air battery are still under development of which some but look promising for the future.
The zinc air battery has been available for years, for example in hearing aids. The large energy density of the battery is very useful in small devices needing a long lasting battery.
The zinc in the battery reacts with air, forming zinc oxide. The overall reaction is as follows:

$2Zn + O_2 \rightarrow 2ZnO$

The Zn/air battery has a high specific energy of 230 Wh/kg but a relatively low specific power of 105 W/kg (Chan and Wong 2004). The Al/air battery has a specific energy comparable with the Zn/air battery of about 225 Wh/kg (Larminie and Lowry 2003), but the potential of the battery is much higher. A specific energy of 1300 Wh/kg for a designed Al/air battery system is reported with a future potential of 2000 Wh/kg (Yang and Knickle 2002). A drawback of the Al/air battery is its low specific power of only 10 W/kg (Larminie and Lowry 2003;Chan and Wong 2004). The overall reaction of an Al/air battery is:

$4Al + 3O_2 + 6H2O \rightarrow 4Al(OH)_{3.}$

The Al/air battery looked very promising but successful commercialization was impeded because of technological limitations (Linden and Reddy 2002). When the Al/air battery is used in a BEV the fuel efficiency (including recycling and battery efficiency) could be 15% and the projected efficiency is 20% (Yang and Knickle 2002).

The Fe/air battery is most suited for recharging of all metal air batteries. It suffers from a lower specific energy than most metal air batteries but has the advantage of potentially lower lifecycle costs because it can be recharged. Fe/air batteries have a specific power of 80 Wh/kg, a specific power of 90 W/kg (Linden and Reddy 2002) and the number of deep cycles capable are 500 (Burke et al. 2007).

The battery to be considered the holy grail of all batteries is the Li/air battery. It has the highest specific energy potential of all EV batteries of 11500 Wh/kg, excluding oxygen (Imanishi et al. 2008). Before the battery can be developed for commercial applications more research have to be done the coming years.

None of the above metal air battery are being used in BEVs that are being commercialised the next years. It is unclear when these types of batteries become available for the use in electric vehicles.

3.2.5 Sodium nickel chloride

The sodium nickel chloride ($NaNiCl_2$) or zebra battery is current under development by the company MES DEA and is used in the Th!nk city EV. MES DEA is the only company in the world that has this type of battery under development. Zebra stands for Zero Emission Battery Research Association but is now linked to the sodium battery developed by MES DEA.

The zebra battery has a positive electrode made of solid nickel chloride and a negative electrode of molten sodium. The central positive electrode is impregnated in a liquid electrolyte of sodium-aluminium chloride surrounded by a ceramic electrolyte (see figure 3.1). During discharge nickel and sodium chloride are transformed into salt and nickel. The overall reaction is:

$$2Na + NiCl2 \longleftrightarrow Ni + 2NaCl$$

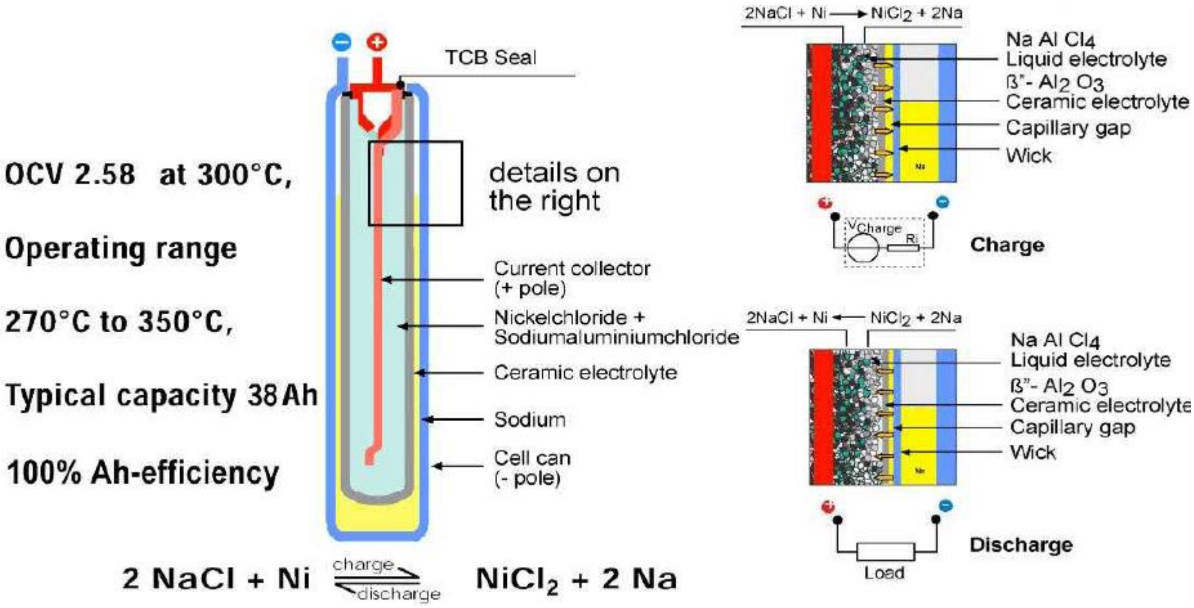

Figure 3.1: The zebra battery (Turconi 2009)

The current zebra battery already has a specific energy of around one hundred Wh/kg and can stand more than 1000 deep cycles (80% DOD). Lifetime is demonstrated to be more than ten years (Dustmann 2004). A drawback of the zebra battery is that it operates at temperatures between 270°C and 350°C. It takes energy to keep the battery at this temperature and selfdischarge rates can be 10% per day (Larminie and Lowry 2003). The battery can be allowed to cool down but will take a day to heat up again as the heating up process goes slowly.

3.2.6 Ultra capacitors

Ultra capacitors are different from batteries. Batteries store their energy chemically where an ultra capacitor stores it physically. A single ultra capacitor cell has two plates (collectors) that are separated by a separator in an electrolyte. The capacitor stores energy electro statically on the collectors. The collectors are made of a material with a very high surface area. Ultra capacitors can be charged and discharged much faster than batteries and are very suitable for storing the energy from regenerative braking, for climbing hills or sudden acceleration (Mierlo et al. 2006). The ultra capacitor has high specific power up to 5000 W/kg (Anderman 2004) and cycle life of over 300,000 cycles but a low energy density of 5 Wh/kg (Chau et al. 1999). Therefore the ultra capacitor cannot solely be used as energy storage for a BEV.

The ultra capacitor is not part of this research as it is not a battery but is mentioned because it can be a part of the total energy storage system in a BEV.

3.3 Battery specifications and price development

3.3.1 Battery specifications

A number of manufacturers in the world already deliver commercially available EV batteries. Table 3.2 shows some of the commercially available batteries and their specifications.

A few batteries currently under development are not yet commercially available, such as the Al-air and Li-air batteries. Also the batteries that are commercially available are still being developed. In table 3.3 the current and projected specifications of batteries suitable for EVs are given. The projected specifications are the predicted specifications that a type of battery will have by the year 2020. Some batteries are already nearing their maximum potential like the Pb-A and Ni-MH and probably will not improve much in the future.

Table 3.3: Current and projected battery specifications

	Now			Projected (2020)			
	Specific Power (W/kg)	Specific Energy (Wh/kg)	Cycle Life (Deep Cycles)	Specific Power (W/kg)	Specific Energy (Wh/kg)	Cycle Life (Deep Cycles)	Sources
Pb/A (VRLA)	200	35	600	300	45	1500	a,b
NiMH	200	65	1000	300	75	1200	c,d
NaNiCl2	150	100	1000	400	120	1500	e
Lithium-ion	300	100	1000	500	150	1500	f,g
Zn/air	90	100-200	NA	110	300	600	h,i
Al/air	10	200-300	NA	16	1300	NA	c,j,d
Li/air				low	600-1000	NA	k,l,m
Fe/air	90	80	600	100	120	1000	h,n

[a](Anderman et al. 2000)
[b](Ruetschi 2004)
[h](Burke et al. 2007)
[i](Bossche et al. 2005)

[c] (Ying et al. 2006)
[d] (Larminie and Lowry 2003)
[e] (Thompson and Tille 2002)
[f] (Kromer and Heywood 2007)
[g] (Ritchie and Howard 2006)
[j] (Chau et al. 1999)
[k] (Viscoa et al. 2009)
[l] (Shimonishia et al. 2009)
[m] (Imanishi et al. 2008)
[n] (Linden and Reddy 2002)

Table 3.2: Commercially available batteries and their specifications (NA means that the parameter is not applicable)

Battery type	Manufacturer	Specific Power (W/kg)	Energy Density (Wh/L)	Specific Energy (Wh/kg)	Life (Years)	Cycle Life (Deep Cycles)	Normal Recharge Time (hr)	High Rate Charge (min)
USABC Minimum Goals		300	230	150	10	1000	6	‹30
VRLA	Yuasa[a]	220	85	34		400	8	
NIMH	Panasonic EV energy[b]	1300		46				
NIMH	SAFT[c]	150	137	66		›2000		
LiCoO2	Thunder sky[d]		150-215	95-135		›1000		NA
LiFePO4	Thunder sky[d]	200	76-115	62-80		›2000		20
	PHET[e]	240	190	125		›500		
LiMn2O4	Thunder sky[d]		55-100	55-70		›300		NA
	Electrovaya[f]	‹2000		170-210	7	›1000		
LiFeMgPO4	Valence[g]	150-200	110-148	80-90		›2600	3	
Lithium-ion (imiev)	Lithium Energy Japan[h]	360	218	80		›1000	6	30
LiTiO	Altair nano[i]		760	72	20	›4000		‹10
Zebra (NaNiCl2)	MES Dea[j]	150-180	150	100-120	›10	1000-2000	6-8	60
Zinc air	Electric fuel[k]	90	223	200	NA	NA	NA	NA
	Power zinc[l]	116	198	165	NA	NA	NA	NA

[a] yuasa-battery.co.uk
[b] peve.jp/e/
[c] saftbatteries.com
[d] thunder-sky.com
[e] phet.com.tw
[f] electrovaya.com
[g] valence.com
[h] lithiumenergy.jp/en
[i] altairnano.com
[j] mes-dea.ch
[k] electric-fuel.com
[l] powerzinc.com

3.3.2 Battery price

One of the most important specifications of the battery is the sales price. Right now prices of a battery pack for an EV well exceeds the goals of the USABC. A way to make predictions on future prices is learning- or experience curve. A curve that is used and accepted by the industry is the cost/volume curve from Kromer and Heywood (figure 3.2).

Today the NiMH battery is still cheaper than lithium-ion batteries but lithium-ion batteries will eventually be less expensive than the NiMH battery when being mass produced.

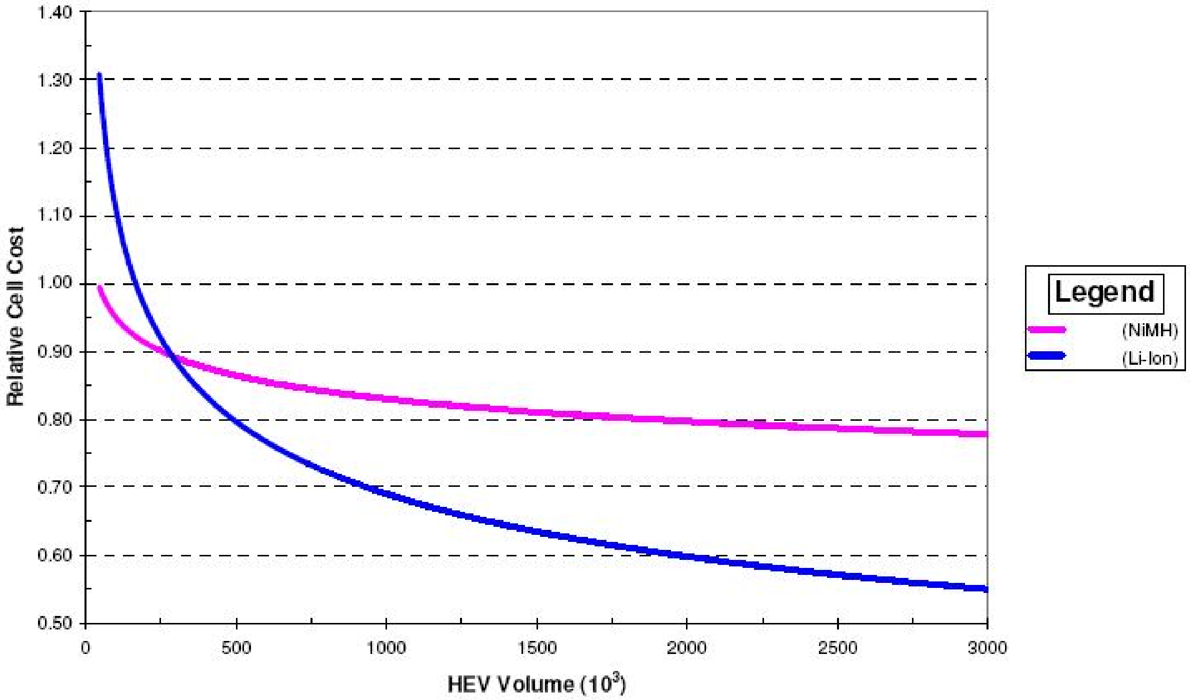

Figure 3.2: NiMH vs. Li-Ion HEV Cell Cost/Volume Curve (Kromer and Heywood 2007)

The progress ratio of a battery can help to make predictions on future prices. However the progress ratios of the different batteries are hard to calculate. The Pb/A battery will not decrease in price the coming decade as the technology is almost mature. NiMH battery prices are also not expected to go down much more as the nickel prices make up most of the battery price (Rade and Andersson 2001). Metal air batteries are not being produced for BEVs on a large scale and data is hard to find on volume and prices. The PR of the lithium-ion and zebra battery is estimated here based on data in literature.
The first produced lithium-ion pack is assumed to be around 1500 €/kWh and at a production volume of 100000 packs a year the price can be as low as 180 €/kWh (Anderman et al. 2000).
With the following formula the PR can be calculated:

$$\mathrm{C_{cum}} = C_0 \mathrm{Cum}^{\mathrm{b}}$$
$$\mathrm{logC_{cum}} = \log C_0 + \mathrm{b}\,\mathrm{logCum}$$

In wich:
$\mathrm{C_{cum}} = 180$
$C_0 = 1500$
$\mathrm{Cum} = 100000$

$$180 = 1500 * 100000^{\mathrm{b}}$$

b = -0.184
PR = 88%

The progress ratio calculated here can give an indication on how the technology will develop until 2020 when 100000 battery packs are produced. A progress ratio for smaller lithium-ion batteries for consumer products was calculated by Nagelhout and Ros (Nagelhout and Ros 2009). They estimated a progress ratio of 83% between 1993 and 2003. An other report used a PR of 92.5% between 2010 and 2030 (Kloess et al. 2009). As with other technologies the price will decrease more in the early stage of development as these PRs indicate. The PR calculated here is the PR between the end of the 90's and 2020. In table 3.4 the current and projected prices of batteries suitable for BEVs are shown.

For the zebra battery the following units are used:

C_{cum} = 140 €/kwh (Kalhammer et al. 2007)
C_0 = 500 €/kwh
Cum = 100000 packs

$$140 = 430 * 100000^{b}$$

b = -0.0975
PR = 93.5%

There are no PRs stated in literature on the zebra battery technology. The PR can not be verified with other literature but can give an indication of the price development. As the battery is only produced by one manufacturer, the price development of the battery is rather difficult to estimate.

There are some predictions on future prices stated in literature. In table 3.4
prices of the different batteries are shown as well as the projected costs of the batteries when being mass produced (more than 100000 units a year, projected for the year 2020).

Table 3.4: Current and projected cost of batteries suitable for BEVs (Prices in €/kWh with an exchange rate of 1.40 USD/euro)

	now (low)	now (high)	now (probable)	projected (low)	projected (high)	projected (probable)	Sources
Pb/A	71	107	89	71	107	89	a,b,c
NiMH	437	571	504	214	250	232	a,c,d,e
Li-ion	402	929	665	179	230	204	c,d,f,g,h,i,j,k
Zebra			429	143	250	196	a,k,l
Zn-air				65	86	76	a

[a] (Chan and Wong 2004)
[b] (Anderman et al. 2000)
[c] (Burke et al. 2007)
[d] (Chan et al. 2007)
[e] (EPRI 2004)
[f] (Eaves and Eaves 2004)
[g] (Gaines and Cuenca 2000)
[h] (Eurlings 2009)
[i] (Hadjipaschalis et al. 2009)
[j] (Kromer and Heywood 2007)
[k] (Kalhammer et al. 2007)
[l] (Chau et al. 1999)

4. Internal combustion engine vehicles

Most passenger cars in the Netherlands run on petrol (79.6%) followed by diesel cars (17%) (BOVAG-RAI 2008). Only 2.9% run on LPG and 0.2% is electric. A typical passenger car, except for the electric car, has a four-stroke internal combustion engine installed. Diesel cars use a diesel engine where under high pressure a mixture of fuel and air is combusted (Compressed Ignition). Petrol and LPG cars have an Otto engine installed where the fuel ignites with a spark (Spark Ignition). A disadvantage of the ICE is the low efficiency. Most of the energy is lost when combusted in the form of hot air. The fuel consumption, lifecycle costs and CO_2 emissions are presented for a few cars in the lower car segments. The first BEV coming on the market will probably be a small passenger car and will not be larger than a passenger car in the lower segments. The results can be used to make a comparison between the ICE car and an electric car in the same segment.

4.1 Car Segments

Passenger cars are divided into segments according to their specifications (ANWB 2008). The segments that are part of the research are segment A, B and C. Segment A are the sub-minis, B the minis and C the compact class. When looking at the car sales in the Netherlands, between 2004 and 2008, the sales of smaller cars increased. The sales in the A segment increased from 10% to 16.5% of the total car sales in the Netherlands. The B segment also increased to 22% and now has the largest share in car sales. The three lower segments presented a share of 60% in total car sales in 2008.

Table 4.1: Reference ICE passenger cars[a]

	Max Power (kW)	Weight (kg)	Catalogue price	BPM (taxes)	VAT	Vehicle cost
A-segment (diesel)						
Smart Fortwo Coupe cdi 3-d pulse	33	780	€ 13,337	€ 0	€ 2,129	€ 11,208
VW Fox 1.4 TDI 3-d	51	1060	€ 15,250	€ 4,110	€ 1,779	€ 9,361
A-segment (petrol)						
Peugeot 107 1.0 12V 5-d XR	50	765	€ 9,290	€ 0	€ 1,483	€ 7,807
Smart Fortwo 1.0 MHD 3-d pure	52	750	€ 10,876	€ 0	€ 1,737	€ 9,139
Mitsubishi i 0.7 mivec turbo i automatic[b]	48	900	€ 12,000	€ 1,452	€ 1,588	€ 8,960
B-segment (diesel)						
Peugeot 207 1.6 HDiF 90 5-d XS	66	1180	€ 21,700	€ 5,733	€ 2,549	€ 13,418
Toyota Yaris 1.4 D4D 5-d SOL	66	1030	€ 23,650	€ 6,224	€ 2,782	€ 14,644
B-segment (petrol)						
Peugeot 207 1.4 Vti XS	70	1153	€ 17,950	€ 3,552	€ 2,299	€ 12,099
Toyota Yaris 1.3 VVT-i 5-d SOL	64	995	€ 16,350	€ 3,149	€ 2,108	€ 11,093
C-segment (diesel)						
Ford Focus 1.6 TDCi 5-d trend	80	1257	€ 25,575	€ 6,708	€ 3,012	€ 15,855
VW Golf 1.9 TDI bluemotion 5-d comfort	77	1262	€ 26,975	€ 7,060	€ 3,180	€ 16,735
C-segment (petrol)						
Ford Focus 1.6 16v 5-d trend	74	1170	€ 21,275	€ 4,388	€ 2,696	€ 14,191
VW Golf 1.4 TSI 5-d trendline	90	1180	€ 21,305	€ 4,396	€ 2,700	€ 14,209

[a] Specifications as given by the car manufacturer derived from www.autoweek.nl and catalogue prices from ANWB autokosten 2008.

[b] Mitsubishi i-car is not for sale in Europe. Catalogue price is estimated based on retail prices in Japan and New Zealand.

A possible explanation for this growth in the lower segments is the lower costs of driving. Smaller cars usually have lower fuel consumption, lower maintenance cost, lower emissions and are fiscal more attractive than larger cars in the other segments.

In table 4.1 a few reference cars from each class are shown with their specifications. The cars are chosen based on the ANWB car costs and the BOVAG-RAI passenger car sales. The Mitsubishi i-car and Smart Fortwo are chosen because both cars also have an electric version.

4.2 W-T-W energy consumption and CO_2 emissions

The energy consumption and CO_2 emissions are divided into a W-T-T and a T-T-W pathway. The fuel consumption and tail pipe CO_2 emissions of the reference cars represent the T-T-W pathway. The energy use of crude oil extraction, refinery and distribution and coherent CO_2 emissions represents the W-T-T pathway.

4.2.1 Fuel consumption and CO_2 emissions

The fuel consumption and the CO_2 emissions of an ICE car are based on the New European Driving Cycle (NEDC). The test cycle is carried out on new cars under laboratory conditions that simulate a normal driving schedule in Europe. First part of the test is an urban cycle where the speed does not exceed 50 km/h and consist of steady driving, accelerating, decelerating and idling. The average speed is 19 km/h and the distance covered is four kilometres. The test is repeated four times.

Second part of the test is an extra urban cycle where the maximum speed is 120 km/h and the average speed is 63 km/h. The distance covered is seven kilometres.

The two tests are combined and weighted based on the distance covered. The fuel consumption is based on the combination of the two test cycles. Figure 1 shows the European test cycle. Today's best T-T-W efficiencies are around 20% for petrol and 25% for diesel cars (Mierlo et al. 2006).

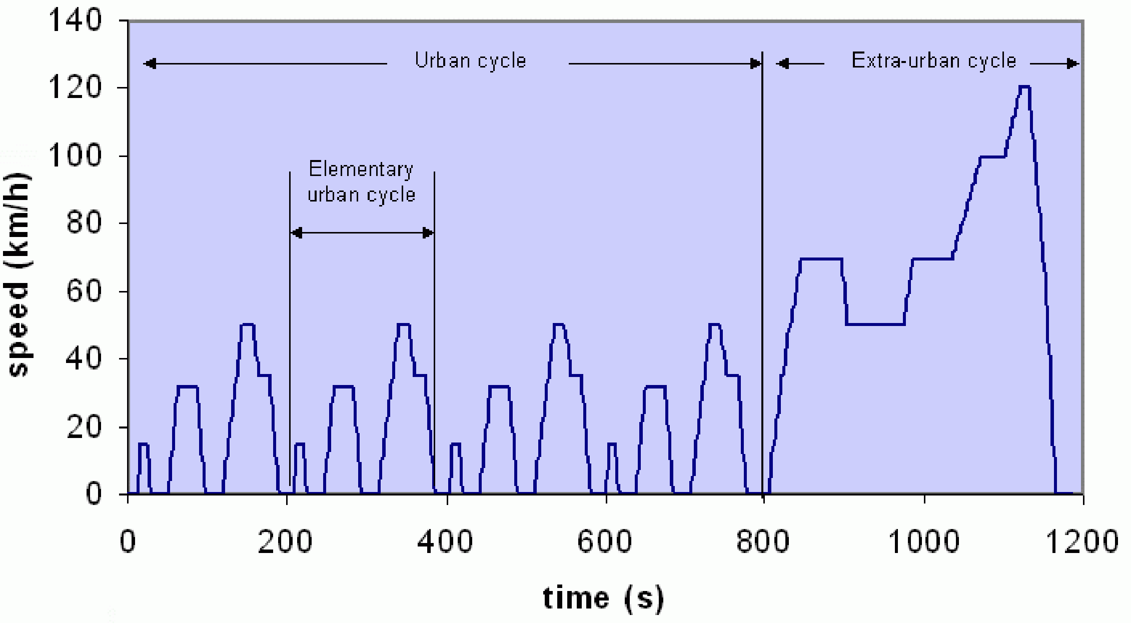

Figure 4.1: The New European Driving Cycle (GOVT.NZ 2009)

Primary energy consumption and CO_2 emissions

The energy lost in the W-T-T pathway is for extracting, transport, production and distribution of the fuel. Extracting the crude oil is done with an efficiency of about 95-97% (Hekkert et al. 2005). The energy lost in transporting the crude oil is around 1% (Ahlvik and Brandberg 2001;GM 2002;Hekkert et al. 2005). Most energy is lost in the refinery where fuel is produced from crude oil. The total efficiency of a refinery, regarding the crude oil input and products as output, nowadays is 94% (Hekkert et al. 2005). Diesel is produced with a higher efficiency than gasoline. Gasoline and diesel distribution is done with an efficiency of around 99 % (Ahlvik and Brandberg 2001;Hekkert et al. 2005). Distribution of gasoline is slightly less energy efficient than diesel. The difference in efficiency between the two fuels is because diesel has a higher energy density. In Table 2 the W-T-T energy consumption and CO_2 emissions of gasoline and diesel are presented.

Table 4.2: W-T-T energy consumption and CO_2 emissions

	Energy consumption* (MJ/MJf)	Deviation (+/-) (MJ/MJf)	CO_2 emission (g/MJf)	Deviation (+/-) (g/MJf)
Gasoline	0.17 [abc]	0.04	12.45 [bc]	2
Diesel	0.14 [abcd]	0.02	12.9 [bcd]	3

** MJ of energy consumed for every MJ of fuel loaded into the tank of the vehicle*

[a] (Ahlvik and Brandberg 2001)

[b] (GM 2002)

[c] (Edwards et al. 2006)

[d] (Silva et al. 2006)

4.2.2 W-T-W Efficiency

The efficiency of the reference cars can be calculated using their fuel consumption and the car aerodynamic specifications. With the formulas on aerodynamic drag, rolling resistance and acceleration force the total force on the car is calculated using the velocity of the NEDC. In excel the total traction power is simulated and an average is calculated with the data in table 4.3 and a data sheet of the NEDC velocity (Appendix A). The additional car weight is the extra weight of one person and the weight of the fuel in the car.

The power to overcome the drag resistance, rolling resistance and acceleration power is the useful energy at the wheels. The fuel consumption of the reference car is the energy supplied to the vehicle. When dividing the energy supplied to the vehicle by the useful energy at the wheels the T-T-W efficiency can be calculated. The W-T-T efficiency can be found in table 4.2 and is 88% for diesel and 85% for gasoline.

Table 4.3: Data assumptions

Rolling resistance coefficient	0.01
Density of air at 20°C (kg/m3)	1.205
Gravitational force (m/s2)	9.81
Additional car weight ICE (kg)	100
Energy content diesel (MJ/l)	36
Energy content gasoline MJ/l)	33

Table 4.4: Car aerodynamic specifications, fuel consumption and power to the wheels

	Cd[1]	Frontal[1] area (m2)	Weight (kg)	Fuel consumption[2] NEDC (l/100km)	Average Power to wheels (kW)
A-segment (diesel)					
Smart Fortwo	0.38	1.95	780	3.4	3.30
VW Fox 1.4	0.32	2.04	1060	4.9	3.68
A-segment (petrol)					
Peugeot 107	0.32	2.03	765	4.5	3.08
Smart Fortwo	0.38	1.95	750	4.3	3.24
Mitsubishi i*	0.3	2	900	5.2	3.25
B-segment (diesel)					
Peugeot 207	0.3	2.12	1180	4.5	3.89
Toyota Yaris	0.3	2.23	1030	4.5	3.65
B-segment (petrol)					
Peugeot 207	0.3	2.12	1153	6.1	3.83
Toyota Yaris	0.3	2.23	995	6	3.58
C-segment (diesel)					
Ford Focus	0.32	2.26	1257	4.8	4.22
VW Golf	0.31	2.22	1262	4.5	4.16
C-segment (petrol)					
Ford Focus	0.32	2.26	1170	6.7	4.05
VW Golf 1.4	0.31	2.22	1180	6.3	3.99

[1] Data found on www.carfolio.com and www.data4car.com

[2] Fuel consumption as given by the car manufacturer

[*] Assumed aerodynamic specification based on data found in (Mitsubishi 2008)

4.3 Lifecycle Costs

The lifecycle costs of the ICE vehicles are calculated using data from the ANWB. The data provided by the ANWB only accounts for the first 60,000 km for gasoline cars and 120,000 km for diesel cars. This research however calculates the costs over the whole lifetime of the vehicle. The lifecycle costs are therefore estimated based on these numbers.

4.3.1 Depreciation

The lifetime of an ICE passenger car is estimated to be 240,000 km (Delucchi 2000;Granovskii et al. 2006) during fifteen years of driving. The value of the passenger cars after 240,000 km is assumed to be zero. The depreciation of the car is calculated by dividing the annual capital costs by the annual number of kilometres driven.

4.3.2 Maintenances and repair

The costs for M & R are estimated based on the data form the ANWB. For gasoline cars it is expected that the cost for M & R are equal for 120,000 km. The other 120,000 km a doubling of M & R costs are assumed. M & R costs of diesel cars are also calculated with a doubling of cost for the last 120,000 km.

4.3.3 Fuel costs

The fuel costs of the reference cars are calculated by multiplying the NEDC fuel economy with the fuel price.

4.3.4 Fixed costs

The fixed cost consists of road taxes, car insurance and other costs. In the Netherlands the road taxes are lower for clean and efficient cars with a CO_2 emission lower than 95 grams per kilometre for diesel and 110 grams per kilometre for gasoline cars. Also the tax on new cars (BPM) is abolished for these clean cars. The road taxes for other ICE cars have gone up since the beginning of 2009. These measures are taken to shift towards a kilometre based tax for passenger cars based on their CO_2 emission.

The insurance costs are based on the insurance costs of the ANWB with all risk coverage and five years no-claim discount. It is expected that after five years the insurance costs are half of the insurance of the new car and one third after ten years.

Other costs that are taken into account are for instance car washes and a membership on road services.

4.4 Future developments

ICEs are still being developed and efficiency improvements can be made. However the coming decade efficiency improvements are expected on other parts of the car. Mass reduction and aerodynamic improvements on passenger cars are most likely the options to improve the fuel consumption. It is assumed that fuel consumption will go down with 10% in 2020. The emissions of the car consequently will go down with 10%. These numbers are in line with other studies (Weiss et al. 2000).

It is difficult to predict future crude oil and fuel prices. The IEA predicted that oil prices will rice to 100 dollar a barrel in 2020 (IEA 2009). What this means for the fuel prices in the Netherlands it is hard to predict. In this research it is expected that the price of gasoline will go up to around €1.65 and diesel to €1.20 in 2020.

The price of a passenger car is not expected to go down except that in 2020 the tax on cars (BPM) is abolished. This will only have effect on cars in the higher segments as the tax for clean cars in the lower segments already disappeared.

On the W-T-T part there are no changes expected. Crude oil extraction and refinery already have been done for many years and large efficiency improvements are not likely.

5. Battery Electric Vehicles

In this part the battery electric vehicle is described. A typical BEV consists of a battery and an electric drivetrain. It does not have a tailpipe, like the ICE vehicle, and has zero direct emissions. But this only account for the T-T-W pathway.

To be able to compare the results of chapter four, a well-to-wheel analysis is made on energy consumption, CO_2 emissions and costs. At first the most relevant components of the BEV are described. The most important part of the BEV, the battery, is already elaborated on in chapter 3.

5.1 Most Relevant components

A typical BEV consists of fewer moving parts than an ICE vehicle and the conversion of electricity to mechanical work by an electric motor is very efficient. Therefore the total vehicle efficiency is around three times higher than an ICE vehicle (Ahman 2001).

The basic components of a BEV consist of a charger to charge the battery. The charger can either be a build-in charger or a stand alone charger at a charging station. The battery is one of the most important parts of the vehicle. In chapter five different batteries are discussed that can be used in a BEV. After the battery an inverter is installed to convert the DC in the battery to the required current needed for the electric motor. A Vehicle Control Unit (VCU) and Power Distribution Unit (PDU) are placed to control all the electronics in the car. A DC/DC inverter is installed to convert the battery voltage to low voltage for the 12V electronics in the car. Figure 5.1 shows all the important components of the BEV.

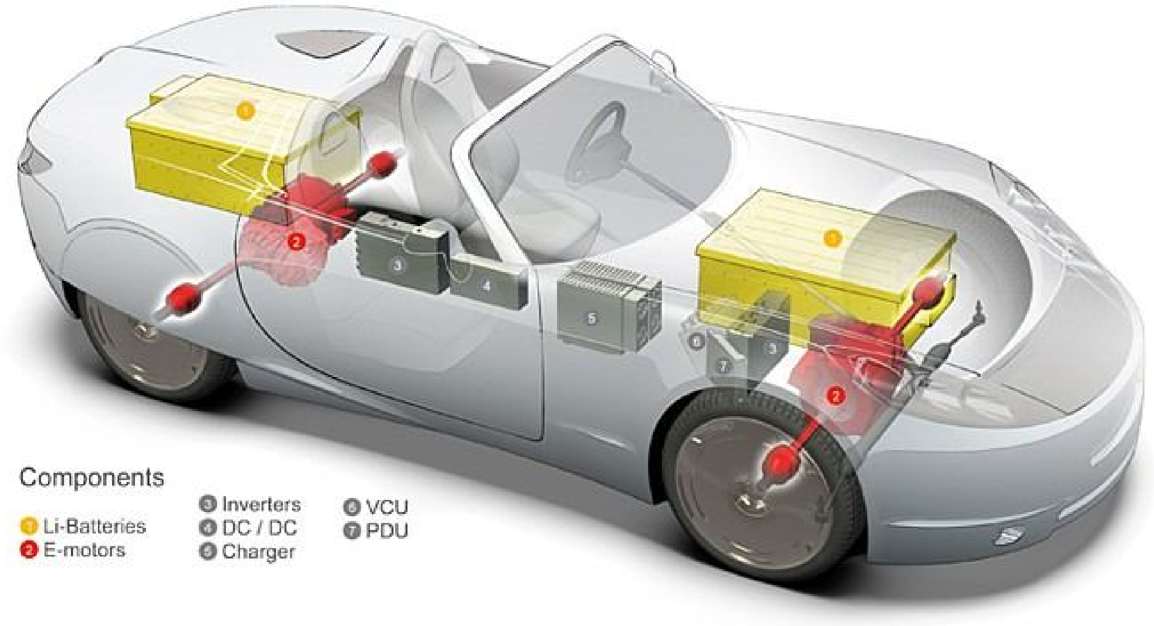

Figure 5.1: Components of a BEV (Image derived from: www.BRUSA.biz)

5.1.1 Charger

Charging a battery is not a matter of just plugging in a BEV on your home 230 V electricity network or on a charger elsewhere. A battery charger needs an advanced control system to regulate the current and voltage going in. Without this the lifetime can be drastically reduced (Larminie and Lowry 2003). A battery for an electric vehicle is in fact a number of cells connected in series. When charging and discharging it can happen that the battery cells carry different charges over time. This is due to the circumstances, like the temperature or production abnormalities, that can differ in the battery cells. If the battery cells are not fully charged once in a while, it happens that one battery cell goes totally flat. This can result in a drastically drop in battery voltage and eventually battery failure. To prevent battery failure and a reduced lifetime the battery cells have to be fully charged regularly. The battery cells therefore have to be designed to withstand overcharging.

Another important feature of a battery should be fast recharging. As it is impossible for everyone to charge their car at home, the possibility for charging it elsewhere should exist. Otherwise the electric car would only be available to a select group of people with home charge abilities. Fast charging can only be done if the battery is charged with a maximum of 80% State of Charge (SoC). This is the capacity of the battery given in a percentage of the total capacity of the battery when it is full. After 80% SoC the battery has to be charged slowly in order to fill the battery completely. More is explained on battery charging in chapter five.

The problem that the BEV is facing nowadays is the lack of standardisation. First of all there is no standard plug to put in the BEV when charging elsewhere than at home.

Also there is no standard for fast charging. Fast charging needs a complex control system in order for the battery to be charged correctly. The stand-alone charger and the control system in the car have to be well designed otherwise charging the battery can cause problems.

To overcome these problems the BEVs and chargers have to be standardised. This way future BEVs can be charged on every stand-alone charger.

5.1.2 Electric motor

There are a few possible electric motors that are suitable for a BEV. A distinction can be made between a DC motor and an AC motor. The electric motor can either be placed in the wheels of the BEV or central in the car. First the possible AC and DC motors for EVs are described. After that the difference between a central motor and an in-wheel motor is explained.

Brushed DC motor

The simplest motor that can be used in automotive applications is the brushed DC motor. This motor is used in all sorts of domestic electric appliances like hairdryers and fans. In figure 5.2 a two-pole brushed DC motor is shown with one coil. The motor consists of a stator with two permanent magnets and brushes and a rotor (coil) with commutator and windings. The force on the left side is upwards where the force on the right side is downwards, causing the coil to turn clockwise. When the wires of the coil with the commutator are clear of the magnets momentum carries the rotor halfway around until it connect with the brushes again. The commutator is constantly changing the direction of the current to assure that the forces are pushing the coil clockwise.

A real DC motor however is using a rotor with multiple coils and a stator with more than one pair of magnets but the principle remains the same. There are three basic brushed DC motors; a parallel, series and separately excited brushed DC motor. For use in electric vehicles the one that can be used is the separately exited motor. The required torque can be controlled at any angular speed giving the motor great flexibility (Larminie and Lowry 2003).

A problem with this type of motor has to do with the commutators and brushes. They are causing friction, limit the speed range and need regular maintenance (Rahman et al. 2000).

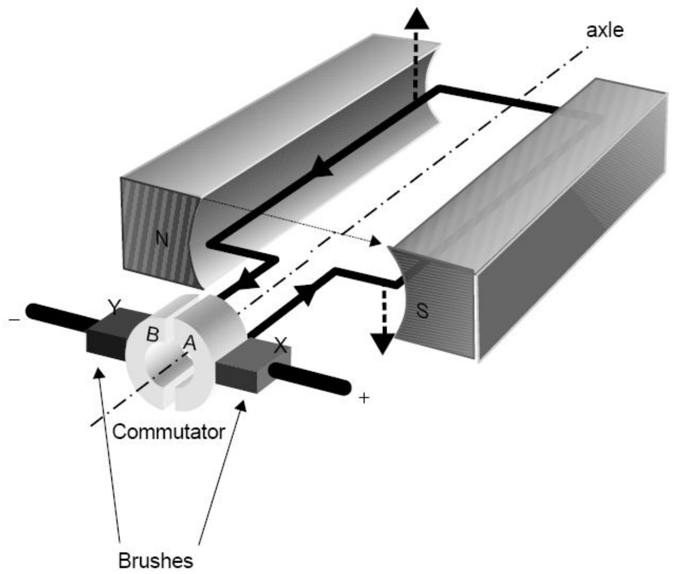

Figure 5.2: The brushed DC motor (Larminie and Lowry 2003)

Brushless DC motor
A brushless DC (BLDC) motor actually is not a DC but an AC motor. The motor needs an alternating current but must have variable frequency. Therefore the current have to be derived from a DC power supply. The BLDC motor is given different names by manufacturers and users of which the most common are permanent magnet synchronous motor (PM synchronous), self-synchronous AC motor, variable frequency synchronous motor and electronically commutated motor (ECM) (Larminie and Lowry 2003).
The motor has a three-phase stator with a number of coils and a rotor with surface mounted permanent magnets. The stator and the rotor are reversed compared to the brushed DC motor where the permanent magnet are mounted on the stator (see figure 5.3).

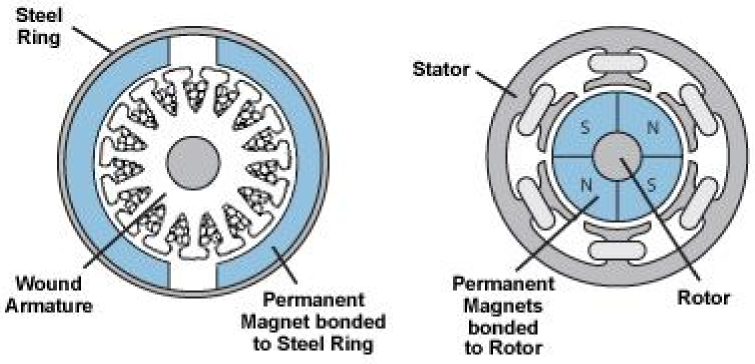

Figure 5.3: The brushed DC motor (left) and the 'Brushless' DC motor (right) (Images derived from www.orientalmotor.com)

The way a BLDC motor works is that the poles on the stator are alternating, in such a way that the rotor is turning clockwise. The pole on the stator pulls the pole on the rotor clockwise and when the poles are in line with each other the current is switched off. Momentum then carries the rotor further and the current is reversed, changing the magnetic field and the poles in the stator. To make sure the motor keeps on turning sensors are needed to determine the position of the rotor. This is often done using Hall Effect sensors.
BLDC motors are very efficient. Torque is high under low speeds and goes down as the speed goes up. A drawback of this type of motor is the price compared to the other possible EV

motors. A BLDC motor needs a strong permanent magnet that can influence the total price of the motor.

Switched Reluctance Motor

The SR motor is a fairly simply motor with an iron rotor and stator (see figure 5.4). The stator is magnetised and attracts the rotor. When the rotor is aligned with the stator (magnetic field is symmetrical) the current is switched off and momentum carries the rotor further and the current is switched on again.

The stator and control electronics of a SR motor are similar to those of a BLDC and induction motor. The rotor of a SR motor however is much simpler, making it cheaper and more rugged than the BLDC and induction rotor. The SR motor does not create back EMF because it has no permanent magnets. It therefore can reach higher speeds. Back EMF is the voltage that is generated when an electric motor with permanent magnets is spinning. The speed of a BLDC motor is limited because of this back EMF.

Also the current in the coil of a SR motor does not need to alternate. It needs an advanced control systems and sensors to adjust the speed and make sure the current is switched on and off on time. Another back draw of the motor is that it is known to be a bit noisy (Freescale 2009). SR motors are not used in commercial EVs and HEVs yet, but because of the good properties and possible low costs of the motor they will become more widespread in the future (Larminie and Lowry 2003;Takau and Round 2003).

Figure 5.4: Three-phase Switched Reluctance motor (Image derived from www.srdrives.com)

AC induction motor

Instead of using a permanent magnet in the rotor (as in the BLDC motor), it is also possible to induce a current in the rotor to create a temporary magnet. This is done in an AC induction motor. The rotor type (see figure 5.5) that is most common in an IM is the ‘squirrel cage’ (Siemens 2009). The rotor consists of a stack of steel laminations with evenly spaced conductor bars around the shaft. The conductor bars are forming a kind of cage.

The conductor bars are electronically linked with end rings.

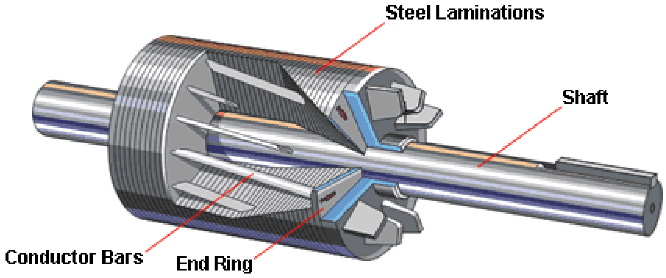

Figure 5.5: Squirrel cage rotor (Siemens 2009)

The rotor of an IM consists of a number of coils with the windings displaced by 120°. When a 3-phase AC is supplied to the rotor a current is induced in the conductor bars of the rotor. It will turn clockwise ‘chasing’ the magnetic field that is going anti-clockwise. The angular speed of the rotor is lower than the magnetic field. This so called ‘slip’ velocity is the relative velocity between the rotor speed and magnetic field.

The technology of the IM is very mature and is used in all sorts of appliances like washing machines, pumps and industrial machines. Therefore it is a popular choice and most used in EVs and HEVs of today (Rahman et al. 2000;Weiss et al. 2000;Campanari et al. 2009).

The Th!nk city electric vehicle and the Tesla Roadster which are already on the market uses a 3-phase AC induction motor. BEVs that are coming onto the market the next years also uses other electric motors. The Mitsubishi iMiev for example (in Europe known as the Peugeot iOn) and the E6 from BYD are equipped with a BLDC motor or Permanent Magnet Synchronous Motor as the car manufacturers names the motor.

In-wheel motor versus central motor

The BEVs that are on the market (for example the Tesla Roadster and Th!nk City) are equipped with a central electric AC induction motor. The central electric motor is cheaper to produce and is also more developed than the in-wheel electric motor.

A central electric motor has a stationary stator and a rotor with a differential that turns the wheels. This is reversed with an in-wheel electric motor where the stator turns the wheels and the rotor remains stationary. Also there is no need for a differential as the amount of power to each wheel can be controlled by the separate in-wheel electric motors. Efficiency gains can be achieved with this type of motor and is already described in an other thesis (Kruithof 2007). However the electronics of an in-wheel motor have to be well developed as the precise amount of energy has to be delivered to each wheel. At this moment there are some safety issues as malfunction of one wheel can result in an uncontrollable vehicle. At this moment it is uncertain when the first BEVs equipped with in-wheel motors will be on the market.

5.1.3 Inverters and controllers

As the preferred electric motors in a BEV are powered by alternating current (Campanari et al. 2009) an AC/DC inverter is needed. Most large motor uses three coils instead of one and therefore need a three-phase AC supply. The AC/DC inverter converts the DC from the battery into three-phase AC to power the electric motor. The inverter can control the frequency and current supplied to the motor and can regulate torque and motor velocity (RPM). The different controllers in the BEV are there to check all the electronics in the car and make sure the battery is working correctly. They also control the car speed, steering, regenerative braking and battery supply.

5.2 W-T-W energy consumption and CO_2 emissions

The BEV does not have any direct CO_2 emissions. All the emissions occur during the conversion of primary fuels into electricity. The energy consumption of the BEV depends on the vehicle efficiency, power generation efficiency and energy consumption for transportation.

5.2.1 Energy consumption and CO_2 emissions

The fuel consumption of a number of BEVs is known and is based on the NEDC or similar driving patterns. In table 5.1 the specifications of a few BEVs that are coming on the market are shown.

The energy used by a BEV can be very different depending on the speed, driving conditions and the use of heaters or air-conditioning. When driving a BEV like the iMiev on the highway the energy consumption can be as high as 200 Wh/km (Mitsubishi 2008). The range of a BEV is very depended on the velocity. The largest distances per battery charge that can be achieved are in city circumstances where the speed does not exceed fifty km/hr. The NEDC has an average speed of 33.6 km/hr and high speeds are only achieved for a small period of time. Therefore the fuel consumption of BEVs tested under these conditions are somewhat optimistic.

Table 5.1: Battery electric vehicles and their specifications*

	Max Power (kW)	Weight (kg)	Frontal area (m2)	Cd	Battery type	Battery capacity (kWh)	Motor	Fuel Consumption[1] (Wh/km)
A-segment								
Smart Fortwo Electric	30	854	1.95	0.38	sodium-nickel-chloride (Zebra)	14	BLDC	120
Mitsubishi iMiev	47	1080	2	0.3	lithium-ion	16	BLDC	125
Th!nk City	30	1038	-	-	sodium-nickel-chloride (Zebra)	28.3	AC-induction	157
C-segment								
Ford Focus Electric	100	1550	2.26	0.32	lithium-ion	23	BLDC	190
Nissan Leaf	80	1585	2	0.28	lithium-ion	24	BLDC	150

**Specifications as given by the car manufacturer*

[1] *Fuel consumptions are based on the new European driving cycle with the exception of the Nissan Leaf. The fuel consumption of the Nissan Leaf is based on the UDDS.*

Primary energy consumption and CO_2 emissions

The energy use and CO_2 emissions of a BEV depends on the way the electricity is generated. The lowest primary energy consumption and CO_2 emissions can be achieved when the electricity comes from renewable energy sources like wind, water or solar power (Campanari et al. 2009). In this research the European electricity mix is used. The energy markets in Europe are becoming more open and electricity in the Netherlands is imported from all over Europe. Also the primary energy consumption and CO_2 emissions of the European mix have similarities with the figures from natural gas (NG) fired power plants. NG account for around 50% of the total fuel input in power plants in the Netherlands (Seebregts and Volkers 2005). The European mix has a primary energy consumption of 2.87 MJ and emits 120.8 g CO_2 for every MJ of electricity produced (Edwards et al. 2006).

5.2.2 W-T-W efficiency

The theoretical efficiency of a BEV is very high compared to the ICE vehicle efficiency.
Table 5.2 gives the efficiencies and losses of different parts of the vehicle as mentioned in other papers.
The charge and discharge efficiency in the table is that of a lithium-ion battery. The total vehicle efficiency with regenerative braking (without the efficiency of charging the vehicle) is around 77%. This is calculated by multiplying the efficiencies of the different parts of the BEV.

Table 5.2: Vehicle efficiency

	Efficiency
Battery charge/discharge[abcd]	0.94
Inverter[de]	0.96
Electric Motor[bd]	0.91
Mechanical losses[bd]	0.98
Losses for heating/airco[b]	0.90
Regenerative braking[bd]	1.07
Total vehicle efficiency	0.77
Battery charger[abd]	0.90
Electricity distribution[abd]	0.93

[a] (Eaves and Eaves 2004)
[b] (Ahman 2001)
[c] (Kennedy et al. 2000)
[d] (Campanari et al. 2009)
[e] (Weiss et al. 2000)
[f] (Mierlo et al. 2006)

The real efficiencies of the BEVs are also calculated using the aerodynamic specifications of table 5.1, the data assumptions from table 4.3 and excel to simulate the power to overcome roll- and drag resistance and the acceleration force during the NEDC. The Nissan leaf is simulated during the UDDS driving cycle. The data assumptions from table 4.3 are also used for simulating the Nissan Leaf except for the roll resistance which is set to 0.007. It is known that the Nissan Leaf will use special tyres with low roll resistance. For the other vehicles it is not known and the roll resistance coefficient is set to 0.01.
As an example the efficiency of the Smart Fortwo electric is calculated here with the following formulas:

$$F_a = 0.5 \cdot C_D \cdot A \cdot \rho \cdot v^3$$

$$F_r = C_R \cdot M \cdot g \cdot v$$

$$F_l = (M * 1.05) \cdot a$$

In which:

F_a= air resistance
F_r = rolling resistance
F_l = linear acceleration
C_D = the drag coefficient of the car
C_R = rolling resistance coefficient
A = the frontal area of the car (m2)
ρ = the density of air
M = the car mass (kg)
g = the acceleration of gravity (m/s^2)
v = the speed of the car (m/s)
a= the acceleration of the car (m/s^2)

In appendix 1 the NEDC and UDDS driving cycles with all the velocities at each second during the cycle can be found. For all the time points in the cycle the total power to overcome the drag- and roll resistance and acceleration force is calculated. The Smart Fortwo has a maximum speed of 112 km/hr and the maximum speed in the NEDC is 120 km/hr. The speed during the NEDC therefore has been maximised to 112 km/hr for the Smart Fortwo. The velocity after 981 seconds in the cycle is for example 70 km/hr or 19.44 m/s. The velocity after 980 seconds is 19.02 m/s. The average speed during the 981st second is (19.02+19.44)/2 = 19.23 m/s. The acceleration during this second is 0.43 m/s^2.

The F_a now is $0.5 \times 0.38 \times 1.95 \times 1.225 \times 19.23^2 = 168$ N and the F_r is 0.01×924 (mass of the car + one person) $\times 9.81 = 91$ N

The acceleration force $F_r = 1.05 * 924 * 0.43 = 417$ N

The total traction power is (91 + 168 + 417) * 19.23 = 13 kW. This calculation is done for the whole cycle, where 25% of the braking power is regenerated and stored in the battery. The other 75% of the braking energy is lost. The average power needed during the whole cycle is 3.26 kW. The energy use of the Smart electric is 120 Wh/km and the average speed during the cycle is 9.33 m/s. The average power delivered to the vehicle is 9.33 (m/s) * 0.12 (kW/h) * 3.6 = 4.03 kW. The vehicle also uses regenerative braking what already is included in the vehicle energy use of 120 Wh/kg. The efficiency of the car can be calculated by dividing the power during the cycle by the power delivered to the vehicle. The efficiency is 3.39/4.28 = 81.1%

The W-T-T efficiency is calculated by multiplying the efficiency of the European Mix with the efficiency for electricity transport and battery charging. The total W-T-W efficiency of a Smart electric is 84% × 29% = 23.6 %

5.3 Lifecycle costs

5.3.1 Depreciation

The price of a BEV is still very high compared to an ICE vehicle in the same segment. A Th!nk city electric vehicle will cost around €38,675 in the Netherlands (MisterGreen 2009) without any subsidies. It is expected that the iMiev will cost around €45,000 and the Nissan Leaf will cost €35,000 without subsidies (Jacobs 2009). Subsidies for electric vehicles are only available for companies who purchase a BEV and not for individuals. This high retail price has a large effect on the cost of driving a BEV. Sales prices of other electric vehicles are not known but are estimated based on the sales price of a Th!nk City, iMiev and articles that are found on the internet. In table 5.3 the breakdowns of the retail prices are given. The battery prices are estimated based on the battery costs in table 3.4 and the capacity of the battery pack in the BEV. The lifetime of a BEV is potentially higher than an ICE vehicle but is limited by the lifetime of the battery. The lifetime of a BEV is estimated to be 10% higher than the reference ICE vehicles (Delucchi 2000) but can be even higher. In this research the lifetime of a BEV is expected to be seventeen years with an average of 16000 kilometres driven each year.

Table 5.3: Breakdown of retail prices of the BEVs

	Retail price	Battery pack price	VAT	Battery pack costs	Vehicle costs
A-segment					
Smart Fortwo Electric	€ 40,000	€ 7,140	€ 6,387	€ 6,000	€ 27,613
Mitsubishi iMiev	€ 45,000	€ 12,665	€ 7,185	€ 10,643	€ 27,172
Th!ink City	€ 39,900	€ 14,433	€ 4,241	€ 12,129	€ 21,401
C-segment					
Ford Focus Electric	€ 55,000	€ 18,206	€ 8,782	€ 15,299	€ 30,919
Nissan Leaf	€ 35,000	€ 18,997	€ 5,588	€ 15,964	€ 13,448

5.3.2 Maintenance and repair

It is expected that M&R costs will be lower for BEVs during their lifetime. M&R can be half of the costs of a ICE (Delucchi 2000) because an electric vehicle has less moving parts and the electric motor is expected to last longer than an ICE. In this research the M&R costs of a BEV are 30% lower than a gasoline car in the same segment during the whole lifetime.
Today's batteries for EVs are not capable yet to last during the whole lifetime of the vehicle (Delucchi 2000;Mierlo et al. 2006). The vehicle batteries are expected to be replaced once during the lifetime of the vehicle. The battery price is not part of the normal M&R but add up to the total costs for M&R. The battery has to be replaced after approximately 10 years. The price of the battery when replaced is expected to be the predicted price stated in chapter 3.

5.3.3 Fuel costs

The amount of electricity drawn from the grid is calculated by multiplying the NEDC fuel economy with the efficiency of charging the battery. The fuel costs of the BEV are the electricity drawn from the grid multiplied by the electricity price. The vehicles in this research are being charged at a home charger. Prices for charging the BEV at a charging station elsewhere are not known yet. Also the first BEVs sold to private owners will be charged at home chargers as there is no good infrastructure for electric cars yet. Therefore the cost of charging a BEV at a charging station is not taken into account.

5.3.4 Fixed costs

The fixed costs consist of the car insurance and other costs. Road taxes for electric vehicles are abolished and are not part of the fixed costs. At this time it is uncertain what the insurance costs will be for BEVs. The costs for insurance are estimated to be as high as an ICE that runs on petrol adjusted to the retail price. Other costs that are taken into account are for instance car washes and a membership on road services and are equal to those of the reference ICE vehicles.

5.4 Modelling a BEV

5.4.1 Aerodynamics and roll resistance

Efficiency improvement of the total vehicle is important to reduce the primary energy consumption and carbon GHG emissions of a BEV. However at high speed the most energy is lost overcoming the drag and rolling resistance of a car. In figure 5.6 the total useful power to the wheels of a Smart Fortwo during the NEDC driving cycle is shown. In the figure it can be seen that during the city circumstances in the cycle at low speeds the power for accelerating the vehicle and the roll resistance are higher than the power needed to overcome the drag resistance. At the highway part of the cycle with higher velocities the most power is needed to overcome the drag resistance. The most important features of a BEV for the city should therefore accompany low roll resistance and a low car weight as the acceleration force and roll resistance make up most of the energy losses. BEVs that are made for high speeds and are driven at the highway for long periods should have low drag resistance. To illustrate what aerodynamics can do with the energy consumption of an electric car, a few parameters are changed on the Smart Fortwo electric car (table 5.4).

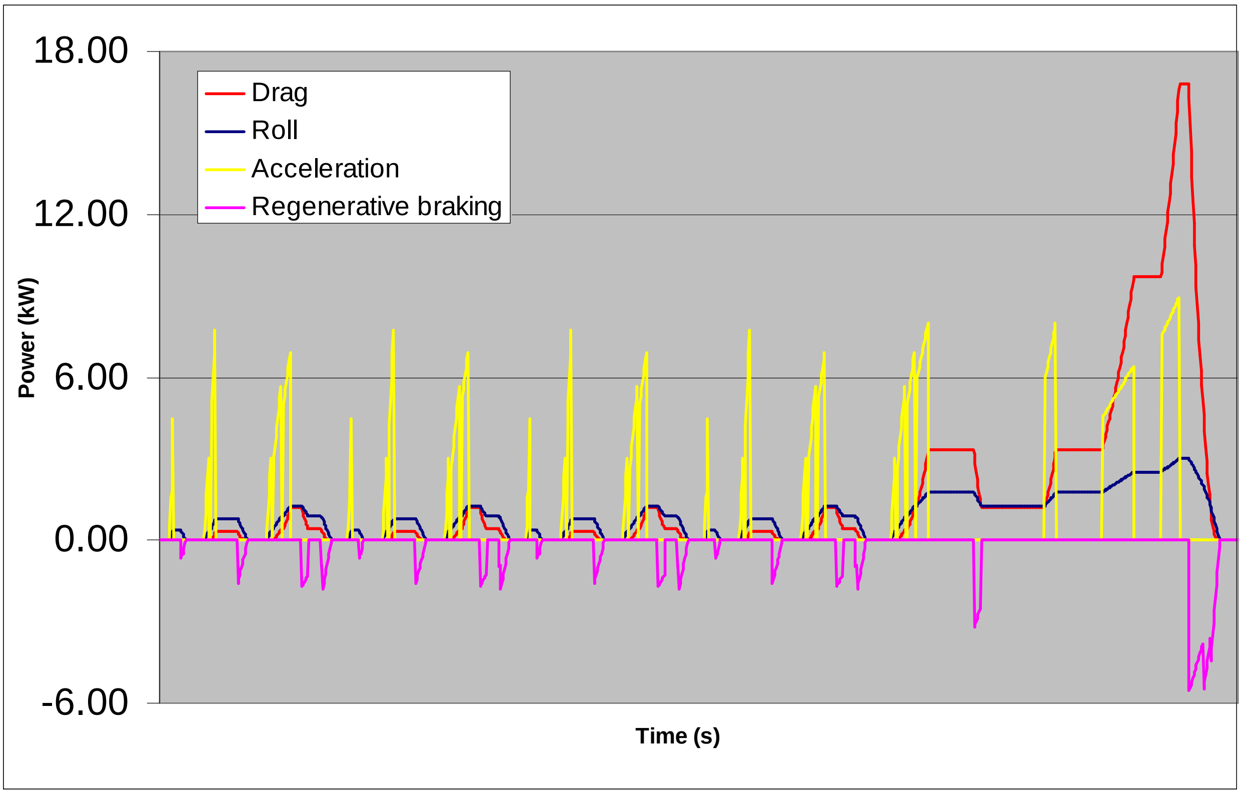

Figure 5.6: Power to the wheels of a Smart Fortwo electric drive during the NEDC driving cycle (the useful regenerative braking power is assumed to be 25% of the total power applied to the wheels during deceleration of the vehicle).

Table 5.4: Effect of parameter change on roll- and drag resistance

	Now	Rolling resistance coefficient 0.007	Weight to 700 kg	Drag coefficient 0.28	All measurements
Drag resistance (kW)	1.53	-	1.53	1.13	1.05
Roll resistance (kW)	0.85	0.59	0.70	0.85	0.49
Accelerational power (kW)	1.01	-	0.84	-	0.84
Regenerative braking (kW)	-0.25	-	-0.21	-	-0.21
Sum (kW)	3.14	2.88	2.87	2.73	2.25

Right now the Smart electric drive has an energy use of 120 Wh/km based on the NEDC.
If a weight reduction of 154 kg could be achieved to 700 kg (what is possible, for instance by improving the specific energy of a battery) the car would use 110 Wh/km. An improvement of the drag coefficient to 0.28 will give the car an energy use of 105 Wh/km. If all measurements of table 5.4 where taken on the car it would only use 86.5 Wh/kg! These improvements are also possible on ICE vehicles but are limited. An ICE vehicle has a central motor that have to be well placed in the vehicle for road stability. This limits the reduction of the drag coefficient, where electric vehicles do not suffer from this limitation. The motor of a BEV is relatively small and light compared to an ICE. The batteries in a BEV can be used for stabilising the vehicle and improve the road stability.

5.4.2 Battery sizing

Estimates on battery size can be useful when modelling a BEV. The battery size of the known BEVs can easily be calculated by multiplying the energy consumption by the range of the car divided by the specific energy of the battery used in the vehicle. The Smart Fortwo for example has a fuel consumption of 0.120 kWh/km. The range of the car is 116.7 km based on the NEDC. This gives the car a battery with a capacity of 116.7 × 0.120 = 14 kWh.

The battery used in the car is the Zebra battery with a specific energy of 100 Wh/kg. The total weight of the battery system is 14/0.1 = 140 kg

Another way of calculating the battery size can be done by using the specifications of the reference ICE vehicles. Some of the ICE vehicles do not have a similar electric version. The battery size of an electric version can be estimated by first calculating the power to the wheels. As an example the Smart Fortwo diesel is used to compare the result with the actual size of the battery of a Smart electric. The Smart has a fuel consumption of 3.4 litres per 100 km and 28.9% powertrain efficiency as calculated in chapter 4. The energy delivered to the wheels over 100 km is 3.4 × 10 (kWh/l, the energy content of diesel fuel) × 28.9% = 9.82 kWh. The efficiency of the Smart electric is 79% as calculated in this chapter. The size of the battery of an electric version of the car based on the Smart Fortwo diesel can be calculated by dividing the energy to the wheels by the efficiency of the electric Smart. The battery need to be 12.42 kWh to drive the car for 100 km. When comparing this with the specifications of the Smart Fortwo electric drive the size of the battery is almost the same. The Smart Fortwo electric has a battery of 14 kWh that can drive the car 116 km. The battery size calculated with the diesel version would be 14.42 kWh if driven for 116 km. Differences in battery size between the real electric drive and the one calculated here are due the fact that there is a difference in power.

5.5 Future developments

5.5.1 CO_2 emissions

The W-T-W CO_2 emissions of a BEV depend on the way the electricity is generated. In this research the European electricity mix is used. The European Union is aiming at a 20% greenhouse gas reduction in 2020 compared to the levels of 1990. They also want that 20% of the electricity generated in the EU comes from renewables. When these targets are met the average CO_2 emission from electricity generation in the EU will go down. Also improvements on battery charging and vehicle efficiency will make the CO_2 emissions go down.

5.5.2 Efficiency

The efficiencies of the BEVs calculated here are already high, but improvements can be made. Improvements are expected on the battery technology, where the charge and discharge efficiency could be higher in the future. Also the use of in-wheel electric motors can improve the efficiency of a BEV. The largest efficiency improvement can be made on the W-T-T pathway. Now a lot of energy is lost in converting primary energy into electricity and the transportation of electricity. The use of decentralised renewable energy can improve the W-T-W efficiency significantly. If BEVs will be charged with, for instance, solar or wind energy at a home the losses for transporting will be very low. Therefore with good system integration the W-T-W efficiency could be close to the vehicle efficiency of about 80%!

5.5.3 Lifecycle costs

Technical learning can reduce the price of products when being mass produced. In chapter 3 a future battery price was estimated. The reduction in price is also expected for the BEV when they are produced on a large scale. Eventually the price of a BEV without a battery pack will be close to that of an ICE vehicle.

6. Results

6.1 Energy efficiency

The well-to-wheel efficiency is presented as the useful energy at the wheels divided by the primary energy use. The W-T-W efficiency is divided into a well-to-tank and a tank-to-wheel pathway. In figure 6.1 a schematic image shows the W-T-W efficiency of three types of Smart Fortwo vehicles. The W-T-T pathway of the diesel car is equal for all the diesel vehicles in this thesis. This is also true for the gasoline and electric W-T-T pathway.

Figure 6.2 shows all the efficiencies for the ICE vehicles and the electric vehicles in the A, B and C classes. The best to worst W-T-W efficiencies of all the vehicles are presented. The tables with the data of the figures can be found in appendix B. When comparing the results it should be noted that there are some differences in engine power between the vehicles. In figure 6.3 the results are separated into the A and C class. Because no B class electric vehicles were researched here the figure on the B class vehicles is lacking.

The T-T-W efficiency is calculated as the useful energy at the wheel divided by the NEDC energy consumption (see section 4.2.2 and 5.2.2). The total W-T-W efficiency is calculated by multiplying the W-T-T efficiency by the T-T-W efficiency.

The best possible efficiency can be achieved when driving a Nissan Leaf followed by the Smart Fortwo diesel. The efficiencies of the BEVs are based on the European electricity mix and can vary according to the way the electricity is generated. It is clear that when using only renewable energy as a primary energy input the efficiency numbers of the BEVs will be much higher. If for instance wind or solar energy is used with an 100% efficiency (the primary energy is considered to be the electricity generated) the efficiencies of the BEVs will be close to the T-T-W efficiencies.

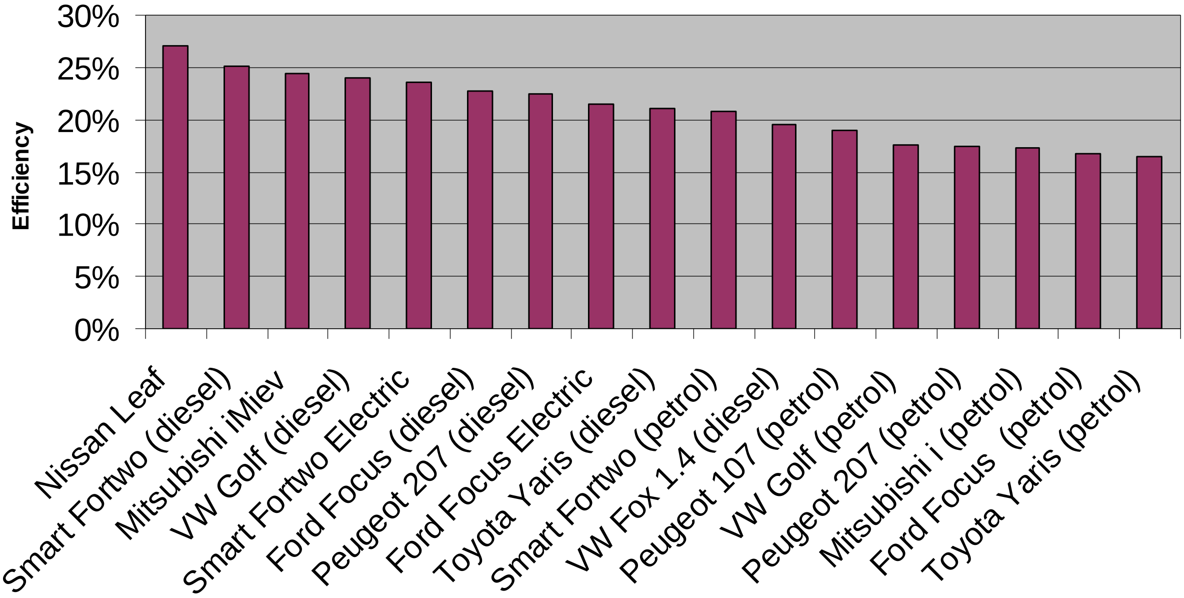

Figure 6.2: W-T-W efficiencies of all the passenger cars, descending from the best efficiency to the worst efficiency (the efficiency of the Th!nk city is not included because vehicle aerodynamic specifications are lacking).

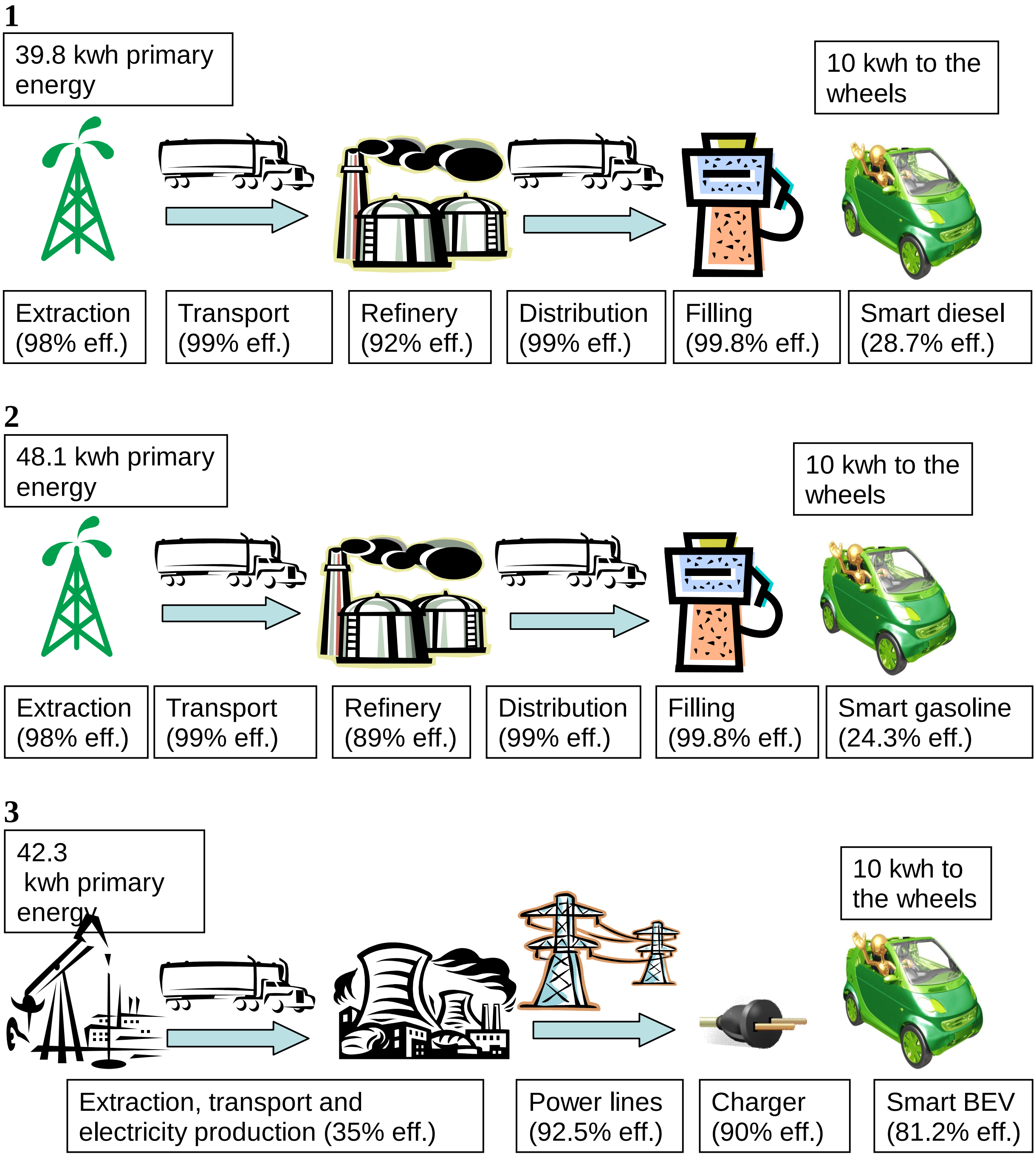

Figure 6.1: Schematic image of the primary energy efficiency of the three types of Smart Fortwo vehicles. The W-T-T pathways (1=diesel, 2=gasoline and 3=electricity) are equal for each vehicle researched in this thesis.

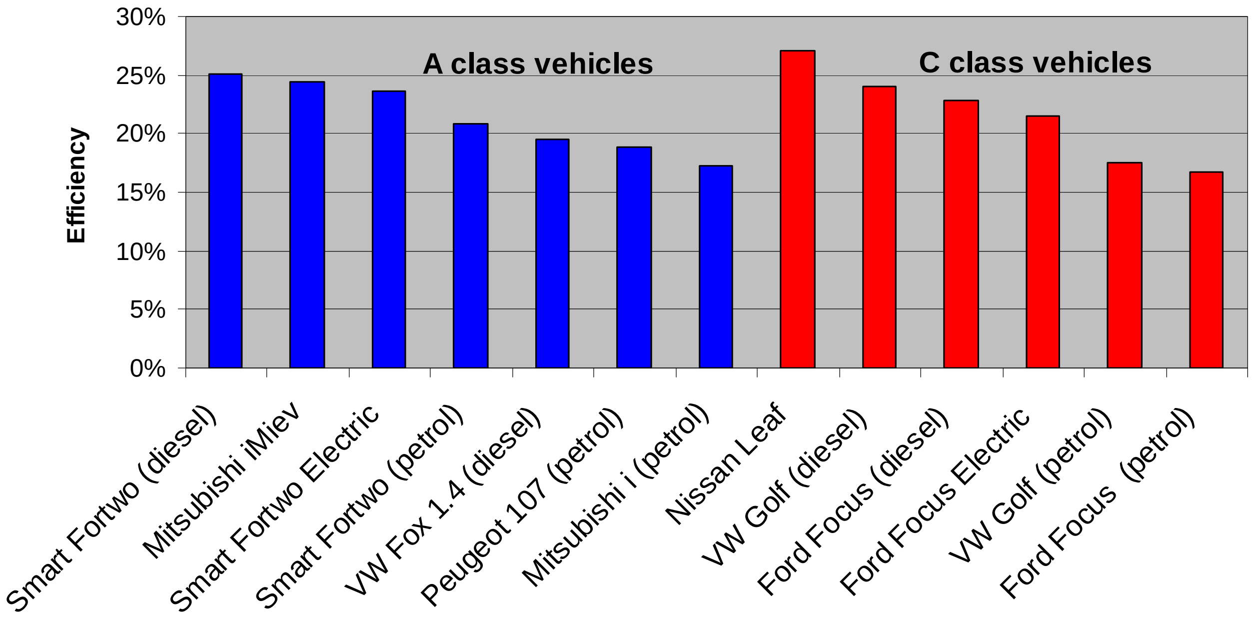

Figure 6.3: W-T-W efficiencies of the A- and C-class passenger cars descending from best to worst efficiency.

6.2 Energy consumption

A high vehicle efficiency does not necessary imply that the vehicle has a low energy consumption. The energy consumption also depends on the vehicles aerodynamic specifications, like the car weight and drag coefficient, and the power of the car.
In figure 6.4 the energy consumption of all the vehicles are shown divided into the W-T-T and T-T-W energy consumption. The W-T-T energy consumption is directly related to the T-T-W energy consumption. It is calculated with the NEDC fuel consumption numbers and the W-T-T energy consumption stated in section 4.2.1 and section 5.2.1. The Nissan Leaf consumes 150 Wh/km measured during the driving cycle of the UDDS. The same vehicle would consume less during the NEDC driving cycle as the acceleration and deceleration is less than during the UDDS. When applying the Nissan Leaf specifications to the NEDC driving cycle using the calculated efficiency during the UDDS it would only consumes 132 Wh/km. This energy consumption is used for the results presented here.

When comparing the energy consumption of the vehicles it should be noted there are differences in engine power. In order to compare the results in a proper way the maximum power of the vehicles should be equal. Therefore in figure 6.5 a distinction is made between A and C class vehicles. The power of the A class BEVs are 30 kW for the Th!nk and the Smart Fortwo and are comparable to the Smart Fortwo diesel. The iMiev has a maximum power of 47kW, comparable to the other cars in the A class with a maximum power of around 50 kW.
The Nissan Leaf has a power of 80 kW, comparable to the diesel cars in the C class. The Ford Focus petrol has the lowest engine power but still consumes the most energy. If the maximum power would be higher the energy consumption would also go up.
The Ford Focus electric has the highest engine power of 100 kW followed by the VW Golf diesel with 90 kW maximum power.

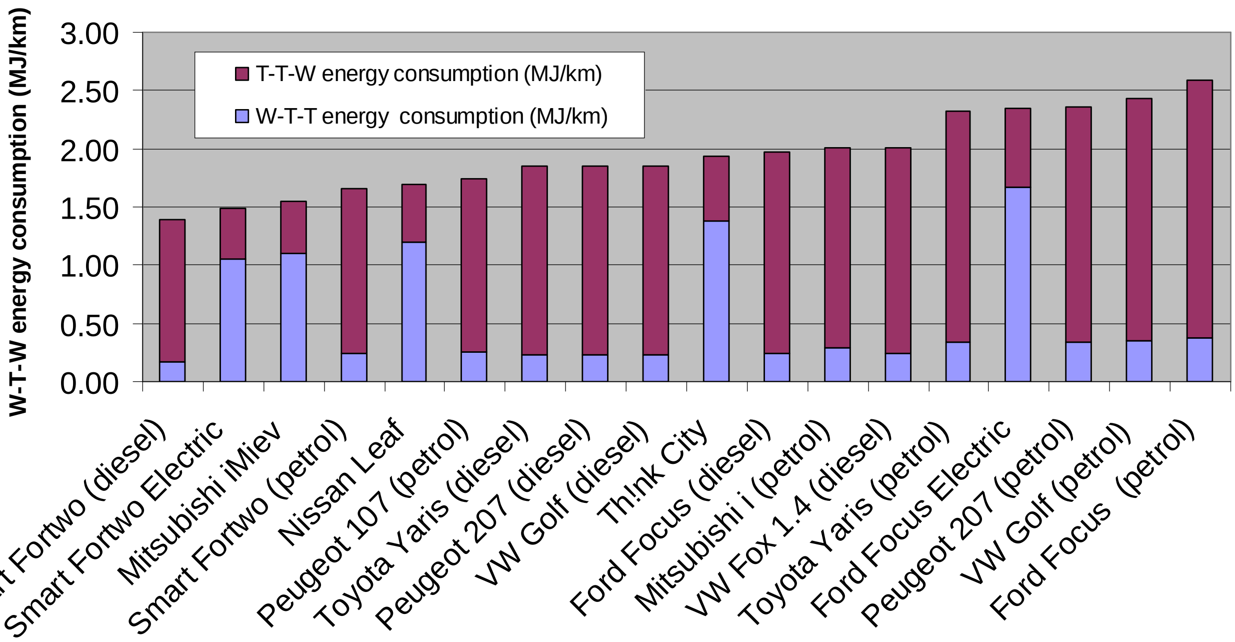

Figure 6.4: W-T-W energy consumption of all passenger cars, ascending from the lowest to the highest energy consumption.

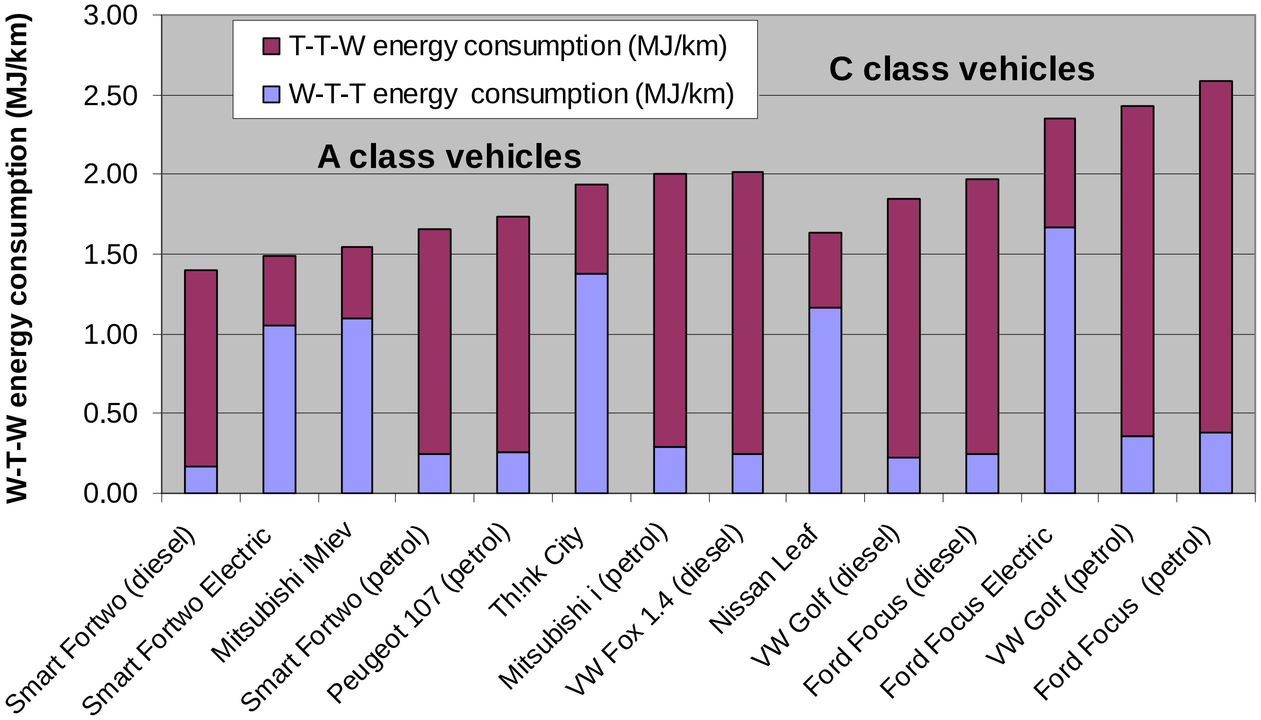

Figure 6.5: W-T-W energy consumption of the A- and C-class passenger cars, ascending from the lowest to the highest energy consumption.

6.3 CO_2 emissions

The European Union is aiming at a 20% reduction of CO_2 in 2020. Cleaner passenger cars can contribute to this goal. To see to what extend the BEV can contribute the ICE vehicles and BEVS are compared on CO_2 emissions. In figure 6.6 the total W-T-W CO_2 emissions are presented in grams emitted per kilometre driven. The BEVs emissions occur during the production of electricity and therefore only have a W-T-T emission.

In figure 6.7 it can be seen that all the BEVs in the same class are emitting less CO_2 than a comparable ICE passenger car. The emissions of the BEVs are calculated based on the average European electricity mix and can vary depending on the way the electricity is generated. The use of renewable energy would reduce the emissions to almost zero.

Given the results in figure 6.7 a BEV emits about 50% less CO_2 than a comparable vehicle in the same class.

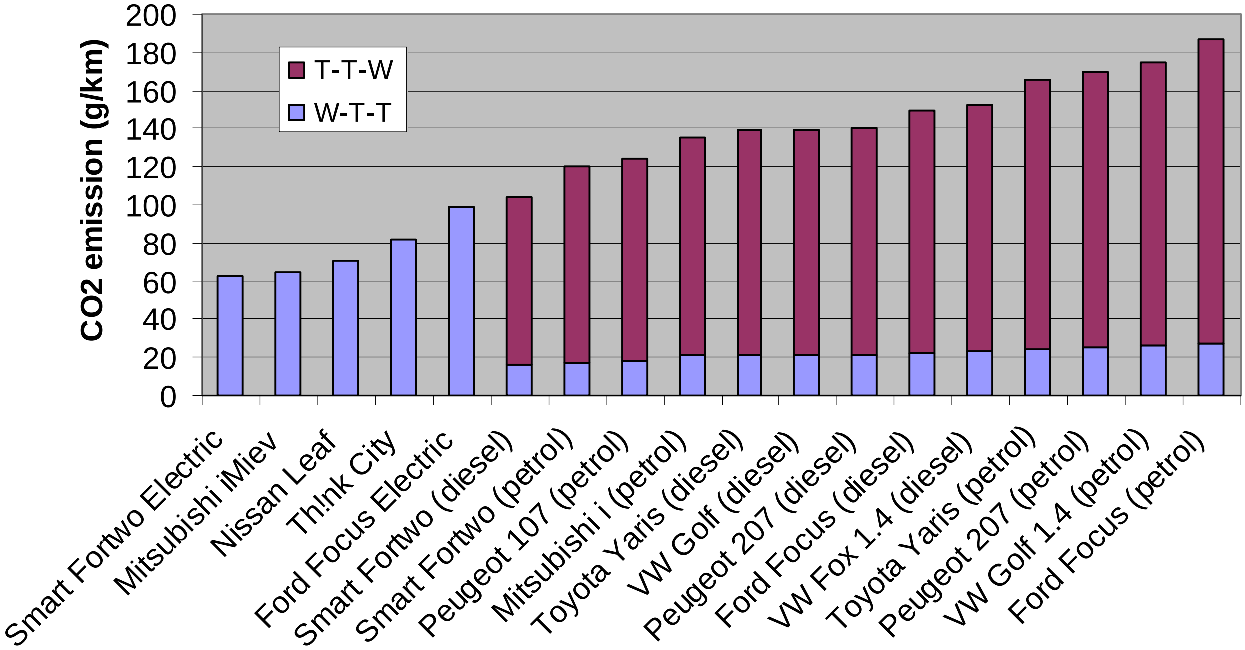

Figure 6.6: W-T-W CO_2 emissions of all passenger cars, ascending from the lowest to the highest emission of CO_2.

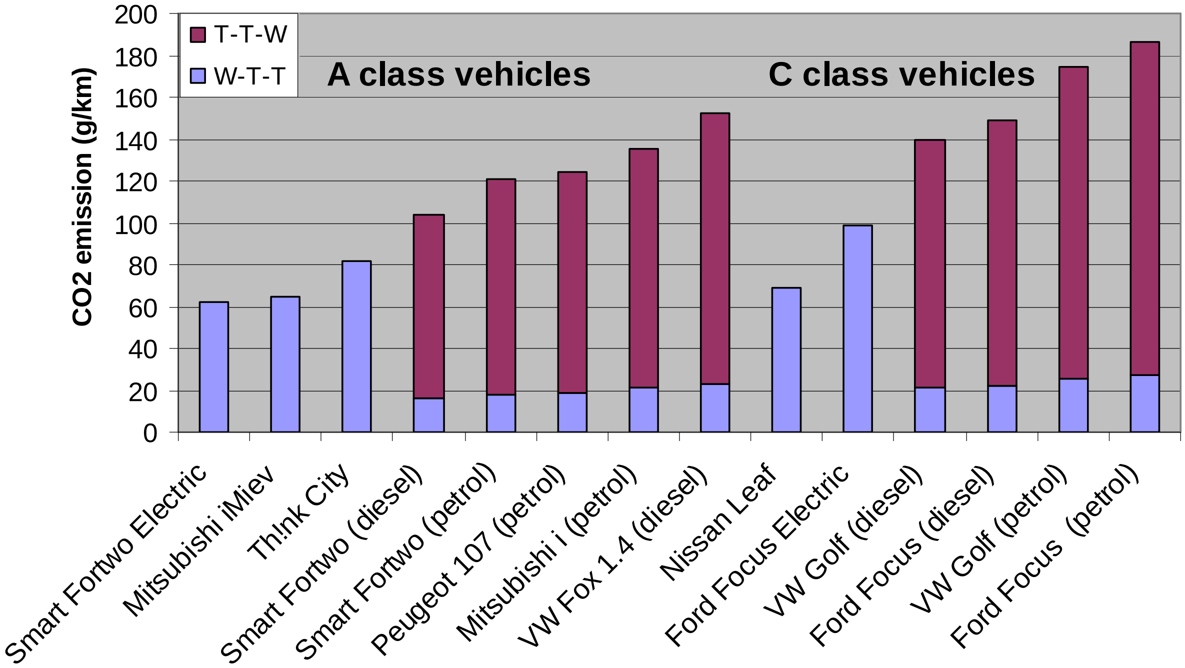

Figure 6.7: W-T-W CO_2 emissions of the A- and C-class passenger cars, ascending from the lowest to the highest emission of CO_2

6.4 Lifecycle costs

Probably the most important part that can contribute to the success of the commercialisation of the BEV is the costs. Right now a small city BEV in the Netherlands would cost around €40,000. Compared to a small ICE city vehicle, which cost around €10,000 this is very high and make up most of the lifecycle costs of a BEV. The results shown here are the untaxed lifecycle costs as well as the taxed lifecycle costs. In figure 6.8 the untaxed lifecycle cost of all the electric and ICE vehicles are shown ascending from the lowest costs to the highest cost per kilometre driven. Figure 6.9 shows the untaxed lifecycle costs of the A and C class vehicles. The differences between the costs of the ICE vehicles in the A class and in the C class are very small. The total untaxed lifecycle costs of the BEVs are around two times higher in the A class. In the C-class the Nissan Leaf will cost 6-8 cents more than an ICE vehicle and the Ford Focus electric costs 19-21 cents more.

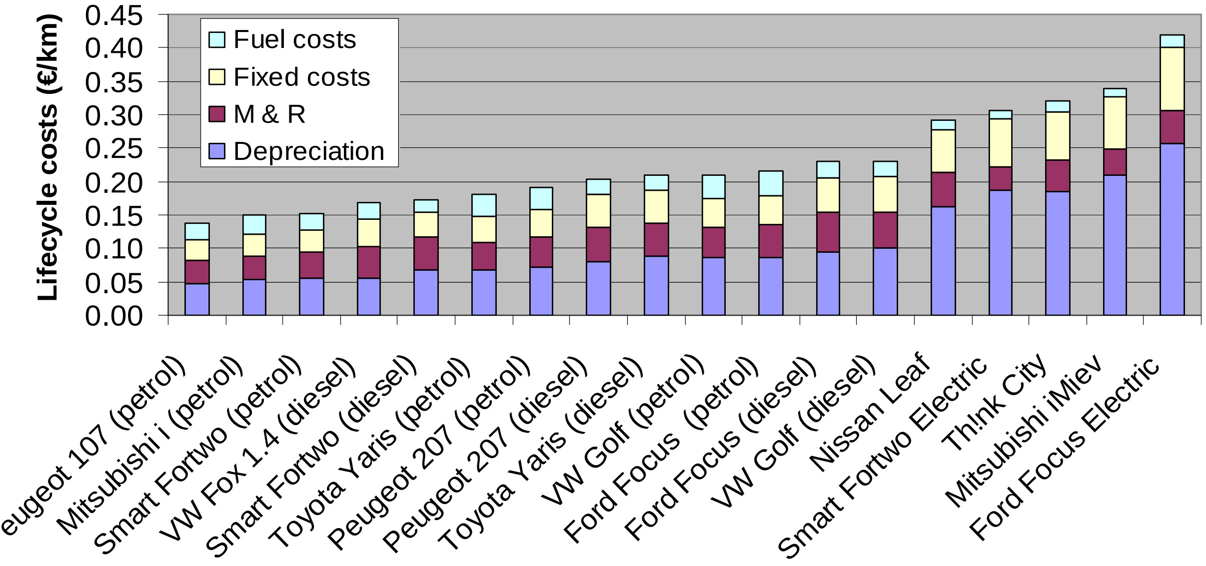

Figure 6.8: The lifecycle costs (without VAT, excise duties and taxes) of all passenger cars, ascending from the lowest to the highest costs per kilometre

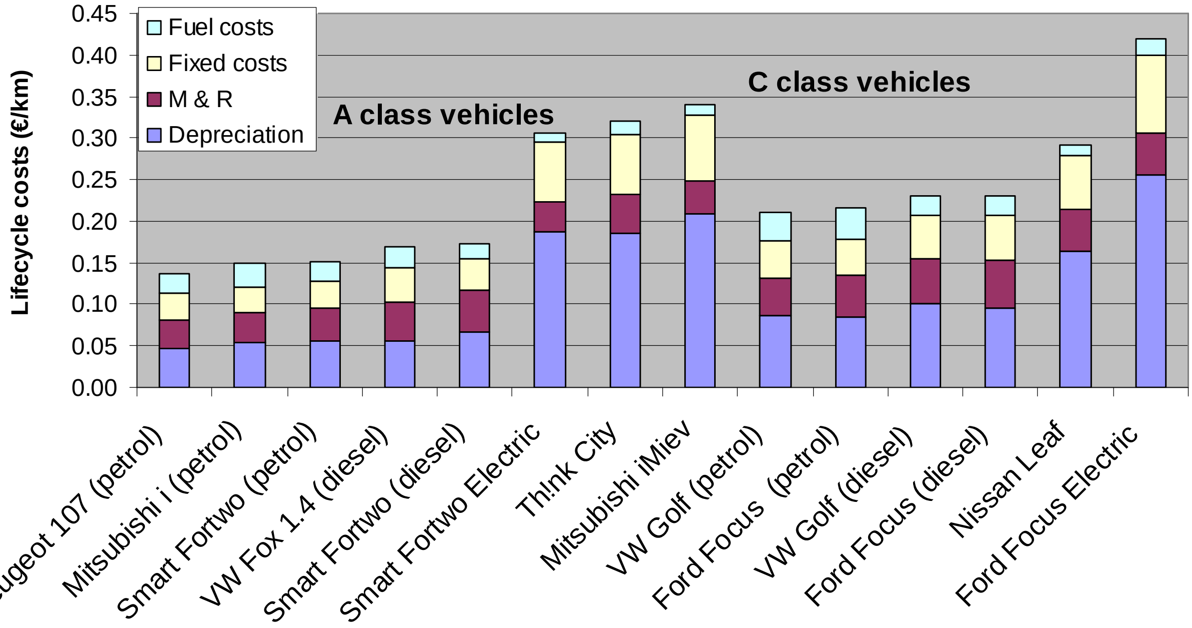

Figure 6.9: Lifecycle costs (without VAT, excise duties and taxes) of the A- and C-class passenger cars, ascending from the lowest to the highest costs per kilometre.

When adding taxes and VAT to the total lifecycle costs the figure will change in the favour of the BEVs. In figure 6.10 the total taxed lifecycle cost of all the electric and ICE vehicles are shown ascending from the lowest costs to the highest cost per kilometre driven.

The fuel costs of the BEVs are just a small part of the total costs. Throughout this thesis a fixed electricity price of €0.24 is used for calculating the fuel costs. The costs for maintenance and repair are almost equal for the BEVs compared to the ICE vehicles. Although BEVs need less maintenance during the lifetime, the replacement of the battery adds up to the total M & R costs. The fixed costs of a BEV mainly consist of the insurance costs each year.

The petrol powered vehicles have the lowest lifecycle costs. The diesel powered cars have higher costs due the high road taxes and a higher depreciation. In this research the average annual kilometres driven are set to 16,000 km. For diesel to become competitive with the petrol powered cars the kilometres driven each year have to go up.

The BEVs in the A class can only compete with the lifecycle costs of the cars in the higher segments. In the C-class the Nissan Leaf have similar lifecycle costs compared to the ICE vehicles in the same class.

Without taxes included the BEVs can not compete with the ICE vehicles. The inclusion of taxes has a positive effect on the outcome, especially for the BEVs in the higher segments.

The low emission vehicles in the A class also benefit from the tax schemes in the Netherlands, which are the abolishment of vehicle tax and road taxes. Therefore the inclusion of taxes in the A class do not benefit the BEVs compared to the ICE vehicles.

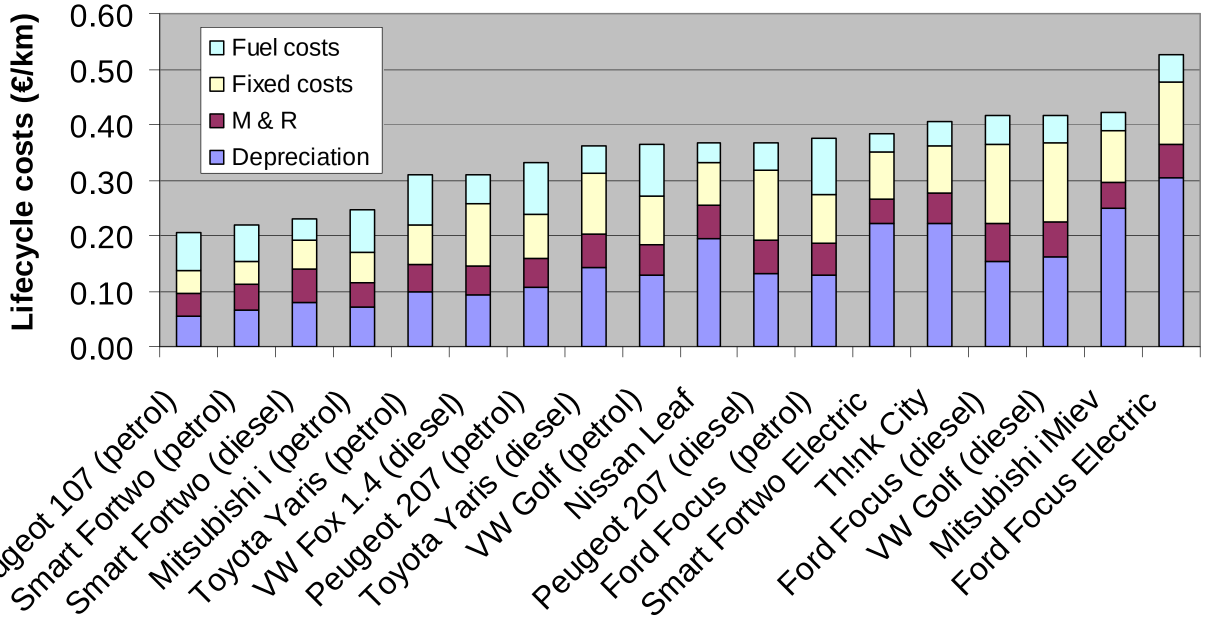

Figure 6.10: Lifecycle costs of all passenger cars, ascending from the lowest to the highest costs per kilometre

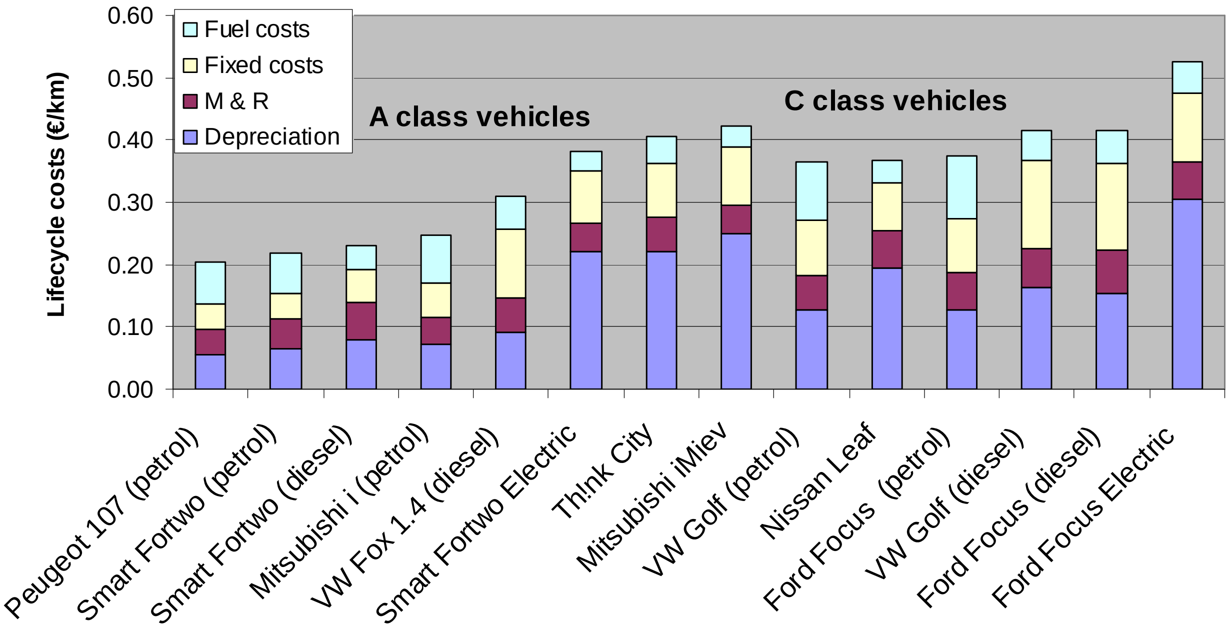

Figure 6.11: Lifecycle costs of the A- and C-class passenger cars, ascending from the lowest to the highest costs per kilometre.

6.5 Sensitivity analysis

A sensitivity analysis has been performed to check the robustness of the results on the vehicle efficiency and lifecycle costs by changing a few parameters. The parameters that have been changed are shown in table 6.1. The efficiency of a BEV depends on more input parameters than stated in table 6.1. Driving under different conditions can reduce the vehicle efficiency. For example turning on the heater or cold conditions affecting the battery performance can reduce the vehicle efficiency. The parameters used in this research however are based on the European standard driving cycle, the NEDC, and under these conditions the efficiency was calculated. The only parameters that were uncertain in the analysis were the roll resistance and the percentage of extra load on the total mass of the vehicle that was used to simulate the vertical acceleration force. The results of the sensitivity analysis can be found in table 6.2.

Table 6.1: Parameters changed for sensitivity analysis

Parameter (Vehicle Efficiency)	**Change from original value**
Roll resistance coefficient	+/- 20%
Percentage of extra load for vertical acceleration	+/- 100%
Parameter (Lifecycle costs)	
Retail price	+/-20%
Discount rate	+/-40%
Price of electricity	+/-50%
Total distance driven during lifetime	+/-20%
Vehicle lifetime	+/-20%
Battery replacement during lifetime	None

6.5.1 Roll resistance

The original roll resistance coefficient of all the vehicles was set to 0.01. For the Nissan Leaf the parameter was set to 0.007 as it is known that the vehicle will be equipped with tyres that have low resistance.

Changing the parameter does not have a large effect on the total vehicle efficiency. The roll resistance only has a substantial impact when driving at low speeds. At higher velocity it requires more power to overcome the drag resistance. During the driving cycle the average power to overcome the drag and acceleration force is larger than the roll resistance. The impact of changing the roll resistance coefficient on the vehicle efficiency during the NEDC is relatively small but substantial.

6.5.2 Extra load for vertical acceleration

The linear acceleration force, calculated as the mass of the vehicle times the acceleration, was increased by 5% to account for the rotating parts to go faster. The efficiency of the vehicle depends on the way it is defined. In the GM report (GM 2002) the vertical acceleration is not taken into account when calculating the efficiency. The effect of changing the parameter to 0% or 10% extra load was checked. Changing this does not have a large effect on the vehicle efficiency. The vehicle efficiency numbers a robust as the uncertainty of the parameters used for calculating the vehicle efficiency are small.

6.5.3 Retail price

The largest impact on the total lifecycle costs of a BEV is determined by the retail price. At this moment it is still uncertain what the retail price of a BEV in the Netherlands will be. The only retail price known is that of a Think City which is currently available in the Netherlands.

The depreciation of a vehicle is very high compared to ICE vehicle because of the large difference in purchase price. A drop in the retail price would lower the total lifecycle costs at almost the same rate. A decrease of 20% in the retail price would lower the total lifecycle costs by 15%.

6.5.4 Discount rate

The discount rate in this thesis is assumed to be 5%. To see what the impact is when changing the parameter it is set to 3% and 7%. The discount rate determines for a part the depreciation of the vehicle calculated as the annual capital cost. Lowering the discount rate by 40% will lower the lifecycle costs by 10%. The outcome of the results in comparison to the ICE vehicles will not change. The discount rate of the ICE vehicles and the BEVs are assumed to be the same. The absolute values of the lifecycle costs will be altered by a change in discount rate but the relative difference in lifecycle cost will not change.

6.5.5 Price of electricity

The price of electricity is assumed to be constant during the lifetime of the vehicle. This is not realistic as the price of energy will go up in time. The effect of price fluctuations of electricity is limited however. Increasing the electricity price by 50% will only lead to an increase in lifecycle costs of 4 to 5%. This relatively small increase is due to the fact that the fuel costs are only a small part of the total lifecycle costs. An increase therefore only has a small impact on the total lifecycle costs.

6.5.6 Total distance driven during lifetime

The distance that a BEV will cover during its lifetime is uncertain. The parameter is changed with 10%. When the total distance will increase the lifecycle costs will be 10% lower. A decrease in distance will increase the costs with 8%. The total lifecycle costs of a vehicle are very dependent on the total distance covered by a vehicle as they are calculated per kilometre. Increasing the total distance that a BEV can cover during the lifetime compared to an ICE vehicle can reduce the lifecycle cost significantly.

Table 6.2: Sensitivity analysis of the vehicle efficiency and the lifecycle costs of the BEVs. The percentages are the changes from the original values of the efficiency and the lifecycle costs. The efficiency change of the Think City is not calculated as there is no result on the efficiency.

Parameter (Vehicle Efficiency)	**Change from original value**	Smart Fortwo Electric	Mitsubishi iMiev	Th!nk City	Ford Focus Electric	Nissan Leaf
Roll resistance coefficient	-20%	-5.2%	-6.0%	-	-6.3%	-4.5%
	+20%	5.2%	6.0%	-	6.3%	4.5%
Percentage extra load for vertical acceleration power to the wheels	-100%	-1.4%	-1.7%	-	-1.8%	-2.9%
	+100%	1.4%	1.7%	-	1.8%	2.9%
Parameter (Lifecycle costs)						
Retail price	-20%	-15.3%	-16.9%	-14.5%	-15.6%	-15.9%
	+20%	15.3%	16.9%	14.5%	15.6%	15.9%
Discount rate	-40%	-8.4%	-8.3%	-7.9%	-8.5%	-8.7%
	+40%	9.0%	8.9%	8.5%	9.2%	9.4%
Electricity price	-50%	-4.2%	-4.0%	-5.2%	-4.5%	-3.6%
	+50%	4.2%	4.0%	5.2%	4.5%	3.6%
Total distance driven during lifetime	-10%	10.2%	10.2%	10.0%	10.1%	10.3%
	+10%	-8.3%	-8.4%	-8.1%	-8.3%	-8.4%
Vehicle lifetime	-20%	-8.6%	-8.8%	-8.2%	-8.4%	-8.6%
	+20%	8.7%	9.0%	8.3%	8.6%	8.8%
Battery replacement during lifetime	None	-2.7%	-2.9%	-5.1%	-3.1%	-3.3%

6.5.7 Vehicle lifetime

The annual distance driven by a passenger car is assumed to be 16,000 kilometres over a lifetime of 17 years. When changing the lifetime of the vehicle the annual driven kilometres change. Reducing the lifetime of a BEV will have a positive effect on the lifecycle costs as they are expresses in €/km. The kilometres driven each year will go up and the fixed cost per kilometre will go down as they are dependent on the vehicles lifetime. The total cost for insurance will go down if a vehicle is driven for fewer years. This effect is also visible for the ICE vehicles.

6.5.8 Battery replacement

The lifetime of a battery determines whether a battery have to be replaced during the lifetime of a BEV. It is expected that the battery have to be replaced once during the 17 years lifetime of a BEV. It could well be that the battery will last longer than the 10 years assumed in this thesis. The change in lifecycle cost when not replacing the battery is limited. The price of a battery pack has dropped significantly ten years from now. The costs per kilometre of replacing a battery pack are low and will not add much to the total M & R costs. The effect is also limited because M & R costs are just a small part in the total lifecycle costs. Most costs are due to a high retail price of a BEV.

7. Discussion

7.1 Battery technology

The development of the battery technology plays a large part in the success of the BEV. The price of a battery pack is a burden for the commercialisation of the BEV as it has a large share in the total lifecycle costs of the vehicle. Not only a price reduction of a battery pack but also improvements in lifetime and specific energy could reduce the lifecycle costs of a BEV. The targets set by the USABC are likely to be achieved the next decade, except for the price of a battery, by the lithium-ion battery and the zebra battery. These goals set by the USABC, a consortium of car manufacturers, could be doubted. The price of $100, - per Kwh is a bit too optimistic and is not going to be achieved the next decade. The question is whether this price goal going to hold back the commercialisation of the BEV. This is probably the case the next decade for passenger cars, as the battery makes up a significant amount of the total price of the vehicle. If the lifetime of the battery could be extended to the lifetime of the BEV, there will be no need to replace the battery. This will reduce the total lifecycle costs of a BEV, but not significantly. The battery will be replaced after nine or ten years from the day the BEV is bought. After a decade from now the price of a battery pack is already dropped with more than 60% according to this thesis. The costs of replacing the battery calculated over the whole lifetime of the BEV of 17 years do not add up much to the total lifecycle costs.
The battery pack has a large impact on the sales price right now. The only way to lower the price of a BEV to a comparable ICE vehicle prices is to wait until the price of a battery pack has dropped to values that can compete with ICE vehicles.

The development of batteries for EVs will go on the coming years resulting in safer batteries with higher specific power and energy. The available batteries of today do not meet the requirements needed for the commercialisation of BEVs yet. However combining high specific energy batteries, such as the metal-air batteries, with high power rechargeable batteries in a hybrid configuration can result in batteries suitable for BEVs. In a hybrid configuration the high energy battery can recharge the high specific power battery that is required for peak power. During light load the high energy battery handles the load and recharges the high power battery. An example of a hybrid battery configuration is the zinc-air bus programme in the United States (ElectricFuel 2009). This bus is equipped with a high specific energy zinc-air battery, a high power Ni-Ca auxiliary battery and ultra capacitors. The ultra capacitors can deliver peak power up to 1000 W/kg and greatly contributes to the system efficiency. The zinc-air battery is mechanically refuelled when empty by a zinc module.
Combining low cost metal-air batteries with rechargeable batteries or ultra capacitors in a hybrid configuration can possibly meet the goals set by the USABC.

An issue that is not researched in this thesis is the scarcity of materials used in batteries. The lithium batteries are considered to be the main battery the next decade for the use in electric vehicles. At this moment lithium is abundant and in the near future no problems are expected with the supply of lithium for advanced batteries. But by 2020 the production capacity of lithium could reach its limits and bump up against supplying constraints (Lache et al. 2008). The price of lithium could go up as a result and make a considerable impact on the total price of a battery pack. If the batteries are recycled and the lithium could be re-used in new batteries a part of the supply problem would be tackled. At this moment there is no market yet for recycling battery packs as the lifetime is about ten years and batteries are just being commercialized.

Around 2020 a good recycling infrastructure should be ready to cope with the maximum production capacity of lithium.

7.2 Energy use, efficiency and emissions

The figures on energy use, efficiency and CO_2 emissions presented in this thesis are based on the NEDC. The representation of this driving cycle on the use of a car in Europe can be argued. First of all the driving cycle simulates low powered vehicles with slow acceleration and deceleration when in reality ascending and descending is more dynamic.

Second of all the vehicles are tested on a roller bench where a flat surface is simulated. In normal driving conditions the road usually have some slopes or hills and weather conditions, like wind or rain, which can have effect on the energy use of a vehicle.

Thirdly, manufacturers can design their car in such a way that under these standard driving conditions the car performs much better that it would in real driving conditions. This is called cycle beating and could increase the energy use and emissions significantly under real driving conditions (Kageson 1998).

The energy use and emissions of the cars researched in this thesis are probably higher in reality as the NEDC does not represent the real usage of a European light duty vehicle. The outcome of this thesis may not be representing real life car usage but can be used for comparing ICE vehicles and BEVs.

Not only can the real usage of a car today have an impact on the energy use and CO_2 emissions. Also the way the electricity is generated can have an impact on the results. The European electricity mix is used to compare the ICE vehicles with the BEVs. In the Netherlands the electricity mix mainly comes from coal and gas fired power plants. When only state-of–the-art coal fired power plants are used with an primary energy efficiency of around 40% or gas fired power plants with about 50% (Campanari et al. 2009) the W-T-W efficiency would be higher. Also the results on CO_2 emissions of the BEVs would change when only electricity from coal fired or gas fired power plants are used. State-of-the-art gas fired power plants emitting around 350 grams per kWh and coal fired power plants around 740 grams per kWh (Seebregts and Scheepers 2007). In figure 7.1 and 7.2 the W-T-W efficiency and CO_2 emissions of the BEVs are shown when coal or gas fired power plants are used.

As figure 7.1 shows, the W-T-W efficiency will be higher if a state-of-the-art power plant is used to generate the electricity to drive a BEV. The average European electricity mix efficiency will gradually go up in time as old and inefficient power plants are being replaced and the share of renewable energy will go up. Diesel and gasoline cars are also becoming more efficient but the efficiency gains are limited. Already a lot of research has been done on ICE vehicles.

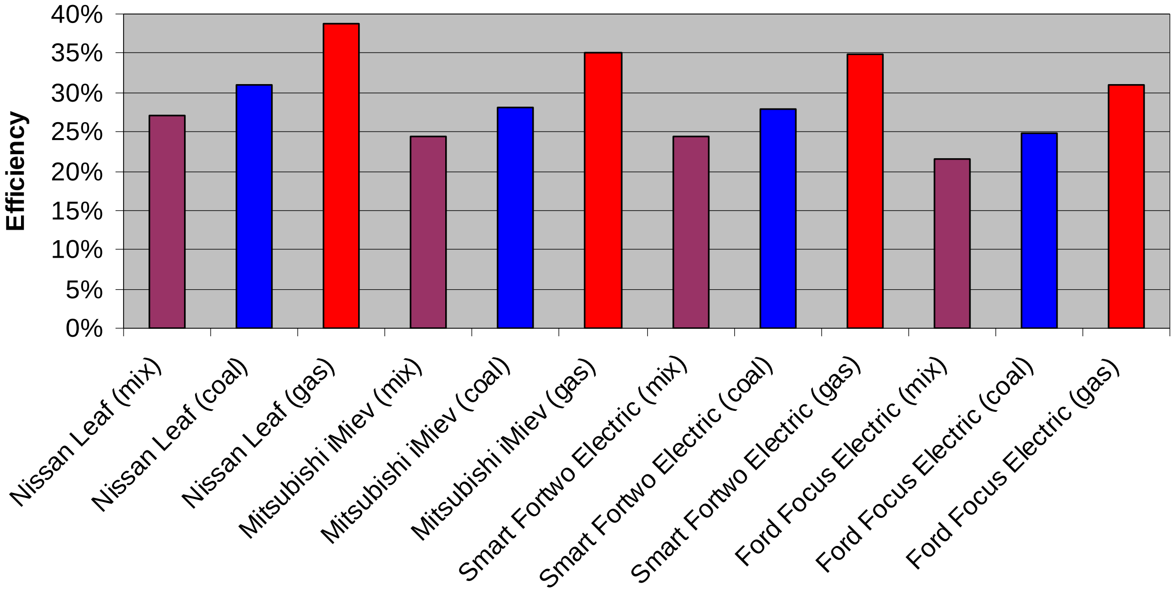

Figure 7.1: W-T-W efficiency of the BEVs when electricity comes from European mix, state-of-the-art coal fired power plants or state-of-the-art gas fired power plants (the primary efficiency used for extraction, transport and electricity production for gas fired power plants is assumed to be 50% and for coal fired power plants 40%).

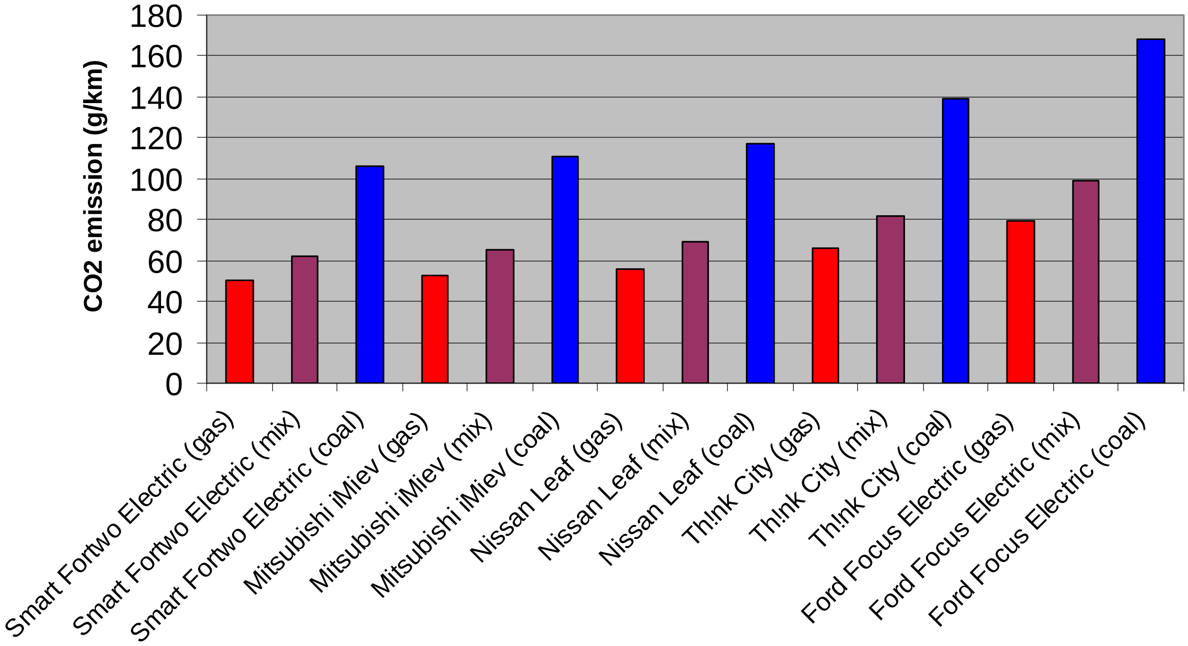

Figure 7.2: W-T-W CO_2 emissions of the BEVs when electricity comes from the European mix, state-of-the-art coal fired power plants or state-of-the-art gas fired power plants.

In figure 7.2 the CO_2 emissions for three electricity pathways are shown. If these emissions are compared with the results in chapter 6, the BEV emits less than an ICE petrol vehicle when a coal fired power plant is used. The Smart Fortwo petrol emits 121 g/km and the diesel version has an emission of 104 g/km. The Smart Fortwo electric emits 108 g/km when the electricity comes from a coal fired power plant. Using the electricity from coal fired power plants in a BEV will not reduce the total emissions of passenger cars significantly. When the electricity is produced in a gas fired power plant the CO_2 emissions will further go down compared to the European electricity mix.

The cars in this thesis are only compared on the emission of the global warming gas CO_2 and not on other emissions like NOx or small particulates. The emission of CO_2 is used here because the European Union focuses on reduction of CO_2. When comparing the vehicles on the effect the exhaust gasses have on the environment and human health the results could be different. Diesel engines for example are emitting more particulates than petrol powered vehicles which are harmful to humans. Power plants are also converting waste into electricity what can lead to carcinogenic emissions like dioxins.
There is also a difference in the source of the emissions. The ICE vehicles are diffuse sources where the BEVs have their emissions at a point source. Power plants are usually situated in a remote area. The impact of the flue gas emissions at a power plant are less harmful than the emissions of ICE vehicles that are driven in dense populated areas.
When taking this into consideration the emissions of ICE vehicles can not simply be compared with the BEV by the emitted emissions per kilometre. If BEVs and ICE vehicles are compared on the emissions, the environmental impact of those emissions should be researched. As this is a complex and time consuming operating this was not part of this research.

7.3 Lifecycle costs

The retail price is an important factor whether consumers will purchase a car. Other factors, like emissions or reliability can also play a role. The fuel economy or monthly fuel costs of a car does not play a large role when buying a car (Mckinsey&Company 2009).
Even if the lifecycle costs of a BEV will be close to a comparable ICE vehicle this will not make consumers buy a BEV. The retail price of a BEV compared to an ICE vehicle will always be higher as the battery is an expensive part of the car. This does not have to be a problem because BEVs have lower fuel costs, lower maintenance cost, lower road taxes and last longer than an ICE vehicle. At some point in time the BEV will reach a retail price at which the total lifecycle costs are equal to the lifecycle costs of an ICE vehicle (see figure 7.3). A small BEV like the Smart Fortwo becomes competitive at a retail price around €15,000. This is €5,000 more than the petrol version. A larger C class model like the Ford Focus electric already becomes competitive between a retail price of €30,000 and €35,000. The Nissan Leaf already has similar lifecycle costs, at a retail price of €35,000, compared to the petrol powered vehicles.
To bridge the gap between the retail price of an ICE vehicle and a BEV, subsidies could be given by the government. Another possibility is that the battery of the car is leased as Project Better Place has in mind (Betterplace 2010). This way the price of the car can compete with ICE vehicles and the fuel costs, including leasing, are comparable.

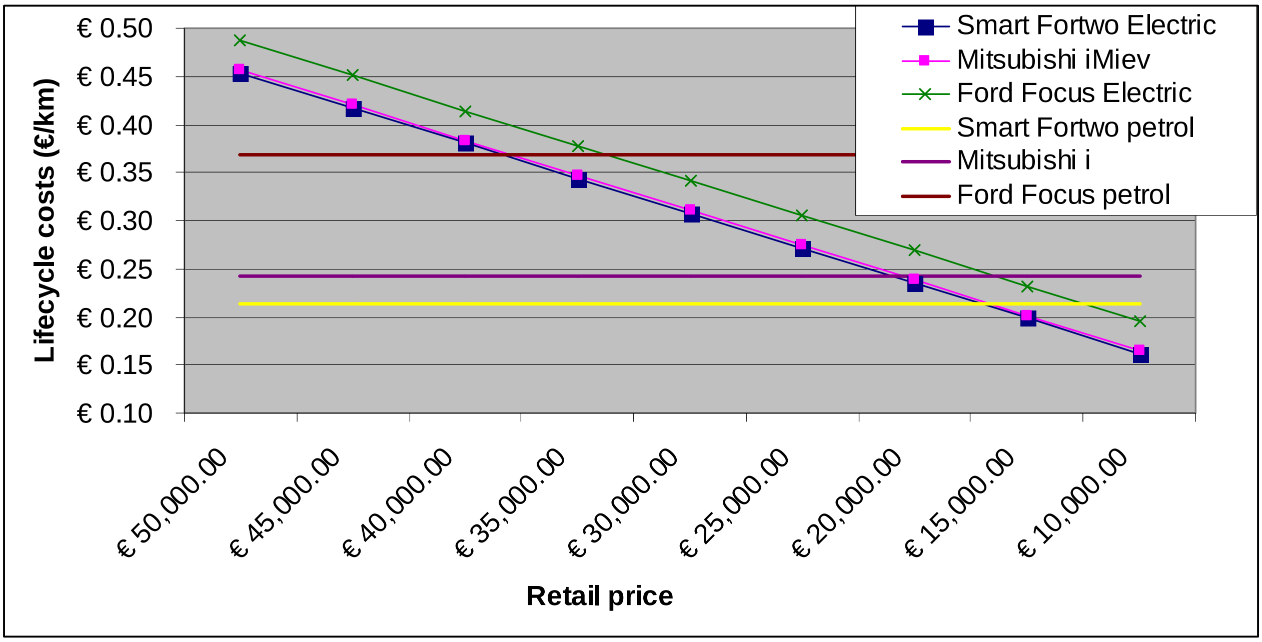

Figure 7.3: The lifecycle costs of a BEV at different retail prices at which the costs becomes competitive with an ICE vehicle (note that the three straight lines represent the lifecycle costs of the ICE vehicles at a fixed retail price).

7.4 Charging infrastructure

The retail price of a passenger BEV will most likely hold back the commercialisation of the vehicle the next decade. A side from the price aspect involved with driving a BEV there are some other issues not researched here that can be a burden for large scale commercialisation of BEVs. One of them is the lack of a good infrastructure for charging a BEV. The distance that an average person in the Netherlands drives by car each day can easily be covered by the BEV with a driving distance of approximately 100 kilometres. The problem is driving long distances that can only be covered when the BEV can be charged rapidly. Even if no long distances have to be covered, charging the vehicle in the Netherlands can only be done at a few charging points or at a 230 Volt home charger. Problem of charging the vehicle at a home charger is the absence of a carport or private parking space at many housings. When charging the vehicle at a home charger it should be within reach of an electric socket. As the majority of the houses in the Netherlands are stacked or situated in cities, only a select amount of consumers could charge the vehicle at home. Even if the BEV would be price competitive with the ICE vehicle the lack of a good charging infrastructure is a factor that can hold back consumers to buy a BEV.

8. Conclusion

8.1 Battery technology development

None of the commercially available batteries suitable for EVs can meet the minimum goals from the USABC for long term commercialisation. Especially the price of a battery pack is a large burden for successful commercialisation.

The lithium-ion battery has the potential the meet the required goals required for long term commercialisation except for the price of the battery. The coming decade it is expected that the lithium ion battery will be the dominant battery type for BEVs. Also the zebra battery will be close to meet the required minimum goals and is a possible candidate as an EV battery. A drawback of this battery type is the high operating temperature.

Breakthroughs in the metal air battery technology are not expected within the next decade. The metal air battery, especially the lithium air, has a potential for high specific energy batteries. The small specific power and recharging however remains a problem for the use in EVs. A hybrid configuration of different types of batteries and ultra capacitors can solve the low power problem of the metal air batteries. It is possible that during this decade hybrid battery configuration in BEVs will emerge.

The prices of the batteries will go down as a result of technological learning but according to the USABC goals this will not be enough for successful commercialisation of the BEV. On the other hand it can be doubted whether these goals are set too high and higher battery prices are also possible for successful commercialisation.

8.2 ICE vehicles and BEVs comparison

The Nissan Leaf has an efficiency of 27.1%, the highest well-to-wheel efficiency of all the vehicles researched in this thesis (figure 6.2). This efficiency is calculated with the European electricity mix. The Toyota Yaris petrol has the lowest W-T-W efficiency of 16.5%.

The best efficiency of the diesel powered vehicles is achieved by the Smart Fortwo with a W-T-W efficiency of 25.1%. Higher W-T-W efficiencies can be achieved by the BEVs if electricity comes from state-of-the-art power plants or from renewable energy sources.

The diesel version of the Smart ForTwo has a primary energy consumption of 1.40 MJ/km, the lowest primary energy use of all the vehicles researched in this thesis (figure 6.4). The Smart Fortwo is followed by the Smart Fowtwo electric, the Mitsubishi iMiev and the Nissan Leaf with primary energy consumptions of 1.48, 1.55 and 1.64 MJ/km respectively. The Ford Focus petrol has the highest primary energy consumption of 2.59 MJ/km.

The potential to reduce the primary energy use from the transport sector with BEVs depends on the way the electricity is generated. At this point the reliance on fossil energy will not be lowered by introducing the BEV on a large scale. The only way to reduce the dependence on fossil energy, by introducing the BEV, is to produce more renewable electricity. When the amount of renewable energy in the European electricity mix would go up significantly the reliance on fossil energy will be lowered.

The W-T-W emissions of CO_2 of a BEV in the A class are around 50% lower than a comparable petrol powered car and 40% lower than a diesel version. The Nissan Leaf emits even more than 50% less than a comparable car in the same class. The Smart Fortwo electric has the lowest W-T-W emission of the researched vehicles and emits 62 grams of CO_2 for each kilometre driven (figure 6.6). All BEVs have lower W-T-W CO_2 emissions than the ICE vehicles when the electricity comes from the European mix.

Even when the electricity is generated in a coal fired power plant, the BEV will emit less than a comparable ICE vehicle. This difference is very limited. The emission reduction could be even higher when a gas fired power plant is used (figure 7.2).
The differences in lifecycle costs between a BEV and an ICE vehicle is substantial (figure 6.10 and 6.11). This difference is caused by the high retail price of a BEV. Even with lower M & R costs, lower fuel costs and a longer lifetime of the vehicle the BEV is still more expensive during the lifetime of the vehicle. The only BEV that can compete with the ICE vehicles in the same segment is the Nissan Leaf. The taxed lifecycle costs of the Nissan Leaf are €0.37/km, the same as the VW Golf petrol. In the A class the BEVs can not compete with the ICE vehicles due to the high retail price. The Peugeot 107 has the lowest lifecycle costs of all vehicles, only €0.20/km. The lowest lifecycle costs of the BEVs in the A class are those of the Smart Fortwo electric. The lifecycle costs are €0.38/km, almost twice as high as the Peugeot 107. In the Netherlands the road and vehicle taxes are based on the emission of the vehicle. Low emission vehicles have no road taxes and also no vehicle tax (BPM). Not only the owners of a BEV benefit from this tax regime but also owners of a few ICE vehicles in the A class do not have to pay these taxes. When looking at the untaxed lifecycle costs in the A class (figure 6.8 and 6.9) the difference between the BEVs and the ICE vehicles is larger than the difference between the taxed lifecycle costs. The Nissan Leaf and Ford focus electric benefit from the tax regime. Owners of the other vehicles in the C class still have to pay road and vehicle taxes. The Nissan Leaf can not compete on untaxed lifecycle costs with the other vehicles in the C-class but due to the tax regime it has similar taxed lifecycle costs.
The battery price has a considerable impact on the retail price of a BEV. It is expected that the price of the batteries will go down if they are produced on a large scale. The same effect is expected when the BEV is produced on a large scale. The BEV will always be more expensive than the ICE vehicle because of the battery pack. The difference in retail price can be reduced to the price of a battery pack (Delucchi 2000). In figure 7.3 it is shown that the BEV can have a 50% higher retail price than a comparable ICE vehicle to have the same lifecycle costs.

8.3 City vehicles

The total tractive effort of a vehicle (total power delivered to the wheels) is the sum of the drag resistance, the roll resistance and the accerational force. The simulation of the tractive effort during the NEDC in excel (figure 6.5) shows that during the urban driving cycle the accelerational force is most dominant followed by the roll resistance. When driving the extra urban driving cycle with higher velocities the drag resistance becomes the dominant power. Reducing the drag resistance of a vehicle is therefore only useful when most of the driving takes place on highway circumstances with higher velocities. Vehicles used in city circumstances with low velocities benefit most when low resistance tyres are applied and the weight is reduced. The BEVs coming on the market are all equipped with low resistance tyres which is more benifitial when driving under urban circumstances.
The efficiency of a ICE vehicle is higher at the extra urban part of the NEDC where the efficiency of a BEV is equal or even lower at the extra urban driving cycle (Weiss et al. 2000). The efficiency losses of an ICE vehicle are larger during the urban part of the cycle because of frequent gear shifting when accelerating. Also when the engine operates at different velocities the engine efficiency goes down. At suburban circumstances with higher and constant velocities the ICE efficiency is the highest (EARPA 2003). The BEV does not require more than one gear and has no efficiency losses during acceleration and deceleration. Instead the BEV uses regenerative braking and stores energy during deceleration.
The efficiency and energy gains are larger when driving a BEV in the city than at the highway compared to a ICE vehicle.

One can conclude from the above that the BEVs appearing on the market the next years are more suited for driving small distances in urban circumstances. The energy and efficiency gains compared to the ICE vehicle are larger in cities than on the highway. Also the energy use goes up with higher velocities, reducing the total distance that can be driven on one battery charge.

8.4 General conclusions

The potential of the BEV in reducing the primary energy consumption and emissions caused by the road transport is very high. The potential of the BEV is dependent on the future source of electricity charged into the car. A high percentage of renewable energy in the European electricity mix will make the BEV a very clean and highly efficient alternative to the ICE vehicle.

The BEV will most likely remain a niche market the next decade as the high retail price will hold back consumers. After 2020, when the lithium-ion batteries are produced on a large scale, the lifecycle costs of a BEV can be lower than a comparable ICE vehicle. By then the success of the BEV will not only depend on the retail price but also on the charging infrastructure and the possibility of driving long distances.

8.5 Recommendations

A few conditions have to be met to accompany a successful commercialisation of the BEV. The Dutch government made a prognoses about the number of plug-in EVs and BEVs in the year 2020 and 2025 (Eurlings 2009). The prediction for the year 2020 is 200,000 electric vehicles and 1,000,000 in the year 2025 in the Netherlands. To achieve these optimistic numbers the retail price of a BEV have to be reduced significantly and a good infrastructure for charging have to be made.

The emission reduction potential and primary energy savings that can be achieved by introducing the BEV is dependent on the amount of renewable energy produced. Therefore a lot of effort has to be put into producing more renewable energy, like wind and solar energy. This should be promoted by the government with tax incentives to make clean energy cost competitive with energy from fossil fuels.

To reduce the retail price of a BEV the production of such vehicles should go up. When the BEV is mass produced the cost will go down. This also the case for the battery packs when being mass produced. To stimulate the sales of BEVs governments should give incentives to companies and consumers.

The infrastructure for charging a BEVs is still very limited. The next decade the infrastructure should be extended drastically. To make fast charging possible more research has to be done on grid capacity and the battery technology. Also standardisation has to take place on the charging infrastructure. Car manufacturers should standardise the way the battery is charged in the vehicle.

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Abbreviations

AC - Alternate Current
BEV - Battery Electric Vehicle
BLDC - Brushless Direct Current
DC - Direct Current
ECM Electronically commutated motor
EES - Electrochemical Energy Storage
EMF - Electro-Motive Force
EV - Electric Vehicle
HEV - Hybrid Electric Vehicle
ICE - Internal Combustion Engine
IM - Induction Motor
LiCoO - Lithium Cobalt Oxide (battery)
$LiFePO_4$ - Lithium Iron Phosphate (battery)
$LiMn_2O_4$ - Lithium Manganese Dioxide (battery)
$LiSO_2$ - Lithium Sulphur Dioxide (battery)
$Li\text{-}SOCl_2$ - Lithium Thionyl Chloride (battery)
LiTiO - Lithium Titanate Oxide (battery)
$NaNiCl_2$ - Sodium Nickel Chloride (battery)
Ni-MH - Nickel Metal Hydride (battery)
Ni-Ca - Nickel Cadmium (battery)
Ni-Fe - Nickel Iron (battery)
Ni-Zn - Nickel Zinc (battery)
NG - Natural Gas
PDU - Power Distribution Unit
PM - Permanent Magnet
RPM - Revolutions per Minute
SRM - Switched Reluctance Motor
T-T-W - Tank-To-Wheel
VCU - Vehicle Control Unit
VRLA - Valve Regulated Lead Acid (battery)
UDDS - Urban Dynamometer Driving Schedule
USABC - United States Advanced Battery Consortium
USCAR - United States Council for Automotive Research
W-T-T - Well-To-Tank
W-T-W - Well-To-Wheel

Appendix A

Velocity data sheet NEDC in m/s with 1 second intervals (data points from top to bottom, left to right)

0.00	0.00	0.00	13.89	0.00	0.00	1.85	13.37	0.00	0.00	4.31	11.81
0.00	0.83	0.00	13.89	0.00	0.00	0.93	13.89	0.00	0.00	3.54	12.33
0.00	1.67	0.00	13.89	0.00	0.00	0.00	13.89	0.00	0.00	2.78	12.85
0.00	2.50	0.00	13.89	0.00	0.00	0.00	13.89	0.00	0.00	1.85	13.37
0.00	3.33	0.00	13.89	0.00	0.83	0.00	13.89	0.00	0.00	0.93	13.89
0.00	4.17	0.00	13.89	0.00	1.67	0.00	13.89	0.00	0.00	0.00	13.89
0.00	4.17	0.00	13.89	0.00	2.50	0.00	13.89	0.00	0.00	0.00	13.89
0.00	4.17	0.00	13.89	0.00	3.33	0.00	13.89	0.00	0.83	0.00	13.89
0.00	5.11	0.00	13.89	0.00	4.17	0.00	13.89	0.00	1.67	0.00	13.89
0.00	6.06	0.00	13.89	0.00	4.17	0.00	13.89	0.00	2.50	0.00	13.89
0.00	7.00	0.00	13.89	0.00	4.17	0.00	13.89	0.00	3.33	0.00	13.89
1.04	7.94	0.00	13.37	0.00	5.11	0.00	13.89	0.00	4.17	0.00	13.89
2.08	8.89	0.00	12.85	0.00	6.06	0.00	13.89	0.00	4.17	0.00	13.89
2.85	8.89	0.00	12.33	0.00	7.00	0.00	13.89	0.00	4.17	0.00	13.89
4.17	8.89	0.00	11.81	1.04	7.94	0.00	13.37	0.00	5.11	0.00	13.89
4.17	8.89	0.00	11.28	2.08	8.89	0.00	12.85	0.00	6.06	0.00	13.89
4.17	8.89	0.00	10.76	2.85	8.89	0.00	12.33	0.00	7.00	0.00	13.89
4.17	8.89	0.00	10.24	4.17	8.89	0.00	11.81	1.04	7.94	0.00	13.37
4.17	8.89	0.00	9.72	4.17	8.89	0.00	11.28	2.08	8.89	0.00	12.85
4.17	8.89	0.00	9.72	4.17	8.89	0.00	10.76	2.85	8.89	0.00	12.33
4.17	8.89	0.00	9.72	4.17	8.89	0.00	10.24	4.17	8.89	0.00	11.81
4.17	8.89	0.83	9.72	4.17	8.89	0.00	9.72	4.17	8.89	0.00	11.28
4.17	8.89	1.67	9.72	4.17	8.89	0.00	9.72	4.17	8.89	0.00	10.76
3.47	8.89	2.50	9.72	4.17	8.89	0.00	9.72	4.17	8.89	0.00	10.24
2.78	8.89	3.33	9.72	4.17	8.89	0.83	9.72	4.17	8.89	0.00	9.72
1.85	8.89	4.17	9.72	4.17	8.89	1.67	9.72	4.17	8.89	0.00	9.72
0.93	8.89	4.17	9.72	3.47	8.89	2.50	9.72	4.17	8.89	0.00	9.72
0.00	8.89	4.17	9.72	2.78	8.89	3.33	9.72	4.17	8.89	0.83	9.72
0.00	8.89	4.78	9.72	1.85	8.89	4.17	9.72	4.17	8.89	1.67	9.72
0.00	8.89	5.40	9.72	0.93	8.89	4.17	9.72	3.47	8.89	2.50	9.72
0.00	8.89	6.02	9.72	0.00	8.89	4.17	9.72	2.78	8.89	3.33	9.72
0.00	8.89	6.64	9.72	0.00	8.89	4.78	9.72	1.85	8.89	4.17	9.72
0.00	8.89	7.25	9.31	0.00	8.89	5.40	9.72	0.93	8.89	4.17	9.72
0.00	8.89	7.87	8.89	0.00	8.89	6.02	9.72	0.00	8.89	4.17	9.72
0.00	8.89	8.49	8.02	0.00	8.89	6.64	9.72	0.00	8.89	4.78	9.72
0.00	8.89	9.10	7.14	0.00	8.89	7.25	9.31	0.00	8.89	5.40	9.72
0.00	8.89	9.72	6.27	0.00	8.89	7.87	8.89	0.00	8.89	6.02	9.72
0.00	8.13	9.72	5.40	0.00	8.89	8.49	8.02	0.00	8.89	6.64	9.72
0.00	7.36	9.72	4.52	0.00	8.89	9.10	7.14	0.00	8.89	7.25	9.31
0.00	6.60	10.24	3.65	0.00	8.89	9.72	6.27	0.00	8.89	7.87	8.89
0.00	5.83	10.76	2.78	0.00	8.13	9.72	5.40	0.00	8.89	8.49	8.02
0.00	5.07	11.28	1.85	0.00	7.36	9.72	4.52	0.00	8.89	9.10	7.14
0.00	4.31	11.81	0.93	0.00	6.60	10.24	3.65	0.00	8.89	9.72	6.27
0.00	3.54	12.33	0.00	0.00	5.83	10.76	2.78	0.00	8.13	9.72	5.40
0.00	2.78	12.85	0.00	0.00	5.07	11.28	1.85	0.00	7.36	9.72	4.52
0.00	1.85	13.37	0.00	0.00	4.31	11.81	0.93	0.00	6.60	10.24	3.65
0.00	0.93	13.89	0.00	0.00	3.54	12.33	0.00	0.00	5.83	10.76	2.78
0.00	0.00	13.89	0.00	0.00	2.78	12.85	0.00	0.00	5.07	11.28	1.85

0.93	0.00	0.00	13.89	0.00	19.44	13.89	13.89	19.44	27.06	33.33	0.00
0.00	0.00	0.00	13.89	0.00	19.44	13.89	13.89	19.44	27.30	33.33	0.00
0.00	0.00	0.00	13.37	0.00	19.44	13.89	13.89	19.44	27.54	33.33	0.00
0.00	0.00	0.00	12.85	0.00	19.44	13.89	13.89	19.44	27.78	33.33	0.00
0.00	0.83	0.00	12.33	0.00	19.44	13.89	13.89	19.44	27.78	33.33	0.00
0.00	1.67	0.00	11.81	0.00	19.44	13.89	13.89	19.44	27.78	33.33	0.00
0.00	2.50	0.00	11.28	0.00	19.44	13.89	13.89	19.44	27.78	33.33	0.00
0.00	3.33	0.00	10.76	0.00	19.44	13.89	13.89	19.44	27.78	33.33	0.00
0.00	4.17	0.00	10.24	0.83	19.44	13.89	13.89	19.44	27.78	33.33	0.00
0.00	4.17	0.00	9.72	1.67	19.44	13.89	13.89	19.44	27.78	33.33	0.00
0.00	4.17	0.00	9.72	2.50	19.44	13.89	13.89	19.44	27.78	32.64	
0.00	5.11	0.00	9.72	3.33	19.44	13.89	13.89	19.44	27.78	31.94	
0.00	6.06	0.00	9.72	4.17	19.44	13.89	13.89	19.44	27.78	31.25	
0.00	7.00	0.00	9.72	4.17	19.44	13.89	13.89	19.44	27.78	30.56	
0.00	7.94	0.00	9.72	4.17	19.44	13.89	14.32	19.44	27.78	29.86	
0.00	8.89	0.00	9.72	4.78	19.44	13.89	14.74	19.44	27.78	29.17	
0.00	8.89	0.00	9.72	5.40	19.44	13.89	15.17	19.44	27.78	28.47	
0.00	8.89	0.00	9.72	6.02	19.44	13.89	15.60	19.44	27.78	27.78	
0.00	8.89	0.83	9.72	6.64	19.44	13.89	16.03	19.44	27.78	27.08	
0.00	8.89	1.67	9.72	7.25	19.44	13.89	16.45	19.44	27.78	26.39	
1.04	8.89	2.50	9.72	7.87	19.44	13.89	16.88	19.44	27.78	25.69	
2.08	8.89	3.33	9.72	8.49	19.44	13.89	17.31	19.44	27.78	25.00	
2.85	8.89	4.17	9.72	9.10	19.44	13.89	17.74	19.44	27.78	24.31	
4.17	8.89	4.17	9.31	9.72	19.44	13.89	18.16	19.68	27.78	23.61	
4.17	8.89	4.17	8.89	9.72	19.44	13.89	18.59	19.92	27.78	22.92	
4.17	8.89	4.78	8.02	9.72	19.44	13.89	19.02	20.16	27.78	22.22	
4.17	8.89	5.40	7.14	10.24	19.44	13.89	19.44	20.40	27.78	21.18	
4.17	8.89	6.02	6.27	10.76	19.44	13.89	19.44	20.63	27.78	20.14	
4.17	8.89	6.64	5.40	11.28	19.44	13.89	19.44	20.87	27.78	19.10	
4.17	8.89	7.25	4.52	11.81	19.44	13.89	19.44	21.11	27.78	18.06	
4.17	8.89	7.87	3.65	12.33	19.44	13.89	19.44	21.35	27.78	17.01	
4.17	8.89	8.49	2.78	12.85	19.44	13.89	19.44	21.59	27.78	15.97	
3.47	8.89	9.10	1.85	13.37	19.44	13.89	19.44	21.83	27.78	14.93	
2.78	8.89	9.72	0.93	13.89	19.44	13.89	19.44	22.06	27.78	13.89	
1.85	8.89	9.72	0.00	13.89	19.44	13.89	19.44	22.30	28.06	12.50	
0.93	8.89	9.72	0.00	13.89	19.44	13.89	19.44	22.54	28.33	11.11	
0.00	8.89	10.24	0.00	14.32	19.44	13.89	19.44	22.78	28.61	9.72	
0.00	8.89	10.76	0.00	14.74	19.44	13.89	19.44	23.02	28.89	8.33	
0.00	8.89	11.28	0.00	15.17	19.44	13.89	19.44	23.25	29.17	6.94	
0.00	8.89	11.81	0.00	15.60	19.44	13.89	19.44	23.49	29.44	5.56	
0.00	8.13	12.33	0.00	16.03	19.44	13.89	19.44	23.73	29.72	4.17	
0.00	7.36	12.85	0.00	16.45	19.44	13.89	19.44	23.97	30.00	2.78	
0.00	6.60	13.37	0.00	16.88	19.44	13.89	19.44	24.21	30.28	1.39	
0.00	5.83	13.89	0.00	17.31	19.44	13.89	19.44	24.44	30.56	0.00	
0.00	5.07	13.89	0.00	17.74	19.44	13.89	19.44	24.68	30.83	0.00	
0.00	4.31	13.89	0.00	18.16	18.75	13.89	19.44	24.92	31.11	0.00	
0.00	3.54	13.89	0.00	18.59	18.06	13.89	19.44	25.16	31.39	0.00	
0.00	2.78	13.89	0.00	19.02	17.36	13.89	19.44	25.40	31.67	0.00	
0.00	1.85	13.89	0.00	19.44	16.67	13.89	19.44	25.63	31.94	0.00	
0.00	0.93	13.89	0.00	19.44	15.97	13.89	19.44	25.87	32.22	0.00	
0.00	0.00	13.89	0.00	19.44	15.28	13.89	19.44	26.11	32.50	0.00	
0.00	0.00	13.89	0.00	19.44	14.58	13.89	19.44	26.35	32.78	0.00	
0.00	0.00	13.89	0.00	19.44	13.89	13.89	19.44	26.59	33.06	0.00	
0.00	0.00	13.89	0.00	19.44	13.89	13.89	19.44	26.83	33.33	0.00	

Velocity data sheet UDDS (USLA4) in m/s with 1 second intervals (data points from top to bottom, left to right)

0.00	10.15	13.19	0.00	16.18	25.26	22.40	0.00	6.48	0.00	15.47	11.44	7.42	0.00	0.00
0.00	10.10	13.32	0.00	16.67	25.26	22.35	0.00	5.36	0.00	15.42	11.27	7.38	0.00	0.00
0.00	9.52	13.55	0.00	17.57	25.26	22.17	0.00	3.89	0.00	14.98	11.18	7.38	0.00	0.00
0.00	8.49	13.72	0.00	18.11	25.21	22.13	0.00	2.41	0.00	14.31	11.18	7.42	0.00	0.00
0.00	7.64	13.81	0.00	18.82	25.08	22.13	0.45	0.94	0.00	13.46	11.18	7.60	0.00	0.00
0.00	7.06	13.86	0.00	19.45	24.94	22.13	1.92	0.00	0.00	12.52	10.91	7.87	0.00	0.00
0.00	7.06	13.81	0.00	20.16	24.63	21.95	3.40	0.00	0.00	11.40	10.33	8.27	0.00	0.00
0.00	7.91	13.59	0.00	20.56	24.41	21.73	4.87	0.00	1.48	10.06	8.85	8.58	0.00	0.00
0.00	8.85	13.32	0.00	20.92	24.23	21.50	6.35	0.00	2.95	8.85	7.38	9.03	0.00	0.63
0.00	9.66	13.37	0.00	21.23	24.14	21.10	7.73	0.00	4.42	7.38	5.90	9.39	0.89	1.48
0.00	10.37	13.50	0.00	21.23	24.01	20.61	8.94	0.00	5.90	5.90	4.42	9.43	2.01	1.97
0.00	10.82	13.72	0.00	21.14	23.96	20.12	10.06	1.16	7.38	4.60	2.95	9.48	3.49	2.91
0.00	11.00	13.95	0.00	21.10	24.10	19.58	10.59	2.64	8.85	3.22	1.48	9.66	4.56	4.11
0.00	11.13	14.22	0.00	21.01	24.14	19.04	11.27	4.11	10.33	1.79	0.00	9.83	5.59	5.05
0.00	11.18	14.39	0.00	21.01	24.18	18.55	11.89	5.59	11.80	0.45	0.00	10.01	6.26	6.04
0.00	11.00	14.48	0.00	21.01	24.18	18.02	12.56	7.06	12.43	0.00	0.00	10.06	6.84	6.53
0.00	10.95	14.39	0.00	21.01	24.05	17.21	13.41	8.54	13.01	0.00	0.00	10.06	7.82	7.33
0.00	11.04	14.17	1.48	21.01	23.87	16.54	13.77	10.01	14.08	0.00	0.00	10.06	8.76	7.47
0.00	11.09	12.79	2.95	21.10	23.69	15.74	14.13	11.18	14.75	0.00	0.00	10.15	9.39	7.38
0.00	11.04	11.31	4.42	21.19	23.51	15.11	14.35	11.44	15.02	0.00	0.00	10.59	9.92	7.38
0.00	11.00	9.83	5.90	21.41	23.29	14.53	14.66	12.29	15.56	0.00	0.00	11.22	10.42	8.14
1.34	11.00	8.36	7.38	21.68	23.42	14.08	15.02	12.96	15.69	0.54	0.00	11.62	10.95	8.58
2.64	11.22	6.88	8.85	21.95	23.25	13.68	15.42	13.41	15.91	1.56	0.00	11.85	11.31	8.99
3.84	11.44	5.41	9.92	22.13	23.20	13.63	15.47	13.46	16.14	2.46	0.00	12.07	11.44	9.61
5.14	11.49	3.93	10.86	22.35	23.11	13.41	15.60	13.41	16.09	2.91	0.00	11.67	11.62	10.06
6.39	11.35	2.46	11.53	22.62	23.02	12.96	15.56	13.28	16.14	3.80	0.00	10.19	11.67	10.06
7.55	11.13	0.98	11.80	22.80	23.07	12.29	15.42	13.10	16.18	4.29	0.00	8.72	11.71	9.88
7.73	11.18	0.00	11.49	23.02	23.02	11.09	15.51	12.87	16.09	4.69	0.00	7.24	11.71	10.15
8.09	11.35	0.00	11.22	23.34	23.60	9.61	15.87	12.52	15.96	5.32	0.00	5.77	11.80	10.42
9.25	11.62	0.00	11.04	23.78	23.29	8.99	16.09	11.18	16.09	6.26	0.00	4.29	11.85	10.51
9.70	11.62	0.00	11.18	24.18	23.92	8.54	16.09	9.70	16.09	7.15	1.48	2.82	11.85	10.06
10.01	11.49	0.00	11.27	24.41	23.92	8.27	16.09	8.23	15.91	7.91	2.95	1.34	11.62	9.66
10.06	11.67	0.00	11.35	24.54	24.14	7.60	16.09	6.75	15.87	8.49	4.42	0.00	11.40	9.16
9.88	11.94	0.00	11.53	24.59	24.54	6.93	16.09	5.28	15.83	8.99	5.81	0.00	10.55	8.05
9.61	12.29	0.00	12.16	24.54	24.77	5.59	16.09	3.80	15.74	9.39	6.53	0.00	9.57	6.71
9.34	12.79	0.00	11.85	24.41	24.86	4.83	16.14	2.32	15.74	9.83	7.15	0.00	8.27	5.36
9.12	13.10	0.00	10.73	24.41	25.03	3.58	16.27	0.85	15.74	10.28	7.60	0.00	7.33	4.02
8.85	13.32	0.00	10.15	24.50	25.03	2.10	16.32	0.00	15.74	10.64	7.60	0.00	6.48	2.77
7.60	13.46	0.00	8.67	24.63	24.94	0.63	16.27	0.00	15.74	10.95	7.60	0.00	5.19	2.01
6.66	13.59	0.00	7.91	24.81	24.68	0.00	16.09	0.00	15.74	11.13	7.82	0.00	3.89	1.34
6.66	13.72	0.00	7.69	24.90	24.36	0.00	15.69	0.00	15.65	11.18	7.91	0.00	2.59	0.94
6.80	13.72	0.00	8.09	25.08	23.96	0.00	15.24	0.00	15.69	11.18	7.91	0.00	1.56	0.22
6.93	13.63	0.00	8.31	25.17	23.47	0.00	14.98	0.00	15.74	11.18	7.82	0.00	0.89	0.22
7.15	13.59	0.00	8.94	25.30	23.02	0.00	14.04	0.00	15.87	11.18	7.60	0.00	0.00	1.43
7.64	13.55	0.00	9.92	25.35	23.02	0.00	12.96	0.00	15.74	11.18	7.55	0.00	0.00	2.91
8.54	13.59	0.00	10.95	25.35	23.02	0.00	11.49	0.00	15.65	11.18	7.42	0.00	0.00	4.29
9.43	13.77	0.00	12.20	25.26	22.84	0.00	10.28	0.00	15.65	11.44	7.60	0.00	0.00	5.59
10.15	13.59	0.00	13.63	25.26	22.40	0.00	9.07	0.00	15.65	11.53	7.64	0.00	0.00	6.26
10.24	13.37	0.00	14.98	25.26	22.35	0.00	7.82	0.00	15.56	11.62	7.60	0.00	0.00	7.15

8.05	12.65	9.34	12.52	7.55	11.40	8.27	9.39	0.00	9.75	9.92	0.00
8.76	12.65	9.57	12.38	6.08	11.44	8.94	9.48	0.00	9.83	10.28	0.00
9.61	12.61	9.83	12.25	4.60	11.40	9.75	9.52	0.94	9.79	10.55	0.00
10.33	12.34	10.10	12.03	3.13	11.18	10.28	9.57	2.41	9.70	10.77	0.00
10.95	12.29	10.37	11.89	1.65	10.77	10.73	9.70	3.89	9.61	10.95	0.00
11.40	12.29	10.73	11.85	0.18	10.59	11.09	10.06	5.36	9.61	10.95	0.00
11.85	12.29	11.18	11.85	0.00	10.37	11.44	10.28	6.84	9.57	10.73	0.00
12.11	12.29	11.62	11.85	0.00	10.24	11.85	10.64	8.31	8.99	10.51	0.00
12.34	12.29	11.89	11.76	0.00	10.06	11.98	10.95	9.43	8.72	10.51	0.00
12.47	12.29	11.89	11.71	0.89	9.83	12.25	11.18	10.28	8.58	10.51	0.67
12.65	12.34	11.98	11.71	2.24	9.66	12.47	11.13	10.51	8.76	10.51	2.15
12.79	12.52	12.07	11.58	3.84	9.16	12.65	11.09	10.28	8.85	10.51	3.62
12.79	12.74	12.16	11.44	5.32	7.82	12.52	11.18	10.06	8.94	10.51	4.96
12.65	13.41	12.43	11.44	6.80	6.35	12.29	11.35	8.94	8.72	10.73	5.99
12.61	13.86	12.56	11.58	7.82	4.87	12.07	11.53	7.47	7.82	10.77	6.80
12.52	14.31	12.87	11.53	8.31	3.40	12.07	11.62	5.99	6.93	10.95	7.20
12.29	14.75	12.92	11.40	8.94	1.92	11.76	11.80	4.52	5.81	11.04	8.40
11.98	14.75	12.96	11.00	9.43	0.45	10.95	11.89	3.04	4.47	11.18	8.63
11.40	15.02	13.01	10.51	9.83	0.00	10.06	12.03	1.56	3.58	11.35	9.16
10.51	15.20	12.96	9.92	10.28	0.00	9.61	12.07	0.09	2.68	11.44	9.52
9.61	15.33	12.56	9.66	10.95	0.00	9.21	12.07	0.00	1.79	11.49	9.52
8.49	15.29	12.29	9.66	11.76	0.00	8.05	12.07	0.00	1.12	11.62	10.24
7.38	15.20	12.07	9.70	12.29	0.00	6.71	12.03	0.00	0.31	11.71	10.01
6.66	15.20	11.53	10.10	12.56	0.00	5.50	11.98	0.00	0.00	12.07	9.83
5.59	15.15	11.18	10.46	12.70	0.00	4.96	11.98	0.00	0.00	12.87	9.66
4.20	15.02	10.95	10.73	12.74	0.00	4.74	11.85	0.00	0.00	12.20	9.43
2.77	14.80	11.09	10.82	12.74	0.00	4.47	11.80	0.00	0.00	12.96	9.16
1.34	14.75	11.22	10.91	12.74	0.00	4.25	11.62	0.00	0.00	13.01	8.94
0.67	14.53	11.40	11.13	12.38	0.00	4.07	11.40	0.00	0.00	12.96	8.76
0.67	14.31	11.49	11.22	12.29	0.00	3.89	11.00	0.00	0.00	12.52	8.27
0.22	14.26	11.71	11.27	12.16	0.00	3.84	10.51	0.09	0.00	11.04	7.82
0.00	14.13	12.03	11.31	11.98	0.00	3.93	9.61	0.67	0.45	9.57	7.38
1.34	14.08	12.29	11.40	11.85	0.00	4.02	8.94	1.56	0.45	8.09	6.93
2.82	13.68	12.43	11.27	11.62	0.00	3.89	7.82	2.91	0.45	6.62	6.26
4.29	13.41	12.70	11.18	11.49	0.00	3.84	7.15	4.38	0.45	5.14	4.92
5.77	13.37	12.96	11.18	11.27	0.00	3.58	6.26	5.36	0.45	3.67	3.58
7.06	13.37	13.05	11.18	10.73	0.00	3.13	4.78	5.77	0.72	2.19	2.32
7.82	13.37	13.01	11.04	9.83	0.00	2.24	3.31	5.81	1.34	0.72	1.12
8.23	13.37	12.96	10.95	9.61	0.00	1.88	1.83	5.63	1.79	0.00	0.00
8.72	13.23	12.92	10.86	9.61	0.00	1.16	0.36	5.72	2.24	0.00	0.00
9.25	13.19	12.74	10.86	9.75	0.00	0.45	0.00	5.86	2.82	0.00	0.00
9.83	13.19	12.56	10.95	10.06	0.00	0.00	0.00	5.86	3.58	0.00	0.00
10.37	13.10	12.52	11.18	10.28	0.00	0.04	0.00	6.26	4.47	0.00	0.00
11.18	12.92	12.52	11.18	10.19	0.00	0.27	0.00	6.93	4.69	0.00	0.00
11.85	12.61	12.34	11.00	10.19	0.00	0.72	0.00	7.60	4.25	0.00	
12.29	12.38	12.16	11.00	10.28	0.00	1.61	0.00	8.31	3.80	0.00	
12.52	12.07	11.89	10.77	10.15	0.00	3.08	0.00	8.81	3.40	0.00	
12.65	11.40	12.07	10.95	10.15	0.00	4.47	0.00	9.39	3.93	0.00	
12.92	10.59	12.29	11.22	10.15	0.54	5.72	0.00	9.61	4.92	0.00	
12.92	9.83	12.43	11.44	10.51	1.79	6.26	0.00	9.75	6.26	0.00	
12.92	9.16	12.52	11.22	10.73	3.26	6.48	0.00	9.75	7.60	0.00	
12.87	8.58	12.43	10.73	11.00	4.74	7.15	0.00	9.61	8.72	0.00	
12.74	8.58	12.52	9.83	11.09	6.21	8.09	0.00	9.48	9.39	0.00	
12.65	8.99	12.52	8.99	11.22	7.60	8.94	0.00	9.61	9.75	0.00	

Appendix B

Tabulated results

Table 1: W-T-W energy efficiencies

	W-T-T efficiency	T-T-W efficiency	W-T-W efficiency
A-segment			
Smart Fortwo (diesel)	87.6%	28.7%	25.1%
Smart Fortwo Electric	29.1%	81.2%	23.6%
Smart Fortwo (petrol)	85.7%	24.3%	20.8%
VW Fox 1.4 (diesel)	87.6%	22.2%	19.5%
Peugeot 107 (petrol)	85.7%	22.1%	18.9%
Mitsubishi i (petrol)	85.5%	20.2%	17.2%
Mitsubishi iMiev	29.1%	84.1%	24.5%
B-segment			
Toyota Yaris (diesel)	87.6%	24.0%	21.0%
Toyota Yaris (petrol)	85.7%	19.3%	16.5%
Peugeot 207 (diesel)	87.6%	25.6%	22.4%
Peugeot 207 (petrol)	85.7%	20.3%	17.4%
C-segment			
Ford Focus (diesel)	87.6%	26.0%	22.8%
Ford Focus (petrol)	85.7%	19.5%	16.7%
Ford Focus Electric	29.1%	74.0%	21.6%
VW Golf (diesel)	87.6%	27.4%	24.0%
VW Golf (petrol)	85.7%	20.5%	17.5%
Nissan Leaf	29.1%	92.9%	27.1%

Table 2: W-T-W energy consumption

	W-T-T energy consumption (MJ/km)	T-T-W energy consumption (MJ/km)	W-T-W energy consumption (MJ/km)
A-segment			
Smart Fortwo (diesel)	0.17	1.22	1.40
Smart Fortwo Electric	1.05	0.43	1.48
Mitsubishi iMiev	1.10	0.45	1.55
Smart Fortwo (petrol)	0.24	1.42	1.66
Peugeot 107 (petrol)	0.25	1.49	1.74
Th!nk City	1.38	0.57	1.94
Mitsubishi i (petrol)	0.29	1.72	2.01
VW Fox 1.4 (diesel)	0.25	1.76	2.01
B-segment			
Toyota Yaris (diesel)	0.23	1.62	1.85
Peugeot 207 (diesel)	0.23	1.62	1.85
Toyota Yaris (petrol)	0.34	1.98	2.32
Peugeot 207 (petrol)	0.34	2.01	2.36
C-segment			
Nissan Leaf	1.16	0.48	1.64
VW Golf (diesel)	0.23	1.62	1.85
Ford Focus (diesel)	0.24	1.73	1.97
Ford Focus Electric	1.67	0.68	2.35
VW Golf (petrol)	0.35	2.08	2.43
Ford Focus (petrol)	0.38	2.21	2.59

Table 3: W-T-W CO_2 emissions

	W-T-T emission (g/km)	T-T-W emission (g/km)	W-T-W emission (g/km)
A-segment			
Smart Fortwo (diesel)	16	88	104
Smart Fortwo Electric	62	0	62
Smart Fortwo (petrol)	18	103	121
VW Fox 1.4 (diesel)	23	130	153
Peugeot 107 (petrol)	18	106	124
Mitsubishi i (petrol)	21	114	135
Mitsubishi iMiev	65	0	65
Th!nk City	82	0	82
B-segment			
Toyota Yaris (diesel)	21	119	140
Toyota Yaris (petrol)	25	141	166
Peugeot 207 (diesel)	21	120	141
Peugeot 207 (petrol)	25	145	170
C-segment			
Ford Focus (diesel)	22	127	149
Ford Focus (petrol)	28	159	187
Ford Focus Electric	99	0	99
VW Golf (diesel)	21	119	140
VW Golf (petrol)	26	149	175
Nissan Leaf	69	0	69

Table 4: Taxed Lifecycle costs

	Depreciation	M & R	Fixed costs	Fuel costs	Total costs (€/km)
A-segment					
Peugeot 107 (petrol)	0.06	0.04	0.04	0.07	0.20
Smart Fortwo (petrol)	0.07	0.05	0.04	0.06	0.22
Smart Fortwo (diesel)	0.08	0.06	0.05	0.04	0.23
Mitsubishi i (petrol)	0.07	0.04	0.06	0.08	0.25
VW Fox 1.4 (diesel)	0.09	0.05	0.11	0.05	0.31
Smart Fortwo Electric	0.22	0.04	0.09	0.03	0.38
Th!nk City	0.22	0.06	0.09	0.04	0.40
Mitsubishi iMiev	0.25	0.05	0.09	0.03	0.42
B-segment					
Toyota Yaris (diesel)	0.14	0.06	0.11	0.05	0.36
Toyota Yaris (petrol)	0.10	0.05	0.07	0.09	0.31
Peugeot 207 (diesel)	0.13	0.06	0.13	0.05	0.37
Peugeot 207 (petrol)	0.11	0.05	0.08	0.09	0.33
C-segment					
VW Golf (petrol)	0.13	0.05	0.09	0.09	0.37
Nissan Leaf	0.19	0.06	0.08	0.04	0.37
Ford Focus (petrol)	0.13	0.06	0.09	0.10	0.38
VW Golf (diesel)	0.16	0.06	0.14	0.05	0.42
Ford Focus (diesel)	0.15	0.07	0.14	0.05	0.42
Ford Focus Electric	0.30	0.06	0.11	0.05	0.53

Table 5: Untaxed Lifecycle costs

	Depreciation	M & R	Fixed costs	Fuel costs	Total costs (€/km)
A-segment					
Peugeot 107 (petrol)	0.05	0.03	0.03	0.02	0.14
Smart Fortwo (petrol)	0.05	0.04	0.03	0.03	0.15
Smart Fortwo (diesel)	0.06	0.04	0.03	0.02	0.15
Mitsubishi i (petrol)	0.06	0.05	0.04	0.02	0.17
VW Fox 1.4 (diesel)	0.07	0.05	0.04	0.02	0.17
Smart Fortwo Electric	0.19	0.04	0.07	0.01	0.31
Th!nk City	0.19	0.05	0.07	0.02	0.32
Mitsubishi iMiev	0.21	0.04	0.08	0.01	0.34
B-segment					
Toyota Yaris (diesel)	0.09	0.05	0.05	0.02	0.21
Toyota Yaris (petrol)	0.07	0.04	0.04	0.03	0.18
Peugeot 207 (diesel)	0.08	0.05	0.05	0.02	0.20
Peugeot 207 (petrol)	0.07	0.04	0.04	0.03	0.19
C-segment					
VW Golf (petrol)	0.09	0.05	0.04	0.03	0.21
Ford Focus (petrol)	0.09	0.05	0.04	0.04	0.22
Ford Focus (diesel)	0.10	0.05	0.05	0.02	0.23
VW Golf (diesel)	0.10	0.06	0.05	0.02	0.23
Nissan Leaf	0.16	0.05	0.06	0.01	0.29
Ford Focus Electric	0.26	0.05	0.09	0.02	0.42