

**Czech Technical University Prague**  
**Faculty of Electrical Engineering**  
**Department of Electric Drives and Traction**



**Diploma Thesis**  
**Electric and Hybrid Vehicle Powertrain Comparison**

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## I. OSOBNÍ A STUDIJNÍ ÚDAJE

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## II. ÚDAJE K DIPLOMOVÉ PRÁCI

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Název diplomové práce anglicky:

**Electric and hybrid vehicle powertrains comparison**

Pokyny pro vypracování:

1. Overview of possible electric and hybrid vehicle powertrain topologies.
2. Compare its advantages and disadvantages.
3. Carry out analysis of power flow and operational modes of hybrid drive with electric and planetary gear power splitter.
4. Discuss obtained results..

Seznam doporučené literatury:

- [1] Čeřovský, Z.; Mindl, P. Efficiency of the unconventional powertrain with electric power-splitter in electric hybrid cars. In: CD International Advanced Mobility Forum 2009. Geneva: IAMF, 2009, pp. 1-7.  
[2] Čeřovský, Z.; Mindl, P. Properties of Hybrid Electric Drive with Electric Power Splitter In: The 11th International Conference on Optimization of Electrical and Electronic Equipment. Brašov: Universitate Transilvania Brašov, 2008, pp. 2-A.2F\_1-2-A.2F\_6. ISBN 1-4244-1545-4.  
[3] Kamil Bayindir, Mehmet Ali Gözükcük, Ahmet Teke: A comprehensive overview of hybrid electric vehicle: Powertrain configurations, powertrain control techniques and electronic control units In: Energy Conversion and Management 52 (2011) 1305? 1313,

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## III. PŘEVZETÍ ZADÁNÍ

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10/07/2017

Datum převzetí zadání

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## **Declaration**

I declare that I have worked on my diploma thesis titled "**Electric and Hybrid Vehicle Powertrain Comparison**" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any their person.

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**Signature**

## **Acknowledgement**

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## **Abstract**

The purpose of this study is to identify the ‘comparison between hybrid and electric vehicle’. In this it will be discussed about the types of drivetrain structures, where it will be talked about the three hybrids and their advantages and disadvantages. Moreover, it will be talked about the life cycle assessment of the three drives technologies. It will also help to understand the Well-to-Wheel analysis (Well-to-Tank and Tank-to-Wheel) and their implementation. Also, a measurement of the energy demand and emission of vehicle performance in TTW approach is considered and also the calculation of energy on the flat road. In the practical approach, the power flow and the energy efficiency of the hybrid electric vehicles will be analyzed.

And also, it will be measured the value of 0% inclination from the road through experiment. On the basis of this measured values, the calculation of further important parameters which are beneficial for the measurement of the energy efficiency of prototype of hybrid electric concept will be determined.

### **Keywords:**

CO<sub>2</sub> emission, battery options, WtW analysis, TtW approach, Energy Efficiency, energy demand, EU-Mix, HEV-CVUT, electric power splitter, GHG emission.

## **Abstrakt**

Účelem této studie je identifikovat "srovnání hybridního a elektrického vozidla". V této práci se bude diskutovat o typech hnacích konstrukcí, také o třech hybridech a o jejich výhodách a nevýhodách. Dále se zde bude hovořit o hodnocení životního cyklu tří technologií pohonů. To všechno pomůže porozumět analýze "Well-to-Wheel" (Well-to-Tank a Tank-to-Wheel) a jejich implementaci. Dále zde bude uvedeno měření energetické náročnosti a emisí vozidel při přístupu TTW, a také výpočet energie na ploché cestě. V praktickém přístupu bude analyzován tok výkonu a energetická účinnost hybridních elektrických vozidel.

V experimentální části bude měřena hodnota sklonu 0% ze silnice. Na základě těchto naměřených hodnot bude určen výpočet dalších důležitých parametrů, které jsou přínosné pro měření energetické účinnosti prototypu hybridní elektrické koncepce.

## **Klíčová slova:**

Emise CO<sub>2</sub>, možnosti baterií, analýza WTW, přístup TTW, energetická účinnost, poptávka po energii, EU-Mix, HEV-CVUT, rozdělovač elektrické energie, emise skleníkových plynů

# Table of content

## *Contents*

## *List of Figures*

## *List of Tables*

<b>1. Introduction.....</b>	<b>1</b>
<b>2. Types of drivetrain structure.....</b>	<b>4</b>
2.1 Series hybrid.....	4
2.1.1 Advantages of the series hybrid configuration.....	6
2.1.2 Disadvantages of the series hybrid configuration .....	7
2.2 Parallel hybrid .....	7
2.2.1 Operation mode .....	8
2.2.2 Advantages of parallel hybrid system .....	9
2.2.3 Disadvantage of parallel hybrid system.....	10
2.3 Combined hybrid.....	10
2.3.1 Advantage of combined hybrid configuration.....	11
2.3.2 Disadvantages of combined hybrid configuration.....	11
<b>3. Plug-in hybrid vehicle (PHEV) .....</b>	<b>11</b>
3.1 Advantages of Plug-in hybrid vehicle.....	11
3.2 Disadvantages Plug-in hybrid vehicle.....	12
<b>4. Electric vehicles.....</b>	<b>12</b>
4.1 Battery electric vehicles (BEV) .....	12
4.1.1 Classification of batteries .....	15
4.1.2 Advantages of electrical vehicles .....	15
4.1.3 Disadvantages of electrical vehicles.....	16
4.2 Fuel Cell electric vehicle (FCEV).....	16
4.2.1 Advantages of FCEV.....	18
4.2.2 Disadvantages of FCEV .....	18
<b>5. Life Cycle Assessment of the three drives technologies.....</b>	<b>18</b>
5.1 Well-to-Wheel analysis (WtW).....	19
5.2 Well-to-Tank approach (WtT) .....	20
5.2.1 Primary energy sources in the WtT-approach .....	20
5.2.2 Specificity of primary energy sources for Electric Vehicle .....	22
5.3 Tank-to-Wheel approach (WtT).....	24
5.3.1. Energy density as an important parameter of efficiency .....	25
5.3.2. Efficiency comparison of the different propulsion concepts.....	27
5.3.2.1. Efficiency of the Internal Combustion Engine .....	29

5.3.2.2. Efficiency of the Battery Engine Vehicle .....	30
5.3.2.3. Efficiency of the Fuel Cell Engine Vehicle .....	31
5.4 Measurement of energy demand and emission of vehicle performance in TtW...	32
5.4.1 Reference road cycle .....	32
5.4.2 Determination of efficiency based on Vehicle Dynamics Model .....	34
5.4.2.1 Rolling resistance force .....	36
5.4.2.2 Aerodynamic drag force .....	38
5.4.2.3 Resistive gravity force .....	39
5.4.2.4 Inertia force .....	40
5.4.2.5 Calculation of energy demand on a flat road for electronic drive .....	40
5.5 Specification of energy demand and GHG emission within the WtW analysis ...	42
<b>6 Carry out analysis of power flow and operational modes of hybrid drive with electric and planetary gear power splitter .....</b>	<b>46</b>
6.1. Introduction of Hybrid Electric power divider in Hybrid electric vehicle .....	46
6.2. Aim of this experiment .....	47
6.3. HEV-CVUT concept of hybrid-electric propulsion system .....	47
6.4. Experimental setup of HEV stand .....	50
6.4.1. Calculated values 0% inclination from the road .....	55
6.4.2. Results .....	58
6.4.2.1. Energy Efficiency of Electrical part of electric power splitter ( $P_{\text{epsel}}$ ) .....	58
6.4.2.2. Energy efficiency of mechanical part of the EPS ( $P_{\text{epsmh}}$ ) .....	58
6.4.2.3. Energy efficiency of Traction motor (TM) .....	59
6.4.2.4. Energy efficiency of AC-DC power converters .....	59
6.4.2.5. Overall efficiency of HEV-CVUT .....	60
<b>7. Conclusion .....</b>	<b>60</b>
<b>Abbreviations .....</b>	<b>63</b>
<b>References .....</b>	<b>64</b>



## List of Figures:

- Figure 1.1:** An Overview of different propulsion concepts into classes.
- Figure 2.1:** Structure of series configuration
- Figure 2.2:** Structure with flywheel
- Figure 2.3:** Structure of fuel cell hybrid electric vehicle
- Figure 2.4:** Parallel hybrid structure
- Figure 2.5:** Block Diagram
- Figure 2.6:** Diverse operating mode
- Figure 2.7:** Structure of a combined hybrid electric vehicle
- Figure 4.1:** Charging of a battery
- Figure 4.2:** Discharging of a battery
- Figure 4.3:** Block Diagram of production of electricity
- Figure 5.1:** Block Diagram of Well-to-Wheel (WtW)
- Figure 5.2:** EU Energy Mix
- Figure 5.3:** Energy density of on-board energy carriers and energy sources
- Figure 5.4:** Energy density comparison of size & weight of various types of batteries
- Figure 5.5:** Gravimetric and specific energy density of various batteries and fuel cells
- Figure 5.6:** Tank-to-Wheel efficiency of different propulsion concept
- Figure 5.7:** Mechanical energy and heat loss in TtW process (only powertrain) of combustion drive and electric drive
- Figure 5.8:** Mechanical energy and heat loss in TtW process (only powertrain) of combustion drive and electric drive
- Figure 5.9:** New European Driving Cycle (NEDC) for passenger cars with speed-time relationship
- Figure 5.10:** Comparison of WLTC and NEDC road driving cycle
- Figure 5.11:** All forces acting on vehicle during the movement
- Figure 5.12:** Asymmetric contact force
- Figure 5.13:** Forces during motion
- Figure 5.14:** Pressure drag in context of aerodynamic drag force
- Figure 5.15:** Efficiency comparison of powertrain (GHGE emission, WtW energy demand); based on Daimler and WtW studies. Concave, EUCAR, JRC and JHFC
- Figure 5.16:** WtW Greenhouse Gas Emission (GHGE) and energy demand of passenger cars with the use of different fuels
- Figure 5.17:** CO<sub>2</sub> emission during whole process (WtW)
- Figure 6.1:** HVC with mechanical power divider
- Figure 6.2:** Power Flow in the configuration of HEV-CVUT
- Figure 6.3:** Electric power Divider (EPS)
- Figure 6.4:** Block Diagram of Experimental Setup
- Figure 6.5:** Experimental setup of four machines
- Figure 6.6:** Other necessary equipment in this control chamber.
- Figure 6.7:** Energy efficiency of electric part of EPS
- Figure 6.8:** Energy efficiency of TM
- Figure 6.9:** Energy efficiency of AC-DC converter

## List of Tables:

- Table 4.1:** Types of battery and its property
- Table 5.1:** Primary energy resources and automotive fuel
- Table 5.2:** Energy balance with upstream chain referring to the supply of 1 kWh
- Table 5.3:** Installed capacities and net power generation referring to type of energy source
- Table 5.4:** Comparison of NEDC and WLTP
- Table 5.5:** Typical rolling resistance coefficient  $C_r$  depend on road condition
- Table 5.6:** Total CO<sub>2</sub> emission during WtW-process in various drives technologies
- Table 6.1:** Measured values of 0%inclination of flat road
- Table 6.2:** Calculated values for 0% inclination of flat road

## **1. Introduction**

The automotive industry is in a constant state of change and is gaining momentum over the five years. For a century the automotive market was dominated by fossil fuels and combustion engines. However, the fast technological development and the increased focus on the environmental impact of drivetrain creates place and necessity for new energy sources and propulsion concepts. Electric drives play in the front rows.

The principle of Internal combustion engine (ICE) works on conventional vehicles that operates on fossil fuel such as gasoline, diesel etc. from oil deposits which are millions of years old. These vehicles emit gases such as hydrocarbon, sulphur oxide, carbon dioxide and carbon monoxide through their outer pipes. These gases are the drivers of global warming and pollution which is very dangerous and responsible for the climate change and life conditions. The daily increasing fuel consumption and increasing fuel prices cause further global problems and it is totally dependent on the number of population and number of vehicles in operation. To resolve the above mentioned issues, the car manufacturers are launching more and more new fuel efficient conventional vehicles with less carbon dioxide emission. This can be improved further by using alternative fuels such as compressed natural gas (CNG), bio-ethanol, biodiesel (is produced from rape oil and is very similar to mineral diesel), hydrogen.

At the latest with the newly launched electric models which are in series production, new key trendsetter appeared on the broader market. Over the last five years, the car manufacturers all over the world intensified their vehicle range in all car categories with electric models such i3 (BMW), Renault Zoe, Smart for four Electronic Drive (Daimler Group), Ampera (Opel), e5 300 EV (BYD, China) and Model S (Tesla, USA). The technological side is not only an indicator for this trend, so that the automotive environment could be changed radically towards electric drives. After the climate agreement in Paris of December 2015, more and more discussions take place in order to banish completely combustion engines and fossil fuels between 2025 and 2035. Although, despite the technical progress and the increasing focus on alternative drives, the electric mobility is still in its infancy. The technological transition will be a big challenge for all traditional car manufacturer and automotive suppliers who are more and more faced with the increasing competition from the Far East, especially China.

Over the last two decades, the mechanical and electrical engineers came up with many ideas for changing the primary fuel from oil to alternative fuels and efficient engine management that enhances the fuel consumption a lot respectively. An overview of different types of vehicles and its power sources is given below in Figure 1.1:

Arrangement of propulsion concepts into classes											
Combustion Engine				Hybrids				Electric Vehicle			
Diesel, Otto, optimized engine, alternative fuels, Concepts A, B, C, D				Full Hybrids, Mild Hybrids Concepts E, F				PHEV, REEV, BEV Concepts G, H, I			
Identifier	A	B	C	D	E	F	G	H	I	J	K
Drivetrain Structure	SI engine, conventional	CI engine, conventional	(HEV) Subhybrid	HEV Microhybrid	HEV Mild Hybrid	HEV Full Hybrid	PHEV Full Hybrid	PHEV Range Extender ICE	EV	PHEV Range Extender Fuel Cell	Fuel Cell Hybrid
Primary Energy Source	Hydro-carbons	Hydro-carbons	Hydro-carbons	Hydro-carbons	Hydro-carbons	Hydro-carbons	Hydro-carbons	Electricity (from grid)	Electricity (from grid)	Electricity (from grid)	Hydrogen
	Advanced, high efficiency si- and diesel technology, alternative fuels: CNG, LPG and even more		Additionally to A or B: start-stop-function by conventional equipment	Additionally to A or B: start-stop-function, with belt driven starter-alternator	Additionally to A or B: regenerative braking, acceleration assistance by integrat. SA	Instead of E: electric launch, acceleration assistance electric driving	Additionally to F: larger battery, plug-in-capability	Propulsion energy stored in the battery, only small ICE to recharge onboard	No onboard recharge unit.	Energy stored in the battery, only small fuel cell and hydrogen to recharge	PEM fuel cell produces electricity from hydrogen

**Figure 1.1:** An overview of different propulsion concepts into classes.[1]

Fuel and electricity are two storage units of Hybrid Electrical Vehicles. Electricity stands for battery which is used as a storage of energy and this energy is used to operate an electromotor (also called motor) and it will be used as a traction motor. Fuel stands for an internal combustion engine which is used to generate the mechanical power and requires a tank to store the fuel.

The hybrid vehicle has both engine and fuel which is depending on the following consideration:

- how motor and engine are connected i.e. parallel, series or combined Hybrid Electrical Vehicles,
- it is also dependent on the share of motor to the traction power, we can distinguish between mild or micro hybrid, full hybrid, power assist hybrid or plug-in hybrid,
- the nature of non-electric source is also a criteria which we can distinguish among the fuel cell, combustion, hydraulic and human power.

It is a matter of common knowledge that the motor plays an important role in the Hybrid Electrical Vehicles drives systems. This motor operates the wheels of the vehicle. However, a conventional vehicle, where the engine must be “ramp up” before the full torque can be reached, at low speed an electric motor gives already full torque. The

motor can provide low noise and high efficiency. Excellent off the line acceleration, good fault tolerance, flexibility and good drive control are the other characteristics in alliance to voltage fluctuation. Hybrid Electric Vehicles include Brushless DC Motor (BLDC), Permanent Magnet Synchronous Motor (PMSM), AC induction motor and Switched Reluctance Motor (SRM) and the front running motor technologies are used.

The possibility to function as a generator is the main advantage of the electromotor. A mechanical braking energy is regenerated in all Hybrid Electric Vehicles. The maximum traction torque is more than the maximum operational braking torque and the mechanical braking system is always installed in a car. In HEV systems, to reduce the current and power losses ( $I^2R$ ), the battery pack should have higher voltage than the Safety Integrity Level (SIL) automotive 12 V. Some accessories like power steering and conditioning are operated by electric motor rather than being connected to the combustion engine.

The following sections give a short overview of the structure and the course of the diploma thesis:

After the description of the introduction, the objective and the course of the diploma thesis, Chapter 1 describes an overview of the different propulsion concepts such as combustion engine, electric engine and hybrid engine. It gives also a short insight into the effects on the environment.

The types of drivetrain structure, such as serial, parallel and combined hybrids are highlighted in Chapter 2. It considers also the advantages and disadvantages of these drivetrain structures.

Chapter 3 and 4 explain the structure and function of plug-in hybrid vehicle and battery vehicle and includes also the explanation of advances and disadvantages. Moreover, a short classification of the types of batteries is given showing the most efficient type of battery.

The entire Life Cycle Assessment of the three propulsion concepts is discussed in chapter 5 and gives details of the Well-to-Wheel process with its sub-processes Well-to-

Tank and Tank-to-Wheel. With the help of this analysis, we are able to assess and compare the CO<sub>2</sub> emissions while the production of fuel such as petrol, diesel out of the primary energy sources respectively electricity generated by battery or fuel cell and also the energy demand and CO<sub>2</sub> emission during the driving mode of the internal combustion vehicle, hybrid and electric vehicle. This chapter also contains the comparison of the efficiencies of the different propulsion concepts. The energy density is also part of this discussion which is an important basis for the determination of the efficiency.

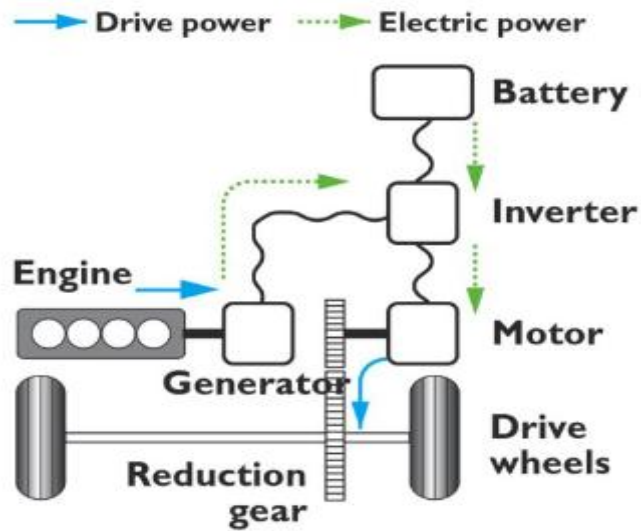
Chapter 6 deals with the carry out analysis of power flow and the energy efficiency of hybrid electric vehicle have been analyzed practically. and operational modes of a hybrid drive with electric and planetary gear power splitter. The aim of this experiment is to calculate the approximate value of energy efficiency of individual components and the total energy efficiency of this experimental setup. These practical sessions have been done in the laboratory of the faculty of electrical engineering. The concept HEV-CVUT is a prototype of hybrid electric vehicle. The determined result shows the overall efficiency of HEV-CVUT.

In the Chapter 7 the author of the diploma thesis gives a conclusion with an outlook of future trends in context of the different propulsion concepts.

## **2. Types of drivetrain structure**

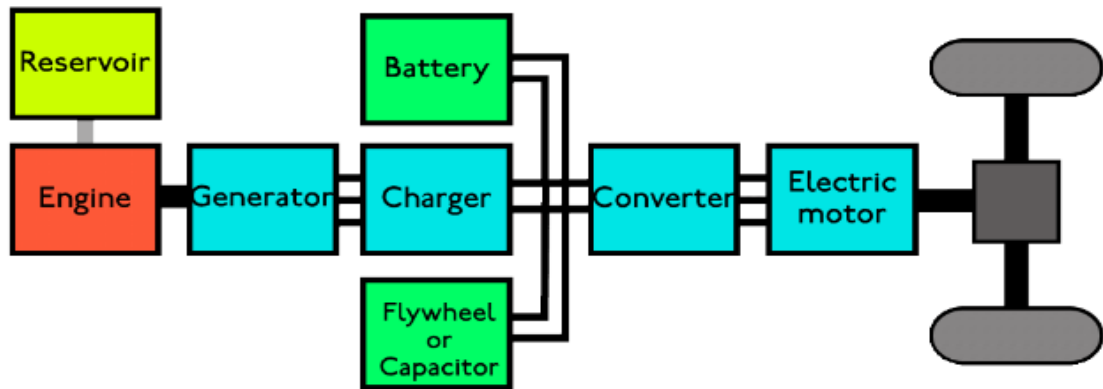
### **2.1 Series hybrid**

In this type of system, the combustion engine spins an electric generator (commonly as 3 phase alternator with rectifier) in place of directly driven the wheels. The only means of providing the power to the wheels is electric motor. The generator works both to charge the battery and give power to an electric motor that helps to move the vehicle. This series configuration already exists a long time such as hydraulic earth moving machine, diesel-electric locomotive and power groups, loaders. The structure of the series hybrid configuration is given below in Figure 2.1:



**Figure 2.1:** Structure of series configuration [2]

There is another structure of series configuration with flywheel as a maximum power unit is show in given below in Figure 2.2:



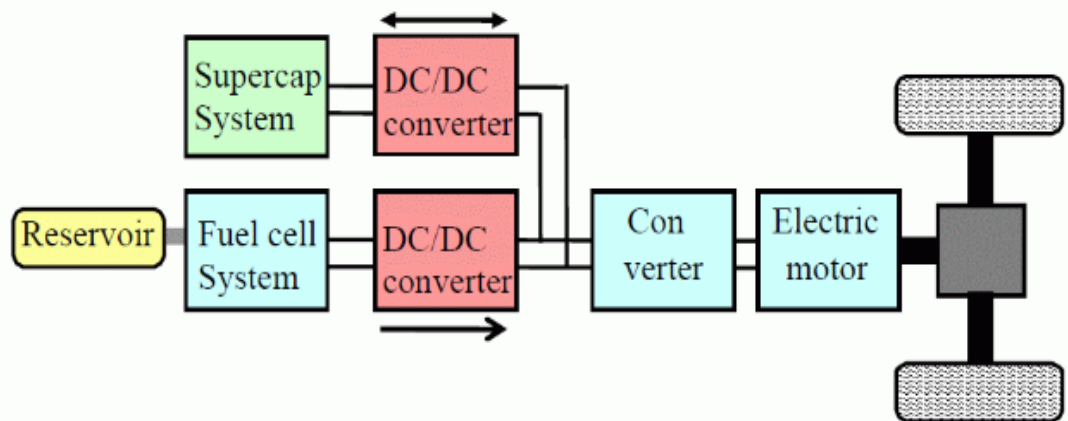
**Figure 2.2:** Structure with flywheel [2]

To improve the efficiency, this series hybrid system should cooperated by flywheel (KERS: Kinetic Energy Recuperation System) which helps to minimizing the losses in the battery. They provide maximum energy and take regenerative energy during acceleration and braking respectively. Therefore flywheel kept charged during low speed and approx. empty at high speed. Deep cycling (charging/discharging) of the battery is reduced and stress factor is being lowered and hence there is chance that battery works according to the manufacturer prescription.

There is no complex transmission between motor and wheel, as electric motor are capable over a wide range of speed. The flexible coupling is required if the motors are connected to the vehicle body.

In some vehicle design, each wheel has its own separate electric motor. There is disadvantage with this configuration that the mass increases and lowering the ride performance. However there is advantage with this configuration that is simplified control of traction motor, all wheel drive and lower to lower the floors which is used in the buses. This type of configuration is used in the 8X8 all wheel drive military vehicles.

This series configuration is always used in fuel cell hybrid electric vehicles: Fuel cell in place of engine generator combination and this structure is shown given below in Figure 2.3:



**Figure 2.3:** Structure of fuel cell hybrid electric vehicle [2]

### 2.1.1 Advantages of the series hybrid configuration

The engine generator can be located anywhere as there is no mechanical linkage among the wheels and combustion engine. The separate electric wheel motor can be installed easily as there are no conventional mechanical transmission elements such as transmission shaft, gear box, etc. The combustion engine can drives in a narrow RPM range, even if the car changes its speed. This type configuration is relatively most efficient during the stop-and-go city driving.



### 2.1.2 Disadvantages of the series hybrid configuration

The total weight and size of the hybrid powertrain are higher based on the fact that the ICE, generator and electric motor have to handle the full power of the vehicle in one. This construction has also higher costs due to the approach of two engines. Furthermore, the power which comes from the combustion engine has to drive through both, the electric motor and the generator. Thus, the total efficiency is lower than the conventional transmission because of several energy conversions.

### 2.2 Parallel hybrid

In this configuration, both an electric motor and an internal combustion engine are connected parallel for mechanical operation.

The following diagram is the structure of parallel hybrid configuration of vehicle and it is illustrated below in Figure 2.4:

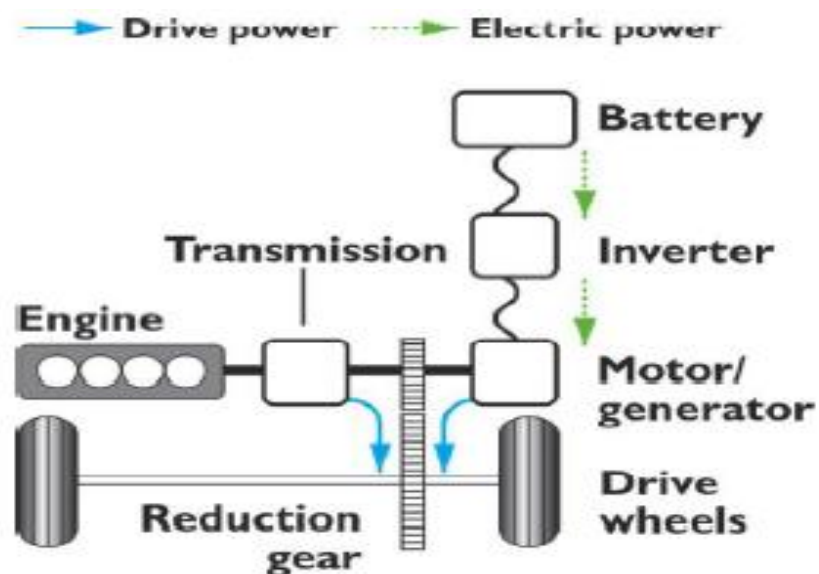
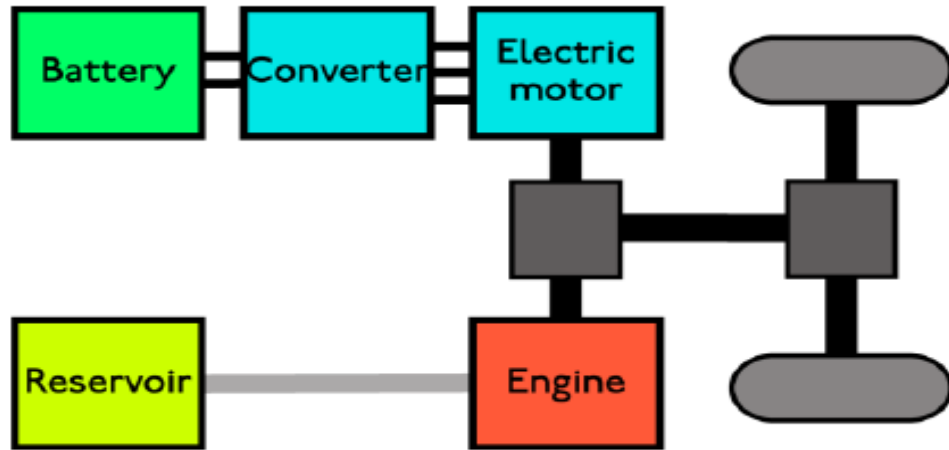


Figure 2.4: Parallel hybrid structure [2]

We can also see block diagram of this configuration as we discussed as same in the series configuration and it is shown given below in Figure 2.5:



**Figure 2.5:** Block Diagram [2]

Most design in this configuration combine a generator and a motor into one unit which is usually located in between the transmission and combustion engine, in place of both the alternator and conventional starter motor as shown in figure 5. During regenerative braking mode, the battery can be recharged. According to the design the mechanical link between the motor and the wheels is fixed for which the battery cannot be charged when the car is in stable position i.e. not moving.

The ICE is not powered or not running, when the vehicle is consuming electrical power only or during regenerative energy mode.

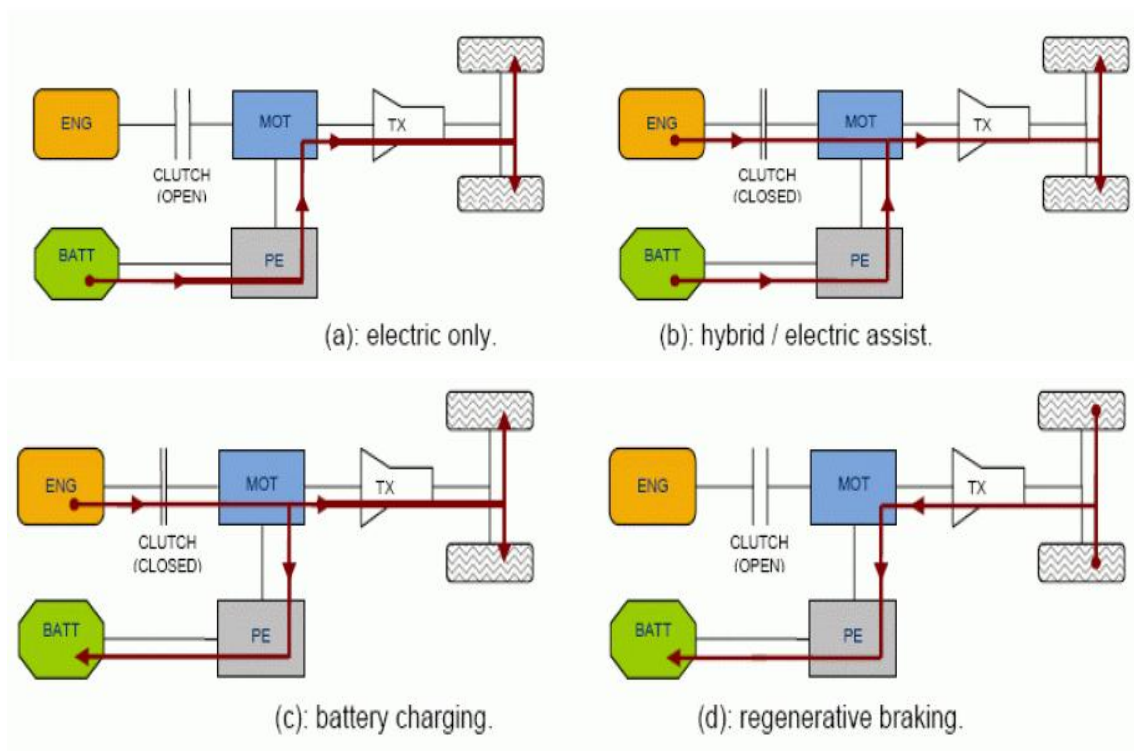
### 2.2.1 Operation mode

The diverse operating mode works in parallel configuration of hybrid vehicle. The following are four sub mode in the diverse operating mode:

1. Electric mode only: The electric motor works only with the power of the batteries during the speed of the vehicle up to 40 Km/hr. During that time the battery is not recharged by the ICE. This mode usually operating around the city and as well as in reverse gear.
2. ICE power only or both ICE and electric power: During ICE Power only, the engine operates at the speed more than 40Km/hr. If the vehicle needs more power(during acceleration or at very high speed) than the current power, the electric motor starts working with the engine which is connected parallel to each other and hence generates more power.

3. Both ICE and Battery charging mode: If the vehicle needed less power, the excess energy is used to charge the battery. In this case it drives at higher efficiency and the engine is operating at higher torque than compulsory torque.
4. Regenerating Braking Mode: During decelerating or braking, the moving vehicle act as a generator and the electric motor gets gain of the kinetic energy of the vehicle.

The following block diagram of Figure 2.6 shows four sub mode of diverse operating mode:



**Figure 2.6:** Diverse operating mode [2]

### 2.2.2 Advantages of parallel hybrid system

Total efficiency is higher than series configuration during long distance driving and the switch flexibility between ICE power and electric power is large. The electromotor can be design less powerful than ICE power as compared to the series configuration. There is requirement of only one electric motor respectively generator.

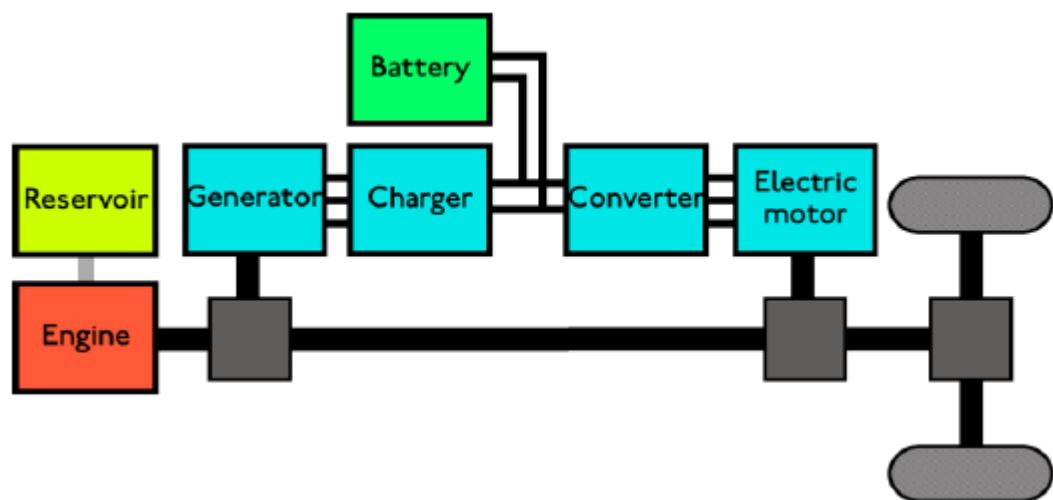
### 2.2.3 Disadvantage of parallel hybrid system

It is rather more complicated system than the series configuration. The battery cannot be charged during standstill position because the ICE is not decoupled from the wheels.

During a low-speed performance, the total efficiency drops as the ICE does not drive in a constant or narrow RPM range.

### 2.3 Combined hybrid

In this configuration it shows features of both series and parallel hybrid system. The connection between the engine and the drive axle is doubling i.e. mechanical and electrical. The mechanism of split power is grants interconnecting electrical and mechanical power. The powertrain is incorporated by the power-split devices. The power delivered to the wheels can be either mechanical or electrical or combination of both power. The same mechanism happens in parallel hybrid system. However, the main phenomenon behind this combined configuration is the power demanded by the driver which is decoupling of power supplied by the engine. The construction is shown in Figure 2.7:



**Figure 2.7:** Structure of a combined hybrid electric vehicle [2]

A larger engine is used to implement acceleration from standstill position than one which needs the steady speed cruising in a conventional vehicle because the torque of the combustion engine is minimal at low RPM. IF we talk about electric motor, it's torque exhibits maximum at standstill and is suitable for enhancing the torque of the engine deficiency at low RPM. However in case of combined hybrid system the engine

can be smaller, less flexible and highly efficient. This leads to a higher total efficiency of the vehicle with less use of regenerative braking mode.

This combined hybrid system drives as a series HEV at lower speed, however in case of higher speed where the efficiency of the series system is lower. It is more expensive system as compared to the pure parallel system because it needs a split power system, an extra generator and more calculating power to control the dual system.

### **2.3.1 Advantage of combined hybrid configuration**

The switch flexibility between ICE and motor is on a maximum level. The decoupling of the power delivered by the engine permits for a lighter, smaller and more efficient ICE design.

### **2.3.2 Disadvantages of combined hybrid configuration**

This system is very expensive and complex as compared to the parallel configuration. The amount of power being transmitted over the electrical path is determining factor of the system efficiency, which leads to a lower efficiency of the electrical path around 70% as compared with the purely mechanical path around 98%.

## **3. Plug-in hybrid vehicle (PHEV)**

This is also another type of hybrid electric vehicle that uses batteries or other energy storage device which can be recharged by plugging it into from charging station. This type of technology shows the behavior of both conventional and pure electric drive

### **3.1 Advantages of Plug-in hybrid vehicle**

It has the Ability to drive on charging sustaining mode (as for the HEV) and charge depleting mode as for the BEV. It has a good capability of grid connection. It emits generally less green house gas and this emission is generally based on the generation of electricity. The driving range of this vehicle is not limited as like battery electric vehicle. It takes advantages from BEV and HEV during driving mode of the vehicle. The local air quality can be improved by PHEV. This type is greatly suitable for urban areas rather rural areas.

### **3.2 Disadvantages Plug-in hybrid vehicle**

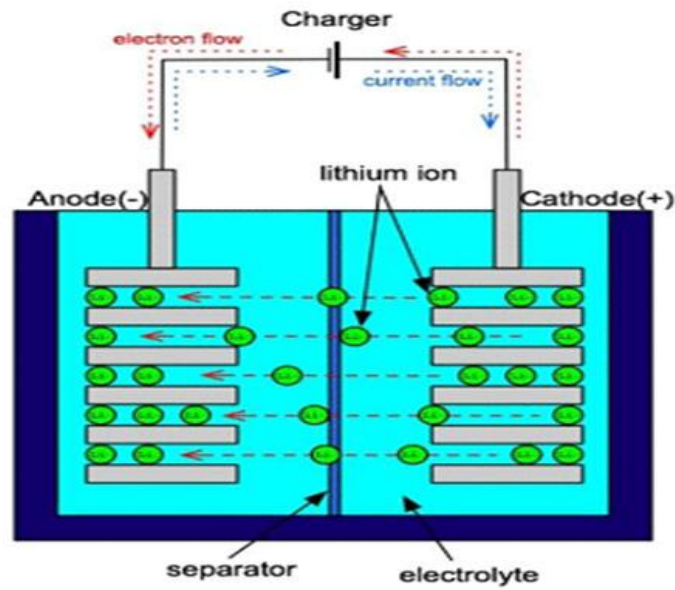
There are few some disadvantages of this type of drive-train. Firstly GHG emission and fuel consumption are depend on many parameters such as AER, CD mode management,  $\eta$  in CD mode and Charging/ driving pattern of the vehicle. The cost of this type is bit expensive as compared to the conventional vehicles due to additional cost of battery and other component related to the this configuration.

## **4. Electric vehicles**

### **4.1 Battery electric vehicles (BEV)**

Electric vehicles are an alternative solution over the conventional vehicles for an environment- friendly effect by means of transportation. The configuration is quite the same as with the conventional vehicles. There is a just only the change of power source and propulsion. The propulsion is done by the electric Traction Motor in place of ICE. The traction battery is the only energy storage unit in an EV and it delivers the electrical energy to the electric traction motor on the vehicle. During the braking mode, the traction motor works as the traction generator and it generates the electrical energy from the kinetic energy of the vehicle, and the whole power flows in opposite direction and charges the battery bank of the vehicles.[3]

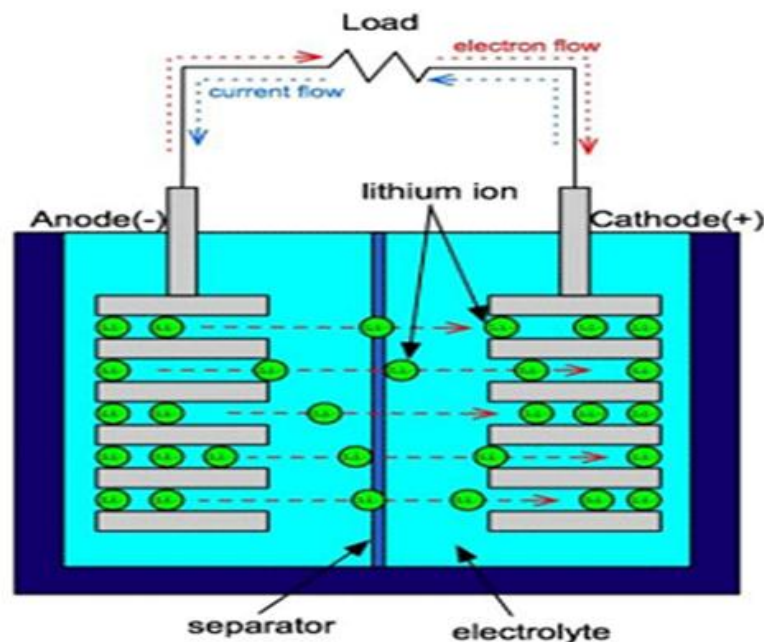
Lithium-ion battery is a rechargeable cell and most commonly used for electrical vehicles. It has a layer of electrolyte (intercalated) made of a lithium compound. In Figure 4.1 and 4.2 it is illustrated that the lithium ions move from anode to cathode when being used in a circuit, and then from cathode to anode when recharging again. This means that the rechargeable lithium-ion anode can both give away electrons, and accept electrons.[4]



**Figure 4.1:** Charging of a battery [4]

The used materials show a big variety which are for the anode i. e. graphite, lithium titanate, tin dioxide and for the cathode i. e. lithium-cobalt (III)-oxide, nickel (II)-hydroxide, tin(IV)-oxide. The electrolyte can be polyvinylidene fluoride, sulfuric acid and the separator is a polyolefin membrane.[4]

During the accelerating mode or propulsion of the car, the traction batteries are getting discharged because it delivers power to the traction motor. This process is shown in Figure 4.2. During the discharge process, the chemical energy is converted to electrical energy due to the electrochemical redox reaction.



**Figure 4.2:** Discharging of a battery [4]

The generated power  $P_g$  is delivered through power pathway to the wheels of the car.

The equation of overall efficiency  $\eta_t$  (4-1) is given below:

$$\eta_t = \eta_{tran} \cdot \eta_{tm} \cdot \eta_b \cdot \eta_{pc} \quad (4-1)$$

The equation contains the following values:

$\eta_{tran}$  = transmission efficiency of the vehicle,

$\eta_{tm}$  = efficiency of traction motor,

$\eta_b$  = efficiency of traction batteries,

$\eta_{pc}$  = efficiency of power control unit of the vehicle.

The traction power of the car  $P_{car}$  (4-2, 4-3) is given as follows:

$$P_{car} = \eta_t \cdot P_g \quad (4-2)$$

$$P_{car} = (\eta_{tran} \cdot \eta_{tm} \cdot \eta_b \cdot \eta_{pc}) \cdot P_g \quad (4-3)$$

The recuperation process starts during the braking mode of vehicle. In this mode, kinetic energy of the vehicle behaves like as source to charge the vehicle's battery.

$$P_{g\_k} = \eta_t \cdot P_{k\_car} \quad (4-4)$$

$$P_{k\_car} = \frac{1}{\eta_t} P_{g\_k} \quad (4-5)$$

The efficiency of electric vehicle  $\eta_t$  varies significantly from 25% to 85% on the basis of working regime, nature of path on which EV drives. The energy efficiency of EV downturn considerably, when the battery is discharged and charged quickly. If this behavior of battery goes on often, then the total process efficiency  $\eta_{ol\_di}$  (4-6, 4-7) of the EV decreases.

$$\eta_{ol\_di} = \frac{P_g}{P_{g\_k}} \quad (4-6)$$

$$\eta_{ol\_di} = \eta_t^2 = (\eta_{tran} \cdot \eta_{tm} \cdot \eta_b \cdot \eta_{pc})^2 \quad (4-7)$$



### 4.1.1 Classification of batteries

Nowadays there is a variety of different types of batteries due to the wide range of used materials with very different requirements concerning voltage, power and capacity. They can be distinguished according to the chemical quality based on chemical redox reactions, interconnection of cells and cell size.

Electrical vehicles are currently operated with lithium-ion batteries because they have the highest specific energy of the cell which is important for the range capacities and weight of the vehicle. Additionally, the higher charge/discharge efficiency of lithium-ion batteries causes less loss to external factors like heating. Table 4.1 shows that the parameters of lithium-ion batteries are more advantageous as compared to nickel metal hybrid (NiMH) and lead-acid (Pb) batteries: the specific energy of the cell per kg of material is far greater than the other two and have a better range of cycle durability.

	Lithium-ion	NiMH	Lead-acid
Specific Energy (Wh/kg)	100-265	60-120	30-40
Energy Density (Wh/L)	250-730	140-300	60-75
Self-discharge rate (per month)	8%	30%	3-20%
Cycle Durability (cycles)	400-1200	500-1000	500-800
charge/discharge efficiency	80-90%	66%	50-92%



Table 4.1: Types of battery and its property [4]

### 4.1.2 Advantages of electrical vehicles

The efficiency of electric vehicle is better as compared to the conventional vehicle due to the process of recuperation. From the economic point of view, electricity cost is cheaper (only about €4,00 for 100 km) as compared to the petroleum cost and this gives another advantage over conventional vehicle. In case of conventional vehicle, the energy which is generated during braking mode is dissipating as heat to the environment and the main driver for a low efficiency. Environmental impact is the most significant role of EV because it does not dissipate any harmful gases to the environment and this shows an ideal solution for environment problem which is created by conventional vehicles. Thus, EV is also called as zero emission vehicles. Electric engines are long

lasting and much simpler designed as a combustion engine so that the maintenance costs are lower.

#### **4.1.3 Disadvantages of electrical vehicles**

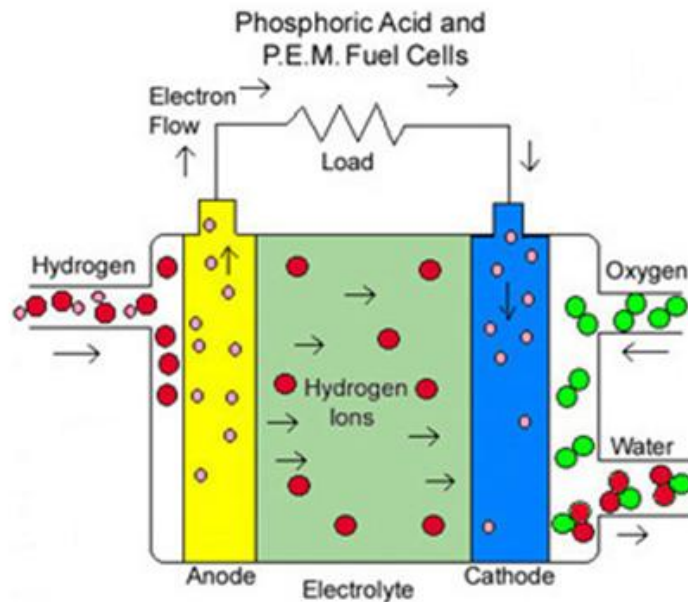
However, there are few drawbacks that show some results with commercial failure. The capacity loss and aging of a battery is influenced by the number of charging/discharging cycles and the temperature (high volatilities have to be avoided especially during the winter and summer season). The inner working of a cell is mechanically stressed due to change of volume for each cycle. In general, the electrical drive has an enormous weight and the energy storage capacity of the traction batteries is relatively low in comparison to the chemical energy of the fossil fuel which is stored in the fuel tank of the conventional vehicles. As consequences, the driving range of EV of one battery charging is much shorter as compared to the standard vehicles. Moreover, battery requires a special arrangement charging unit and this takes long time to charge the full battery. During the evolution of EV cars, the use of electric cars is limited due to the scarcity of the infrastructure to charge the vehicles on-road. An alternative solution is the Plug-In-Hybrid technology or Range Extender (combustion engine with generator). Another is that the second car of an household is a BEV in case that the average driving distance is on a low level < 50km, a car is in average In general, a car is 23 hours a day stationary. This means, a car can be recharged for many hours at home or at work. Another disadvantage is the high price of a lithium-ion battery which is attributable to the raw material extraction respectively the production of the battery and the resulting environmental burden. Eco-friendly recycling processes are in place, but currently with very limited capacities.

#### **4.2 Fuel Cell electric vehicle (FCEV)**

FCEV is another type of electricity vehicle and it operates by electricity which is produced on-board from oxygen and hydrogen which contains a vast amount of chemical energy. In chemical reaction hydrogen gas can be generated by various sources such as electrolysis of water, natural gas and biogas by using the heat and catalysts. This hydrogen gases is stored in the FCEV vehicle in the form of compressed

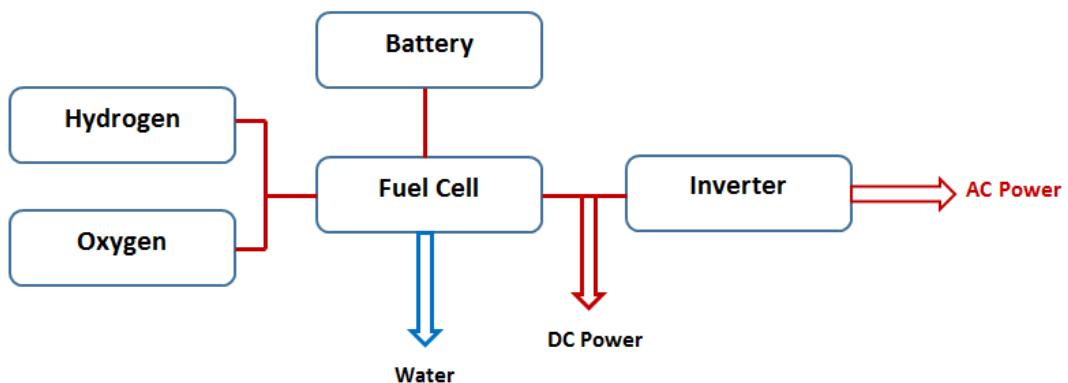
gas. It is non-corrosive, environment-friendly and non-toxic gas and it is widely used for industrial purpose. [5]

Figure 4.3 shows the construction of a fuel cell which is similar to a battery. It also contains anode, cathode and an electrolyte. Instead of the lithium-ions the fuel cell reacts with hydrogen ions.



**Figure 4.3:** Operation of phosphoric acid and Proton Exchange Membrane fuel cells [6]

The fuel cells in a FCEV are electrochemical devices that use the chemical reaction to convert hydrogen into useful electrical energy. However, there is no direct conversion into thermal energy and further to mechanical energy in the conventional vehicles and hence efficiency of FCEV is higher than ICE. Figure 4.4 illustrates the production of electricity from the fuel cell.



**Figure 4.4:** Block Diagram of production of electricity from the fuel cell

#### **4.2.1 Advantages of FCEV**

The efficiency of fuel cells (up to approx. 60%) is substantially higher than the efficiency of conventional vehicles due to the chemical process respectively the higher energy density. The chemical reaction reduces the wear which occurs in case of mechanical work. However, overall efficiency is less than the battery because there are many conversions such as distribution, transfer, charging battery and electrolyze during the energy process (Well-to-Wheel). It is the only refuelable power source vehicle which is unlimited available as in comparison to oil. Additionally, fuel cells satisfies the zero emission vehicle conditions because is generates only water vapor and there is no direct CO<sub>2</sub> emissions during the vehicle process (Tank-to-Wheel). [5]

The driver can fill the hydrogen from hydrogen fuel station and it takes around 6 to 7 minutes to refill the full tank. These forms of these vehicles have range of 400-650 km which is comparable to conventional engines.

#### **4.2.2 Disadvantages of FCEV**

The principle operation of fuel cell vehicle seems to be simple and easy to operate and various patterns have already developed and launched in the market. However, it has a poor dynamic response that makes control system more complex. Concerning the fuel supply there are combined drawbacks of FCEV in Europe due to lack of infrastructure of hydrogen fueling station and on-board hydrogen storage and hence the mass production of FCEV is still far away in Europe. Moreover, hydrogen is not available in free form and needs some process to extract the pure hydrogen which causes still some CO<sub>2</sub> emission during this process. For the production of hydrogen, the electricity must be needed in the most common process of hydrogen production i.e. electrolysis of water. In comparison to batteries the costs are much higher due to the platinum coating which is needed in a fuel cell.

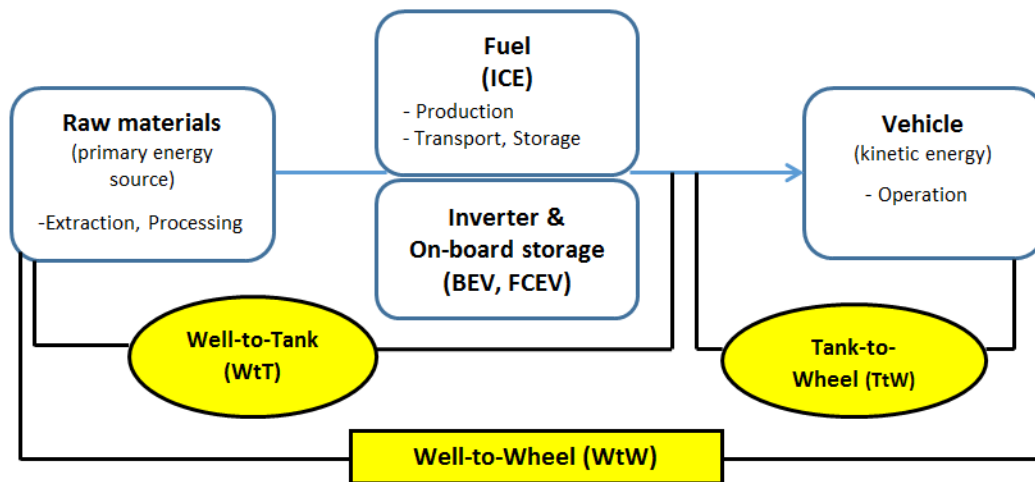
### **5. Life Cycle Assessment of the three drives technologies**

For a better comparability of the three drives respectively the used fuels throughout the entire energy chain, the life cycle assessment is an important tool to work out clearly the total energy consumption, energy conversion efficiency and emission impact including their carbon footprint.

## 5.1 Well-to-Wheel analysis (WtW)

The Well-to-Wheel analysis is the tool for evaluation of the environment impact of fuel or energy of conventional, hybrid and electric vehicles throughout its whole lifespan, so called life cycle assessment. This allows an accurate assessment of the different type of drives by means of a full analysis from the extraction and processing of fuels respectively energy sources to the conversion into kinetic energy. The main purpose of the WtW-analysis is to calculate the direct and indirect emission of various types of gases such as carbon dioxide (CO<sub>2</sub>), carbon monoxide (CO), nitrogen oxide (N<sub>x</sub>O) and methane (CH<sub>4</sub>) throughout the whole path from the production till the vehicle operation. The objective of the WtW-analysis is to perform a reliable statement regarding WtW energy demand and greenhouse gas emission (GHGE).

The Figure 5.1 shows the block diagram of this Well-to-Wheel analysis which is divided into two parts: the first is related to the production and processing of the primary energy sources and the energy supply to the vehicle, so called the Well-to-Tank (WtT) system. It describes the energy process. The second is the Tank-to-Wheel (TtW) system which characterizes the final use of the primary energy source and types of powertrain options respectively, meaning the absorbed energy (fuel, electrical energy) to conversion of fuels to kinetic energy [7]. This part describes the vehicle process. All in all, WtW comprises the indirect (WtT) and direct (TtW) emission respectively the primary energy consumption of the upstream chain (WtT) and the final energy consumption (TtW).



**Figure 5.1:** Block Diagram of Well-to-Wheel (WtW)

## 5.2 Well-to-Tank approach (WtT)

The Well-to-Tank-systems is the energy process and starts with production of fuels for the extraction of the raw materials such as natural gas, crude oil, biomass or electricity and terminates with the pure fuel in the tank of the vehicles. This process contains the energy demand and all indirect greenhouse gas emissions of the upstream fuel supply from source to tank. The energy demand also considers energy losses, i. e. from power to high-voltage lines.

### 5.2.1 Primary energy sources in the WtT-approach

As shown in Table 5.1, the different finished fuels can be produced from various primary energy resources within the upstream chain. The fuels are petrol, diesel, hydrogen or electricity for different propulsion drives.

Primary Energy Resource	Type of Fuel					
	Petrol, Diesel	CNG	Hydrogen	Synthetic Diesel	Electricity	Heat
Crude Oil	X				X	X
Coal			X	X	X	
Natural Gas		X	X	X	X	X
Biomass		X	X	X	X	X
Wind					X	X
Nuclear					X	X
Electricity			X			

**Table 5.1:** Primary energy resources and automotive fuel [8]

The level of emission which arises from the road traffic does not only depend on the propulsion concept. In fact, the used energy sources play an important role and also their entire energy balance, in particular as regards CO<sub>2</sub> emission. In the discussion about the most effective fuel and future powertrain concepts, it is important to analyze the corresponding upstream chains which are needed for the production and supply of the fuels. The fossil fuel diesel has the highest energy content (9.97 kWh/l) compared to petrol (9.03 kWh/l), Super E85 (7.63 kWh/l) and bio natural gas (5.83 kWh/l). [9] In Table 5.2 it is shown the energy balance (energy demand in relation to energy content; for better comparison the energy content is standardized with 1 kWh) during the production and supply of 1 liter of fuel taking into account the upstream chains of different liquid fuels. Though diesel has the highest energy content, the energy balance is negatively influenced due to the highest energy demand during the upstream production. This gives an idea, that an objective assessment of the WtW process is only possible, if all parameters from the source to the wheel (WtW) are assessed and compared.

Type of fuel	Energy demand for production (kWh)	Energy content (kWh)	Energy balance (kWh)
Petrol	0.60	1.0	0.40
Diesel	0.72	1.0	0.28
Bio natural gas	0.59	1.0	0.41
Super E85	0.34	1.0	0.66

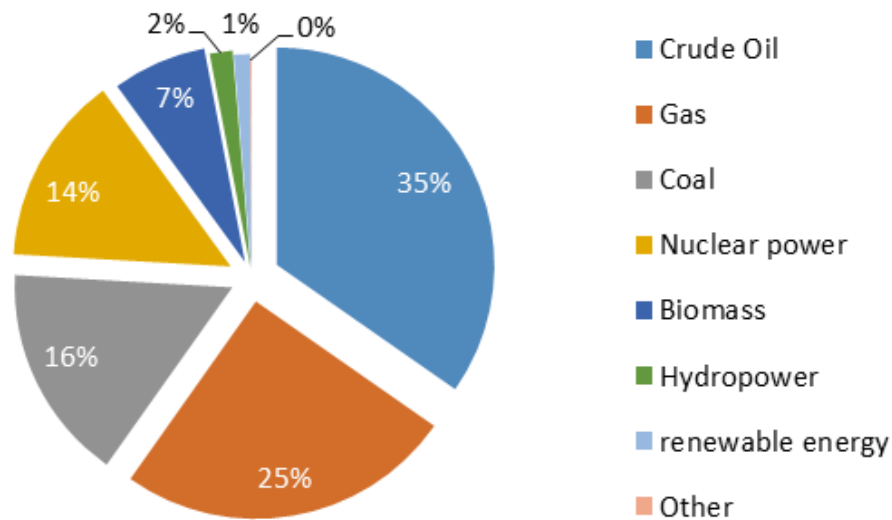
**Table 5.2:** Energy balance with upstream chain referring to the supply of 1 kWh [9]

Low carbon fuel such as bioethanol (substitute for petrol and super fuels) and biodiesel (substitute for diesel) can reduce CO<sub>2</sub> emission significantly. However, it is important which conversion process is chosen during the production of these alternative drives so that the life cycle assessment is positive respectively better than the one of the conventional fuels. [10]

### 5.2.2 Specificity of primary energy sources for Electric Vehicle

For BEV and FCEV, the grid mix it is of vital importance because the WtW emission is directly scaled with the emission of the grid generation. Currently, the primary energy source of European BEV is based on the EU energy mix. As shown in Figure 5.2., this mix contains a high share in crude oil (35%), gas (25%) and coal (16%). Renewable energies have only a share of 10%. Thus, the CO<sub>2</sub> emission of BEV is currently higher and can be minimized in the future by using more renewable sources (wind, photovoltaic) within the EU energy mix. As a result, the CO<sub>2</sub> emission during WtT process would be also further reduced significantly.





**Figure 5.2:** EU Energy Mix [11]

The Table 5.3 shows the share of the individual energy sources on net installed power plant capacity and the contribution to the net power generation. The installed capacity describes the potential or the capacity (calculated capacity) of a plant. The value is specified in GW, MW or KW. The net power generation describes the output (actual production/power generation = electrical energy) of the plant which is available for the power supply after deduction of on-side power. From physical perspective it is ‘work at grid’ and the value is specified in MWh or KWh.

Type of power plant (2011)	share of net installed capacity in %	share of net power generation in %
Wind	17.3	8.0
black coal	16.4	18.1
natural gas	15.4	14.1
Photovoltaics	14.9	3.3
brown coal	11.9	24.3
heating oil, pump storage, others	10.4	5.2
nuclear power	7.2	17.6
hydro (without pump storage)	3.3	3.3
biomass, other renewable energies	3.2	6.1

**Table 5.3:** Installed capacities and net power generation referring to type of energy source [12]

In reality, the plants are not fully utilized and a high installed capacity does not mean inevitable a high power generation and depends on availabilities. The photovoltaic respectively wind plants generate only a maximum capacity in case of intensive solar

radiation or sufficient wind is available. The still air and darkness limit the net power generation and is also the reason why their share in installed capacity is significantly lower. Moreover, the starting and shutdown of brown coal, nuclear and biomass plants are the most expensive and have the lowest adjustment performance. In light of this and the very low actual net power generation of wind and photovoltaic plants their net power generation is substantially higher than their installment capacity. Thus, the ratios of net power generation are shifted especially in favor of nuclear and brown coal plants. However, efficiency of wind is 60% and brown coal 40-50%. [13]

### 5.3 Tank-to-Wheel approach (WtT)

The Tank-to-Wheel (TtW) system is the vehicle process and describes the final use of the various fuels in combination of the corresponding powertrain operation. It considers the chain of effects from the absorbed energy (fuel, electrical energy) up to the conversion in kinetic energy for vehicles ( $E_{kin}$  with energy unit in kWh or MJ). Energy consumption of TtW is stated in line-specific energy unit kWh/100km. This process contains the final energy demand and all direct greenhouse gas emissions.

$$E_{kin} = 0.5 \cdot m \cdot v^2 \quad (5.1)$$

The values of the equation are:

$m$  = mass in kg

$v$  = speed of the vehicle in 100km/h

While the WtT fuel emissions are given for the individual fuels and development paths, the TtW emission is mileage-specific and besides the types of powertrain topologies also dependent on the individual driving behavior (frequent journeys to the mountains, fast motorway driving, use of a lot of comfort functions) and recuperation effects which can improve the TtW efficiency and emission. In general, the two last-name factors are not considered in the average values [12]. The TtW chain can be further influenced by the car manufacturers via air and rolling resistance, weight reduction and improved efficiency of the powertrain technologies. All in all, the TtW-system is used to make vehicle technology comparable concerning efficiency and emission (further explanations see Section 5.4).

### 5.3.1. Energy density as an important parameter of efficiency

Energy carriers differ in energy density, transport, storage as well as expenses and efficiency of their use. Their energy content is usable for the energy conversion processes. The primary energy sources are naturally available materials such as fossil energy carriers (crude oil, coal, natural gas) respectively alternative carriers (biomass) and secondary energy carriers (hydrogen, ethanol) which are produced by conversion of the first-mentioned energy sources. Dependent on the energy source, the forms of energy are different: thermal, electrical mechanical (i.e. flywheel), chemical (fossil/alternative fuels) and electro-chemical (batteries). The energy density is called calorific value for fuels and capacity for batteries.

The volumetric energy density is quantitative and expresses the stored energy with the unit per liter Wh/L or MJ/L. This value can be specified i.e. for various types of rechargeable batteries (accumulators) and limits the on-board energy quantity of an electric vehicle for a maximal given space requirement of the battery. This gives a statement regarding the vehicle construction (weight of the vehicle). Figure 5.3 shows that liquid fuels, especially diesel, have the highest volumetric energy followed by gaseous fuels, such as CNG and hydrogen. Batteries show the poorest volumetric density result. Concerning specific energy, gaseous fuels are ahead of liquid fuels.

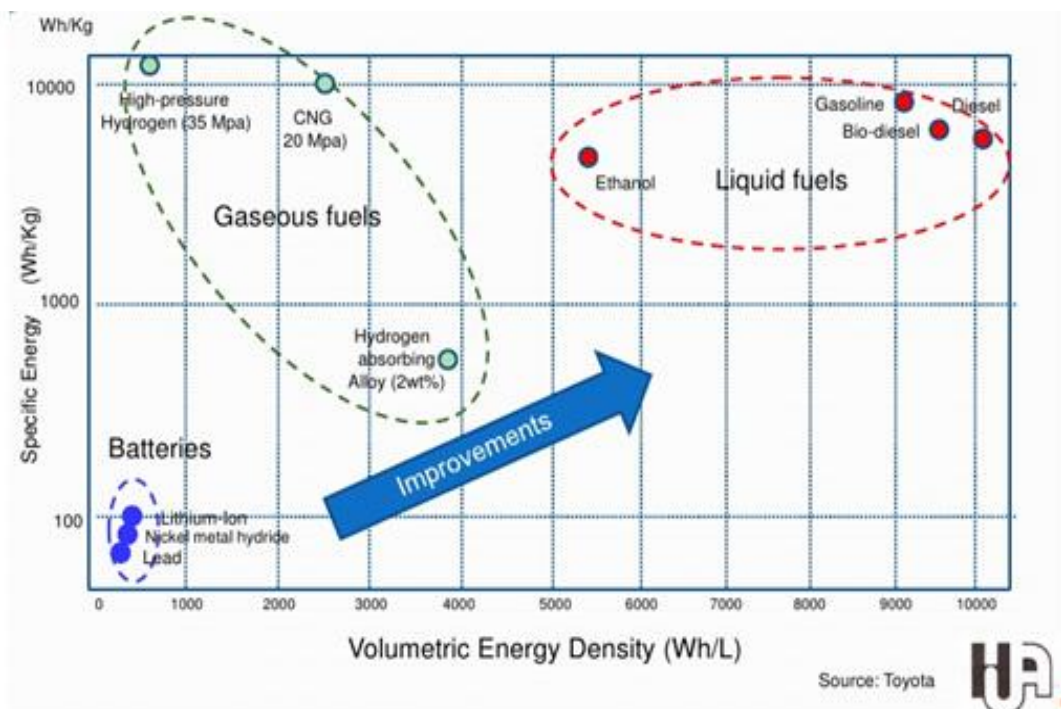
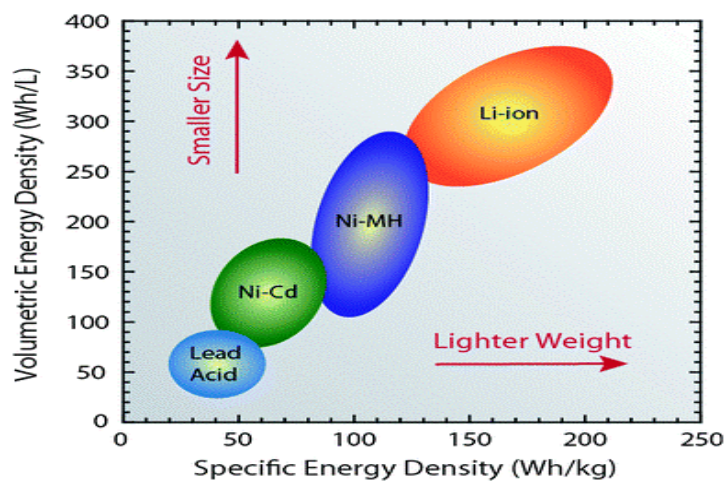


Figure 5.3: Energy density of on-board energy carriers and energy sources [14]

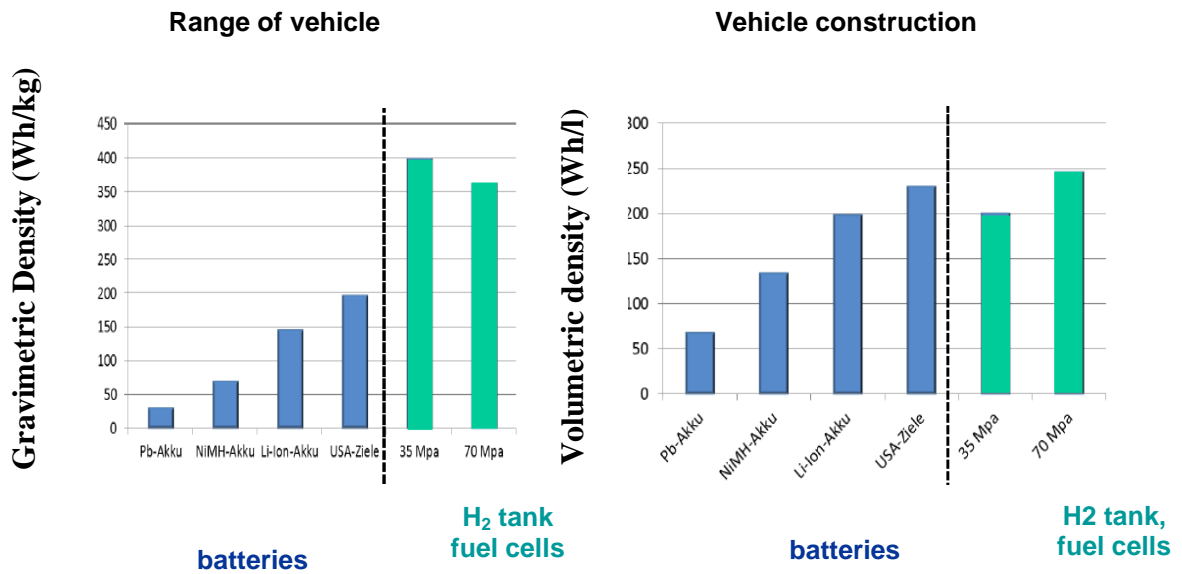
For accumulators and fuel cells of electric cars a high power density, also called specific energy or gravimetric energy, is preferable. The unit per mass is Wh/kg or MJ/kg for energy converter (combustion engines, electrical engines) respectively energy storage (batteries, fuel cells). In this context, the storage capacity is very important. Based on the power density the range capacities and weight can be specified. It is the aim to reach a high value so that the transport expenses for the energy carrier can be kept low, but also to obtain a long operating time and a high range of a vehicles respectively low weight of the vehicle. Additionally, this tends to reduce the energy consumption for the production and the environmental emission.

Figure 5.4 expresses that the lithium-ion cells (Li-ion) is the high-performance battery with the highest specific energy up to 200 Wh/kg and the best conditions for small size and light weight which is needed for the performance of electrical drives.



**Figure 5.4:** Energy density comparison of size & weight of various types of batteries [15]

As demonstrated in Figure 5.5, the volumetric and gravimetric density of batteries is much lower than the one of the fuel cells. Thus, it is a challenge to design battery operated vehicles with a large range. However, based on the lower heat losses of batteries during the charging process, the efficiency of batteries is higher than in comparison to fuel cells.

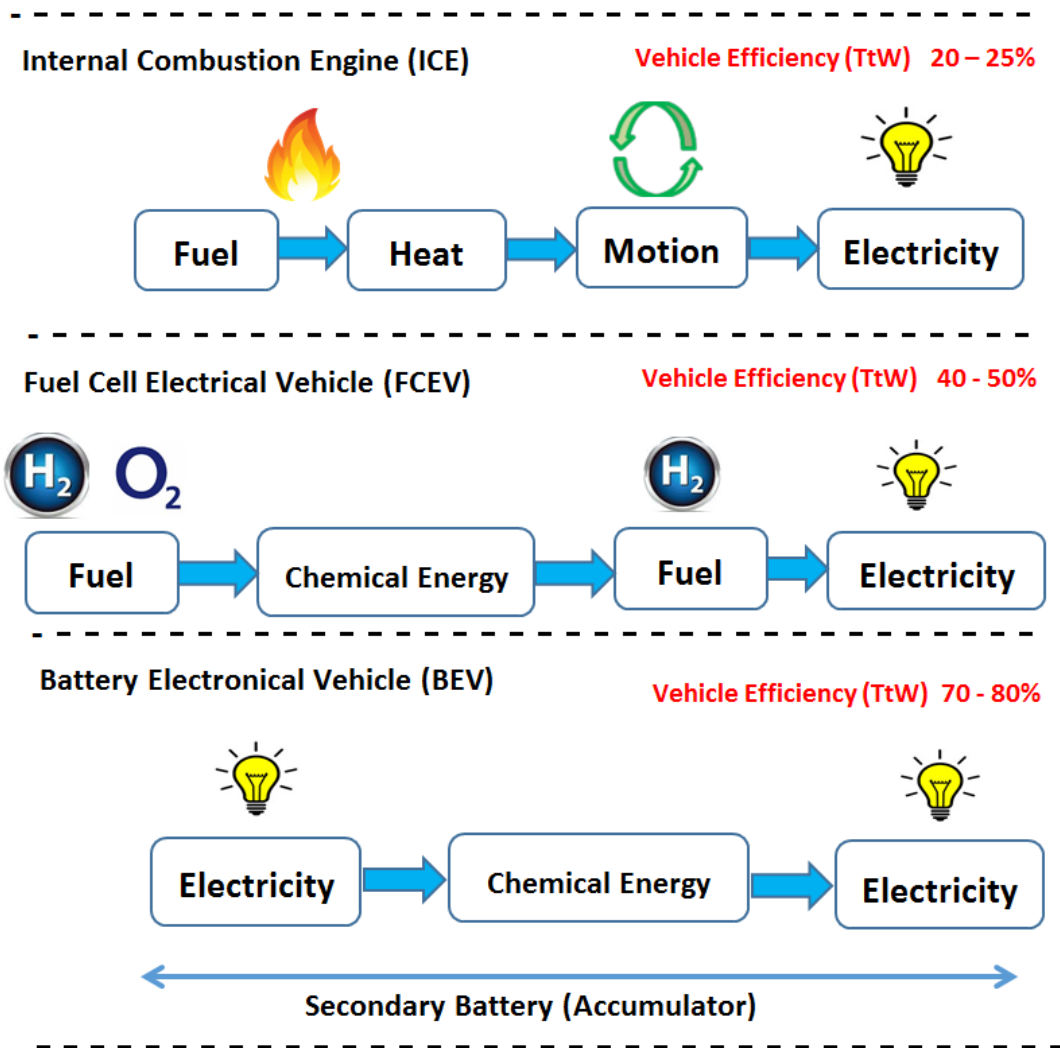


**Figure 5.5:** Gravimetric & specific energy density of various batteries and fuel cells [16]

The production of chemical energy carriers causes the highest heat losses and is the central problem during storage and usage. The life-span of an accumulator is limited due to the number of recharging cycles which is mainly dependent on the operating conditions. For the optimization of accumulators it is necessary to accept compromises, i.e. the optimization of the battery's power density a battery will be borne by lower storage capacities and life-span.

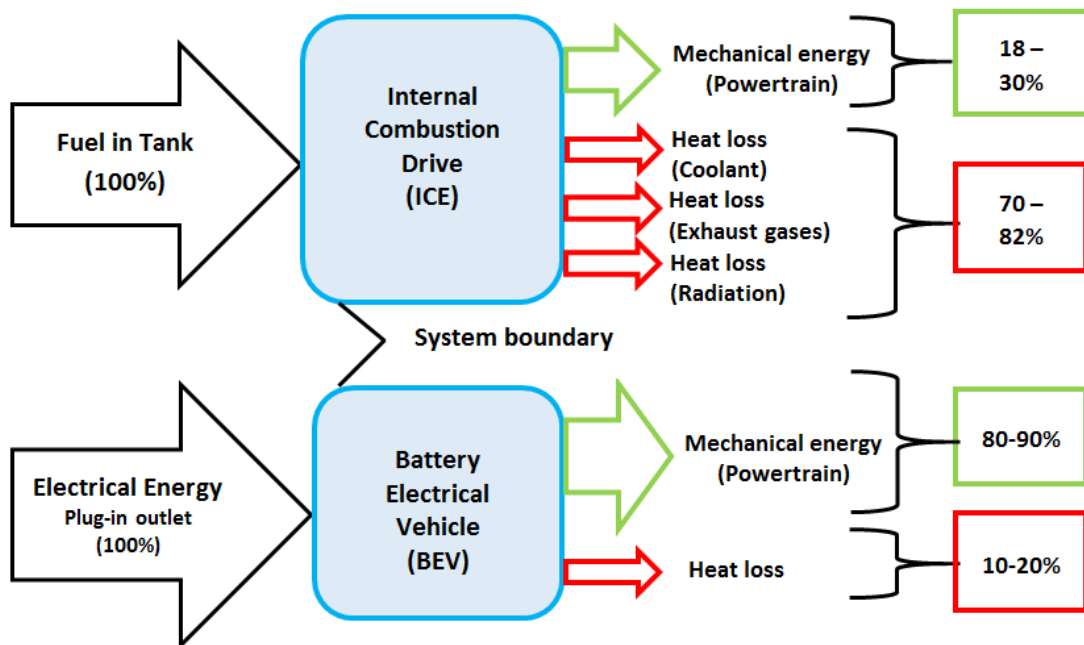
### 5.3.2. Efficiency comparison of the different propulsion concepts

The transformation of fuel into kinetic energy is distinct and linked to the types of vehicle technology such as internal combustion engine (ICE), electric engine (BEV, FCEV) or hybrid engine (HEV) by combining of ICE and electric drive. Due to this fact, the efficiency of individual propulsion concepts also varies with each other. This is illustrated in the Figures 5.6, 5.7, 5.8 which show that the most efficient powertrain is the BEV (up to 90% efficiency), followed by FCEV (up to 58%) and ICE has the poorest efficiency (up to 30%).

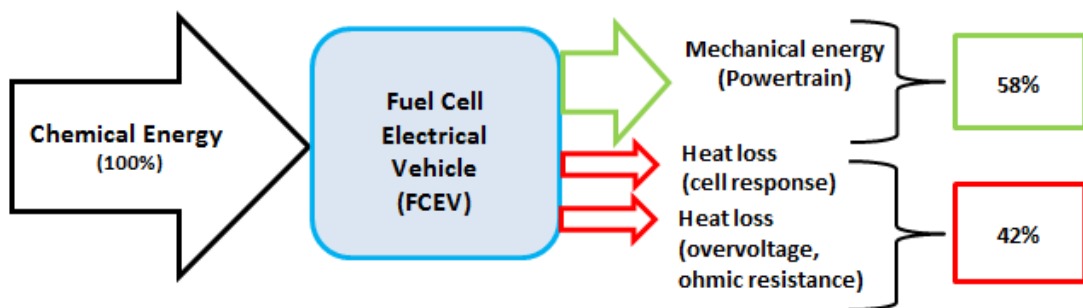


**Figure 5.6:** Tank-to-Wheel efficiency of different propulsion concept [17]

The figure 5.6, 5.7 and 5.8 point out that the reason for the major difference of efficiency is based on the deviating percentage of mechanical energy of the drive during the conversion of fuel energy respectively electrical energy. Especially the combustion drive has a high share of heat loss (approx. 80%) as compared to the battery electric drive (up to 20%) and fuel cell electric drive (approx. 40%).



**Figure 5.7:** Mechanical energy and heat loss in TtW process (only powertrain) of combustion drive and electric drive [18]



**Figure 5.8:** Mechanical energy and heat loss in TtW process (only powertrain) of combustion drive and electric drive

### 5.3.2.1. Efficiency of the Internal Combustion Engine

The heat loss of ICE is driven by the fact that approx. 80% of the energy which is contained in the fossil or alternative fuels serves mainly for heating the environment. This heat loss of fuel energy is given in three different ways:

- 1) 43% of the fuel energy is related to exhaust gases arising from the exhaust silencer. It is possible that a fraction of these exhaust gases is used for setting the exhaust gas turbocharger in rotation. The engine itself is also a source for losses, because it has to be constantly cooled so that it is not overheating.
- 2) 27% of the fuel energy gets lost due to needed cooling water for avoiding the overheating of the engine. During winter a part of this effect is used for heating of the vehicle interior.
- 3) 9% of the thermal energy is lost to the environment via convection, heat conduction and thermal radiation (heating of the engine during the operation up to approx. 80%).

This means, only 21% of the fuel energy reaches the crankshaft. However, the drive wheels still have to be reached which causes a further loss of 1% for v-belt driven generator which ensures the power generation and 2% for gearbox, differential gear, transmission shaft and different axes. At the end of the TtW process, 18% remain for the ICE drive.

#### **5.3.2.2. Efficiency of the Battery Engine Vehicle**

Accumulators (rechargeable batteries), fuel cells and electrolytic capacitors store energy in electrochemical form. The process at loading is broadly reversible, so that the occurring energy loss is relatively low. The intensity of self-discharge strongly depends on the type of battery which is usually moderate. The energy density is essentially higher compared to all other capacitors, however very low compared to the energy density of fuel cells. Thus, the weight of a BEV is higher than that of a FCEV, so that more weight (mass) requires more stored battery energy than hydrogen energy. Based on that, it is difficult to design battery-operated electric vehicles with a long range.

In pure electrical vehicles approx. 4% are linked to battery loss for the thermal management. The efficiency of a high quality electrical drive has a value of 94%. [12] The auxiliary units may consume 4%. Taking into account that the braking energy is fed back to the battery based on energy recuperation (switch to generator mode of the electrical drive during the braking process), the overall efficiency of an electric drive is in a range of 70 - 90% (different results exist in practice)[12]. For the fast storage of the electrical brake energy, a super capacitor it is possible to charge super condensers. In



summary, from 10 kWh energy content of the electrical energy in a range of 7 kWh and 9 kWh reaches the drive wheels. [12]

### 5.3.2.3. Efficiency of the Fuel Cell Engine Vehicle

The performance data and operating behavior of a fuel cell are determined by thermodynamics and the kinetic of the electrode process. The instantaneous power of a fuel cell is the product of cell voltage and electricity. While the fuel cell feeds electricity in the outer circuit, the cell voltage arises due to the increasing temperature. The fuel cell reaches its highest output at medium voltage levels. This means, at the half of the off-load voltage on a high current density level, shortly before the cell voltage is dropping. The more electricity flows, the more the cell voltage is abruptly decreasing (due to ohmic losses in the electrolytes and on the electrodes). Heat losses derive from

- (i) the voltage drop arises at the internal resistance (resistance of electrolyte and electrode reactions) and is based on the kinetic inhibited electrode reactions, also called overvoltage  $\eta$  (5-2).

$$\eta = U(I) - U_0 = I(R_i - R_{el}) \quad (5-2)$$

The equation has the following values:

$I$  = cell voltage, current

$U(I)$  = clamping voltage (electricity flows)

$U_0$  = off-load voltage (electricity is zero)

$R_i$  = internal resistance

$R_{el}$  = resistance of electrolyte

- (ii) The ohmic resistance of the electrolytes and on electrodes.

The reason for the overvoltage is the slower electrode process which acts like a resistance and limits the charge transport. This kinetic process is inhibited due to the fact that it is not running at any speed. The slowest part step determines the whole electrode reaction and the flowing current density. The overvoltage depends on electrode material, type, concentration and flow of the electrolytes and rises with the increasing temperature and current density respectively decreases with increasing

electrode surface. To keep the heat loss low, the internal and electrolyte resistance have to be on a low level. This can be achieved by a fast electrode reaction, large electrode surface, high conductance of the electrolytes and lower electrode gap.

For comparison of fuel cells, the energy density (power referring to electrode cross-section) is better than current density. A high level of the energy density of the used energy accumulator is significant for the attainable range. If the energy density is on a higher level, the efficiency (up to approx. 60%) of the accumulator is also getting higher [19]. However, the specific energy demand is getting larger, but at the same time the investment costs are decreasing.

## **5.4 Measurement of energy demand and emission of vehicle performance in TtW**

### **5.4.1 Reference road cycle**

In the 1990, the standard European exhaust emission regulations with the EU standard values (Euro-norm Euro 1; further developed to current Euro 6) were introduced which are determined using a legally mandated method, the New European Driving Cycle (NEDC), on a test bench. This road driving cycle was originally designed for petrol-based vehicles and expresses the relation between speed and time during the defined drive mode. Nowadays, it is now also used for diesel vehicles and to estimate the electric power consumption and driving range of HEV and BEV. [20]

One goal of this legal requirement was to provide a standard cycle in Europe and a basis for the comparison of car models from different vehicle manufacturers concerning fuel consumption and emission within the TtW process.[21] Another is to provide instantaneous driving forces required to overcome the aerodynamic, rolling, grade and resistance. [22]

The applied and practically used simulation models are generally adapted to the NEDC road driving cycle and the main results of the vehicle simulations are:

- **Fuel energy demand (MJ/km)** of passenger car to perform the NEDC cycle
- **GHG (g CO<sub>2</sub>eq/km)** emitted during the cycle by the car engines/fuel combinations [20]

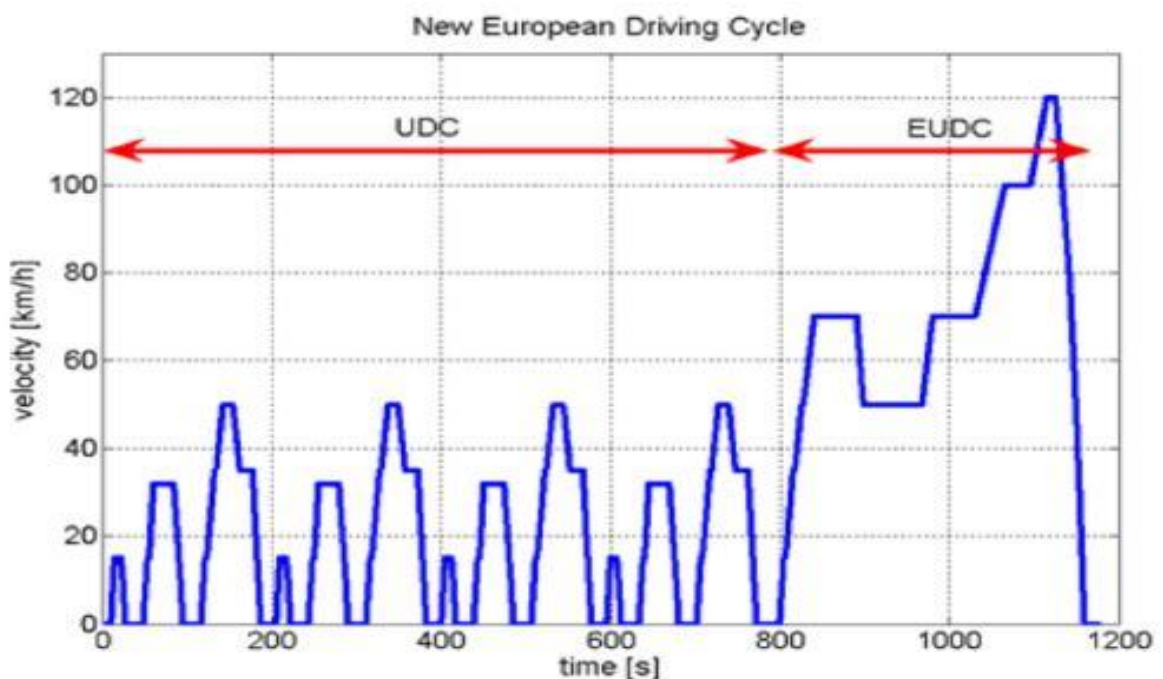
The Figure 5.9 gives an overview of the entire NEDC (total time 1,180s) for standardized testing procedures with two cycles:

**1) Urban Driving Cycle (UDC)**

- max. speed of 50 km/h and time of 780 s
- four phases with 195 s each
- Average speed of 19 km/h

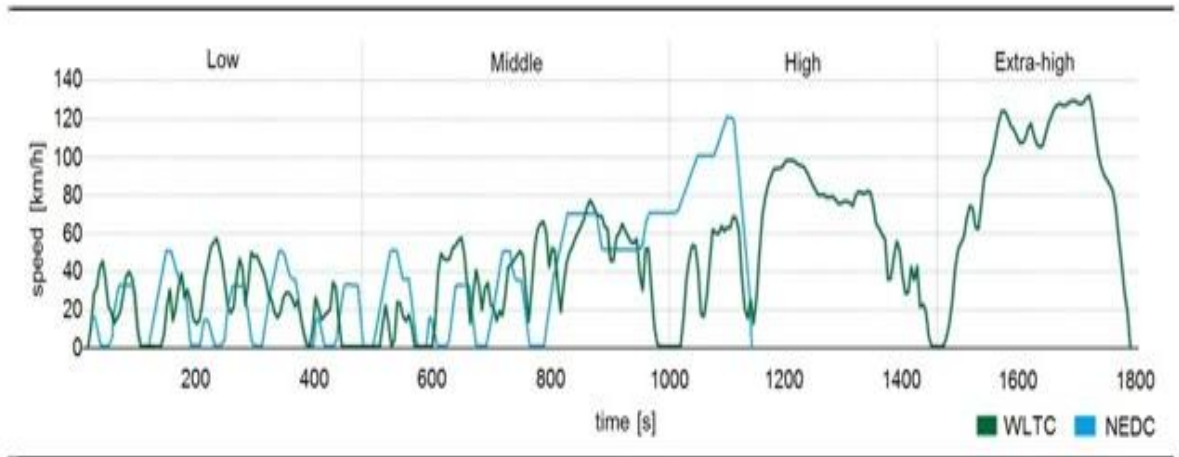
**2) Extra-Urban Driving Cycle (EUDC)**

- max. speed of 120 km/h and time of 400 s
- one phase
- Average speed of 62.6 km/h.



**Figure 5.9:** New European Driving Cycle (NEDC) for passenger cars with speed-time relationship [23]

The NEDC is increasingly attracting criticism due to the missing dynamic of the test procedure and a low average speed of 34 km/h. Moreover, the customer choices like different driving habits / profile, road conditions and cabin comfort changed in the meantime. It is expected that by 2020+ the Worldwide Harmonized Light vehicles Test Procedure (WLTP, not finally defined yet) will be used for the testing of vehicle fuel consumption and emission instead of NEDC.



**Figure 5.10:** Comparison of WLTC and NEDC road driving cycle [24]

Figure 5.10 illustrates that this new approach is more dynamic, has many more accelerations and braking cycles than the NEDC and the aim is to simulate the reality as closely as possible.[21] The main parameters of the two road driving cycles are indicated in Table 5.4.

	WLTP	NEDC
Starting temperature	cold	Cold
Cycle time	30 min	20 min
Idle time element	13%	25%
Cycle length	23.25 km	11 km
Speed (average/max.)	46.5 km/h / 131 km/h	34 km/h / 120 km/h
Propulsive power (average/max.)	7.5 kW / 47 kW	4 kW / 34 kW
special equipment considered for	- - - onboard electrical system	weight aerodynamics not considered
air-condition	not considered	not considered

**Table 5.4:** Comparison of NEDC and WLTP [21]

#### 5.4.2 Determination of efficiency based on Vehicle Dynamics Model

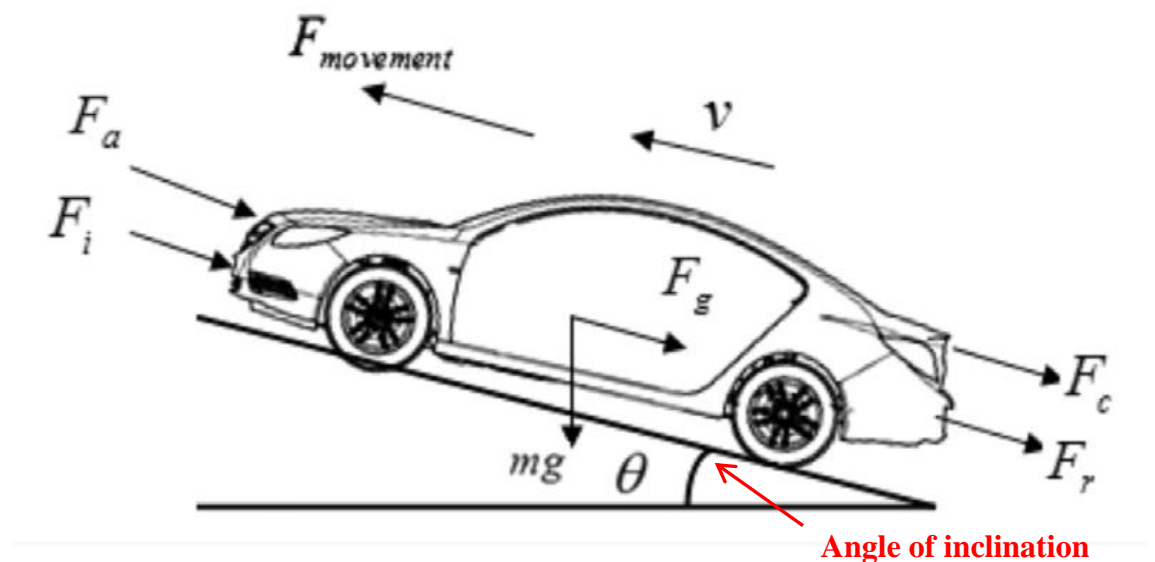
During the drive motion the cars are affected by the following four resistive forces: Aerodynamic Drag Force  $F_a$ , Rolling Resistance Force  $F_r$ , Resistive Grade Force  $F_c$ ,

Inertia Force (acceleration resistances)  $F_i$ . An optimization of fuel consumption can be obtained by improvement of the aerodynamic of the vehicle which reduces the air resistance. Moreover, the reduction of rolling resistance of the tyres has a positive effect by reducing the fuel consumption. [22]

Vehicle dynamics are considered in mathematical simulation models (Kinematic Model) for the specifications of the different type of drive, such as ICE, EV and HEV. Such a Vehicle Dynamic Model enables to obtain the tractive effort (traction power)  $F_t$  or  $F$  movement and the needed propulsion energy for specific vehicle and driving conditions. Based on that, the efficiency of the propulsion system for the entire driving cycle can be analyzed. The model considers car specifications (car weight, efficiency of transmission, ICE fuel consumption and output power of EV/HEV, efficiency of electrical power converters). Additionally, environmental conditions are included in the model, i.e. road conditions, wind speed/direction, air density.

Figure 5.11 shows the four vehicle driving resistances which are summed up to the tractive effort  $F_t$ (5-3) with the equation

$$F_t = F_r + F_a + F_c + F_i \quad (5-3)$$



**Figure 5.11:** All forces acting on vehicle during the movement [25]

### 5.4.2.1 Rolling resistance force

The rolling resistance force  $F_r$  is based on the relation of the car tyres and the road surface during the motion of vehicle. This is created by the hysteresis (energy loss due to heat) of the material of the tyres and the forces pushing on the tyres during the contact of the tyres to the surface of the road. It is expressed as followed:

$$F_r(t) = m \cdot g \cdot (C_{r0} + C_{r1}) \quad (5-4)$$

$$F_N = m \cdot g \quad (5-5)$$

$$C_r = \frac{d}{r} \quad (5-6)$$

The values and constants of the equation (5-4), (5-5) and (5-6) are:

$m$  = mass of the vehicle

$g$  = local acceleration of gravity (G)

$F_N$  = normal force

$C_{r0}$  = rolling resistance coefficient of stationary vehicle

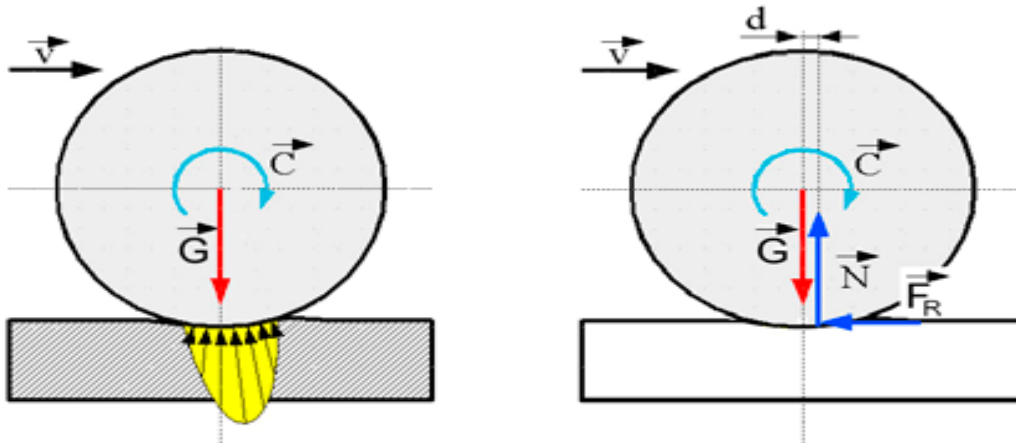
$C_{r1}$  = rolling resistance coefficient of moving vehicle

$r$  = wheel radius

$d$  = distance

The force of rolling resistance does not change at higher speeds. However, because there is a lot more heat being produced at higher speeds, the vehicle needs more power (energy per second) to work against rolling resistance.

The contact force between vehicle and surface becomes asymmetric due to the deformation during motion on the surface (Figure 5.12). The replacement of contact forces by static equivalent single forces results in (i) the normal force  $F_N$  which moves forward and (ii) in the rolling resistance force  $F_r$  towards the direction of motion of the vehicle (Figure 5.13).



**Figure 5.12:** Asymmetric contact force ; **Figure 5.13:** Forces during motion [12]

The road resistance coefficient is a dimensionless number which depends on material properties and geometry of the vehicle, i.e. tyres depend strongly on the air pressure and road condition as shown in Table 5.5. The best rolling resistant coefficient is given for asphalt and concrete roads.

rolling element/rolling element track	road resistant coefficient $f$
car tyre on asphalt, truck	0.006-0.010
car tyre on asphalt, passenger car	0.011-0.015
car tyre on concrete	0.01-0.02
car tyre on gravel	0.020
car tyre on cobblestone	0.015-0.03
car tyre on pot-holes track	0.03-0.06
car tyres on ground	0.05
car tyre on packed sand	0.04-0.08

**Table 5.5:** Typical rolling resistance coefficient  $C_r$  depend on road condition [12]

These coefficients are dependent on the angle of inclination of the vehicle to the road surface which is expressed in the formula:

$$(C_{r0} + C_{r1} \cdot v(t)^2) \approx f(t) \cdot \cos \Theta(t) \quad (5-7)$$

The new elements of the formula are:

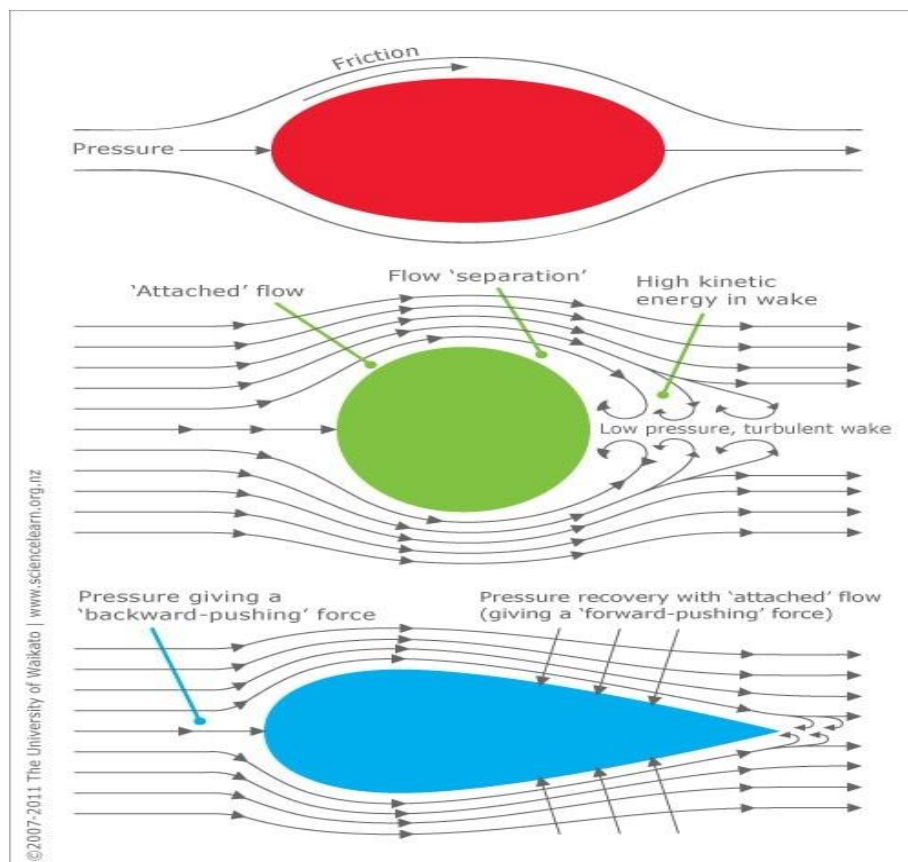
$f$  = equivalent coefficient of rolling resistance between the tyres and the road surface

$\Theta$  = angle of inclination of the road surface upon which the vehicle is travelling.

The rolling resistance force  $F_r$  depends on weight of the vehicle  $m$ , the road resistance drag  $f$  and the angle of inclination  $\theta$ . This force is constant without taking into account the speed of the vehicle and has a tendency to be a dominant resistive aspect at relatively low speeds. The minimization of the rolling resistance can be achieved by keeping the air pressure of tyres on a high level and by reducing the hysteresis respectively driving on a smooth surface.

#### 5.4.2.2 Aerodynamic drag force

Drag is caused by the friction of the vehicle while the force of wind or air resistance is pushing in the opposite direction to the motion of the vehicle. As shown in Figure 5.14, a pressure drag is caused by the air particles being more compressed (pushed together) on the front-facing surfaces and more spaced out on the back surfaces. This is caused when the layers of air separate away from the surface and begin to swirl – this is called turbulent flow.



**Figure 5.14:** Pressure drag in context of aerodynamic drag force [26]



The aerodynamic force is calculated as follows:

$$F_a = C_D \cdot 0.5 \cdot \rho \cdot A \cdot (v(t) - v_w)^2 \quad (5-8)$$

The values of the equation are:

$C_D$  = aerodynamic drag coefficient (passenger car approx 0.3)

$\rho$  = density of the ambient air (approx 1.2 kg/m<sup>3</sup> at 20°C)

$A$  = cross-sectional area of the vehicle

$v(t)$  = velocity (i. e. vehicle speed) in the direction vehicle travel

$v_w$  = wind speed in the direction of vehicle travel

Fa (5-8) changes with the wind speed and wind direction and is proportional to the square of the speed of the vehicle  $v(t)$ . Based on that Fa can be larger (headwind) or smaller (tailwind) and has a tendency to be on a small level at low speed and increases rapidly with higher velocity.

The aerodynamic drag coefficient can be reduced by an optimized vehicle's shape. The ideal aerodynamic shape for a vehicle / body is a teardrop with  $C_D = 0.4$  (vans are in a range of 0.5 – 0.7, passenger cars wedge-shaped within the body integrated headlamps/bumpers and optimized cooling air flow are in a range of 0.3 – 0.4). Based on that, the airflow stays more attached to the surface so that the wake left at the back is much narrower. This makes the low-pressure zone much smaller so the pressure drag will be smaller and the fuel efficiency improves. An additional positive effect can be achieved by the improvement of the atmospheric surrounding such as temperature, altitude and humidity. Due to the fluctuating values of these components, the density of ambient air  $\rho$  can be significantly influenced by them.

#### 5.4.2.3 Resistive gravity force

A further force which affects the vehicle is the gravitational force  $F_c$  (5-9) which is a result of the earth gravity to the vehicle mass  $m$  with the following formula:

$$F_c = m \cdot g \quad (5-9)$$

If the vehicle moves on level-road,  $F_c$  creates force components in the direction of the vehicle movement which is the resistive gravity force  $F_s$  (5-10). This is the force propelling or decelerating the vehicle on a level-road angel of inclination  $\theta$ :

$$F_s = F_c \cdot \sin \Theta (t) \quad (5-10)$$

The values of the equation are:

$\Theta (t)$  = grade angle in relation to the horizon vehicle movement

$m$  = mass of the vehicle

$g$  = local acceleration of gravity (G)

The resistive gravity force  $F_c$  depends on the slope of the roadway respectively which angle of inclination has the vehicle to the road. If the vehicle is climbing a grade and  $F_c$  is in the same direction as the rest of the resistive forces, then the value is positive ( $\Theta (t) > 0$ ). In a scenario of a downgrade road the value is negative ( $\Theta (t) < 0$ ) and the force propels the vehicle.

#### 5.4.2.4 Inertia force

Besides the velocity and the position, the acceleration is a central element in the kinetics. Newton's second law of motion states that if you do place a force on an object, it will accelerate and it will change its velocity in the direction of the force. This means, the mass inertia of the vehicle is manifested through the inertia force or acceleration force  $F_i$  and summarized with the equation:

$$F_i = m \cdot a (t) = m \cdot \frac{\Delta v (t)}{\Delta t} \quad (5-11)$$

The acceleration  $a$  (measured in m/s<sup>2</sup>) is directly proportional to the force  $F_i$ : if you are pushing on an object, three times harder, the acceleration will be three times greater. Especially in the acceleration phase of a vehicle from 0 to 100 km, this aspect has a high significance. This force aimed in a positive direction will create a positive change in velocity ( $a > 0$ ). In case of  $a < 0$ , the acceleration force creates a negative change in velocity (a negative acceleration). Under constant-speed driving conditions ( $a = 0$ ), the acceleration force has mostly a value of low or zero.

Additionally, the acceleration is inversely proportional to the mass of the vehicle: if you are pushing equally on two objects, and one of the objects has five times more mass than the other, it will accelerate at one fifth the acceleration of the other.

#### 5.4.2.5 Calculation of energy demand on a flat road for electronic drive

Based on the example of the Renault ZOE (electrical drive, width 1.56 m, height 1.40 m, weight 1,943 kg) the influencing forces are calculated as follows:

1) Aerodynamic drag force  $F_a$ :

$$F_a = 0.5 \cdot A \cdot \rho \cdot (v(t) - v_w)^2 \cdot C_D \quad (C_D \text{ with } 1 \text{ kg m}^2/\text{s}^2) \quad (5-12)$$

$$\begin{aligned} F_{a \text{ Renault ZOE}} &= 0.5 \cdot (1.56 \text{ m} \cdot 1.40 \text{ m}) \cdot 1.2 \text{ kg/m}^3 \cdot (100 \text{ km/h})^2 \cdot 0.3 \text{ kg m}^2/\text{s}^2 \\ &= 0.393 \text{ kg/m} \cdot 10^{10} \text{ m}^2 \cdot / (12.96 \cdot 10^6 \cdot \text{s}^2) \\ &= 303 \text{ kg/ s}^2 \end{aligned}$$

$$F_{a \text{ Renault ZOE}} = 303 \text{ N}$$

At a speed of 100 km/h the aerodynamic drag force is 303 N and at a speed of 50 km/h, this force is only one quarter (76 N) due to the quadratic function of speed of  $v_w$ .

2) Rolling resistance force  $F_r$ :

$$F_N = m \cdot g \quad (5-13)$$

$$F_{N \text{ Renault ZOE}} = 1,943 \text{ kg} \cdot 9.81 \text{ m/s}^2 = 19.061 \text{ kg m/s}^2$$

$$F_{N \text{ Renault ZOE}} = 19.061 \text{ N}$$

$$F_r(t) = F_N \cdot (C_{r0} + C_{r1}) \quad C_r = 0.011 - 0.015 \text{ (car tyres on asphalt)}$$

$$F_{r \text{ Renault ZOE}} = 19.061 \cdot 0.013 \quad C_r \text{ average} = 0.013$$

$$F_{r \text{ Renault ZOE}} = 248 \text{ N}$$

For a distance of 100 km ( $s$ ) at a speed of 100 km/h ( $v_w$ ), the Renault ZOE needs an aerodynamic drag force of 303 N and rolling resistance force of 248 N.

The required energy of electric vehicle (without resistance gravity and inertia force) is calculated as follows:

$$E = (F_a + F_r) \cdot s \quad (5-14)$$

The quotation has the new value:

$s$  = distance

(i) The required energy is calculated as follows with a speed  $v = 100$  km/h:

$$\begin{aligned} E_{\text{Renault ZOE}} &= (303 \text{ N} + 248 \text{ N}) \cdot 100 \text{ km} \\ &= 5.51 \cdot 10^7 \text{ Nm} \\ &= 5.51 \cdot 10^7 \text{ Ws} \\ &= 15.3 \text{ kWh} \end{aligned}$$

(ii) The required energy with a speed  $v_w = 50$  km/h:

$$E_{\text{Renault ZOE}} = (76 \text{ N} + 248 \text{ N}) \cdot 100 \text{ km}$$

$$\begin{aligned}
&= 3.24 \cdot 10^7 \text{ Nm} \\
&= 3.24 \cdot 10^7 \text{ Ws} \\
&= 9 \text{ kWh}
\end{aligned}$$

Taking into account the electricity costs of € 0.25, the electricity costs for a distance of 100 km are € 2.25. A conventional engine consumes 7.0 liter fuel per 100 km so that at a fuel price of € 1.40 the costs result in € 9.80. This calculation shows that the fuel costs for a distance of 100 km are 2.5 times higher of an ICE than the electricity costs of a BEV. [12]

### 5.5 Specification of energy demand and GHG emission within the WtW analysis

The direct energy demand of a vehicle and the direct combustion-related emissions (TtW) as well as the indirect energy demand and emissions inclusive fuel and power production (WtT) must be shown separately. This is especially needed to present correctly the climate impact of alternative drives respectively biofuels in comparison to the conventional approaches. This means that during the WtW analysis the four following parameters have to be assessed: [27]

- WtW energy demand (primary energy consumption)
- TtW energy demand (final energy consumption)
- WtW greenhouse gas emission
- TtW greenhouse gas emission.

The entire WtW analysis demonstrates the WtW energy demand and GHG emission which are associated with

- excluding the energy content of the fuel itself (i.e. WtT energy demand) per unit energy of the fuel
- the energy demand by the vehicle (i.e. TtW energy) per unit distance covered on the basis of the NEDC Road Driving Cycle.

In general, the energy values denote the total primary energy demand to move the vehicle over a span of 1 km on the basis of NEDC cycle. The following equations show the WtW energy demand and GHG emission during the entire WtW process:

#### **Total WtW energy (MJ/100 km)**

$$= \text{TtW energy (MJ}_f\text{/100 km)} \times (1 + \text{WtT total expended energy (MJ}_{xt}\text{/MJ}_f))$$

The values of the equation are:

$MJ_f$  refers to the energy contained in the fuel.

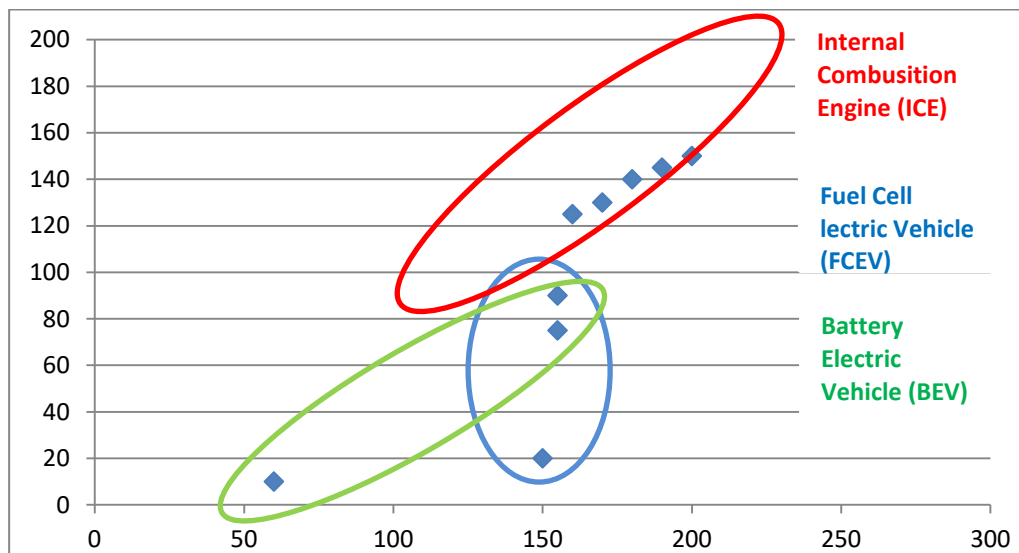
$MJ_{xt}$  refers to the total/fossil additional external energy needed to produce 1 MJ of fuel from the primary energy resource.

GHG figures represent the total grams of CO<sub>2</sub> equivalent emitted in the process of delivering 100 km of vehicle motion on the NEDC cycle. [20]

**WtW GHG (g CO<sub>2</sub>eq/km)**

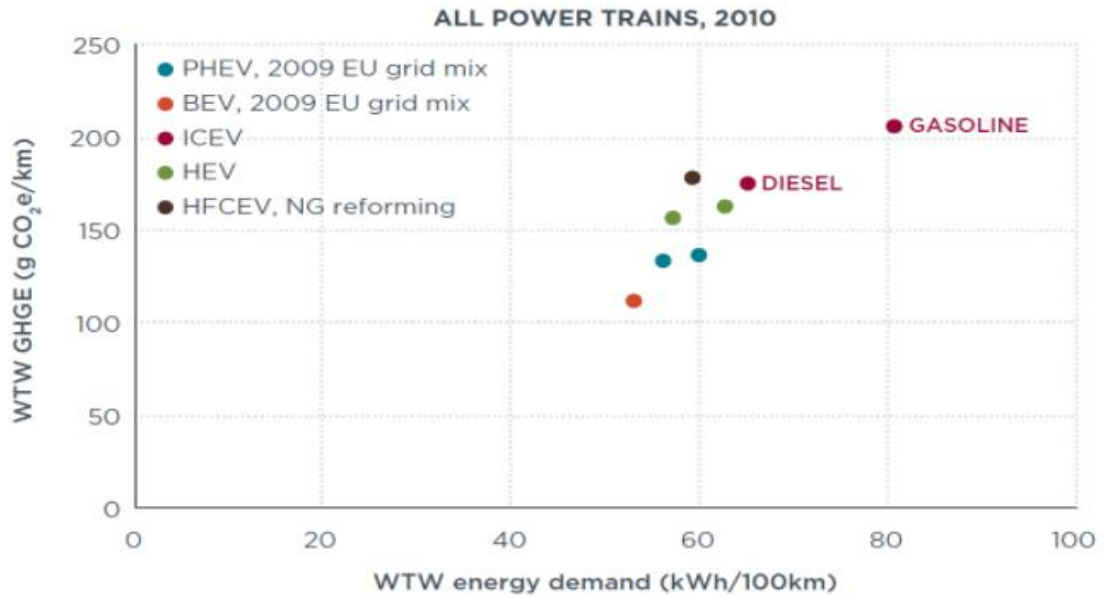
$$= \text{TtW GHG (g CO}_2\text{eq/km)} + \text{TtW energy (MJ}_f\text{/100km)} / 100 \times \text{WtT GHG (g CO}_2\text{eq/ MJ}_f\text{)}$$

Figure 5.15 shows greenhouse gas emission (GHGE) versus energy demand during the WtW process. The WtW analysis discloses the differences concerning the greenhouse emissions and efficiency of the various drives. A key component of electric vehicles is the applied energy mix (e. g. European energy mix) due to the direct scaling of WtW emission and the emission resulting from electricity production.



**Figure 5.15:** Efficiency comparison of powertrain (GHGE emission, WtW energy demand); based on Daimler and WtW studies. Concave, EUCAR, JRC and JHFC [17]

Figure 5.16 shows the CO<sub>2</sub> emission depending on the energy demand of mid -range passenger cars of different powertrain technologies and the use of different fuels.



**Figure 5.16:** WtW Greenhouse Gas Emission (GHGE) and energy demand of passenger cars with the use of different fuels [7]

For hybrid drives (PHEV, HEV) it shows two different fuels for the operation i.e. diesel and gasoline. It is also shown that pure electric vehicle (BEV) emits – based on EU grid mix - the least amount of greenhouse gas as compared to all other vehicle technologies. For BEV the grid mix it is of vital importance because the WtW emission is directly scaled with the emission of the grid generation. Currently, the primary energy source of BEV is based on EU energy mix with a high share in fossil fuels which is the driver of the greenhouse effect. Thus, there is still potential for further reduction of the CO<sub>2</sub> emission by using more renewable energies within the EU energy mix. Biofuels have a shorter emission cycle than fossil fuels which results in lower emissions as of fossil.

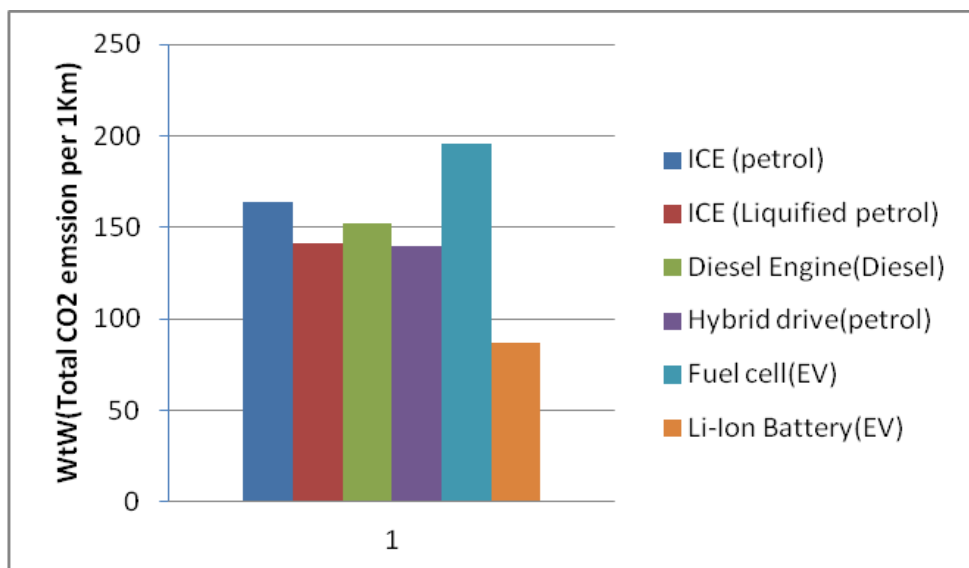
To assess the emission potential of the different alternative drives it is important to consider the entire fuel cycle. Table 5.6 shows the total amount of CO<sub>2</sub> emission during the whole WtW process per 1 km in various drives topologies.

Types of drive	Types of fuels	Production method	Primary energy source	CO2 emission for 1 km		
				WtT	TtW	WtW
Petrol engine	Petrol	Refining	Crude oil	24	140	164
Petrol engine	Liquefied petroleum gas	Conditioning	Natural gas	15	126	141
Diesel engine	Diesel	Refining	Crude oil	24	128	152
Diesel engine	Biodiesel	Esterificaiton	Rape oil	- 50 *)	133	83
Hybrid drive (petrol engine)	Petrol	Refining	Crude oil	20	120	140
Fuel cell (electric drive)	Hydrogen	Electroysis	EU electricity mix	196	0	196
Li-ion battery (electric drive)	Hydrogen	Power station	EU electricity mix	87	0	87

\*) Negative balance due to credit note out of extraction of by-products during the fuel production

**Table 5.6:** Total CO<sub>2</sub> emission during WtW-process in various drives technologies [7]

The above mentioned is also illustrated in Figure 5.17:



**Figure 5.17:** CO<sub>2</sub> emission during whole process (WtW)

The emission in context of WtT system (energy unit is g CO<sub>2</sub>eq/km) is dependent on the primary energies meaning the type of fuel which have a different effect on the CO<sub>2</sub>. Based on the current energy mix with its high share in conventional fuels, e. g. coal and oil, the CO<sub>2</sub> emission of electric drives is higher than the emission of gasoline, diesel and bio fuels. Based on changing energy mix in favour of renewable energies, the emission of alternative drives will further decrease. In the process of TtW, the CO<sub>2</sub> emission is mileage-specific. It depends on driving behavior and is not only on the types of drivetrain topologies. The rebound effect or individual driving behavior which is not represented in the average values shown in the table 1, esp. in case of biodiesel. Considering the greenhouse gas neutral effect, the CO<sub>2</sub> emission is dependent on the plant that is used for the production of the fuels. Thus, it releases much shorter CO<sub>2</sub> emission in case of biofuels as compared to fossil fuels and benefits from by-products which are gained during fuel production. The Table 1 emphasizes that in the TtW process the value of CO<sub>2</sub> emission for electric drives is zero.

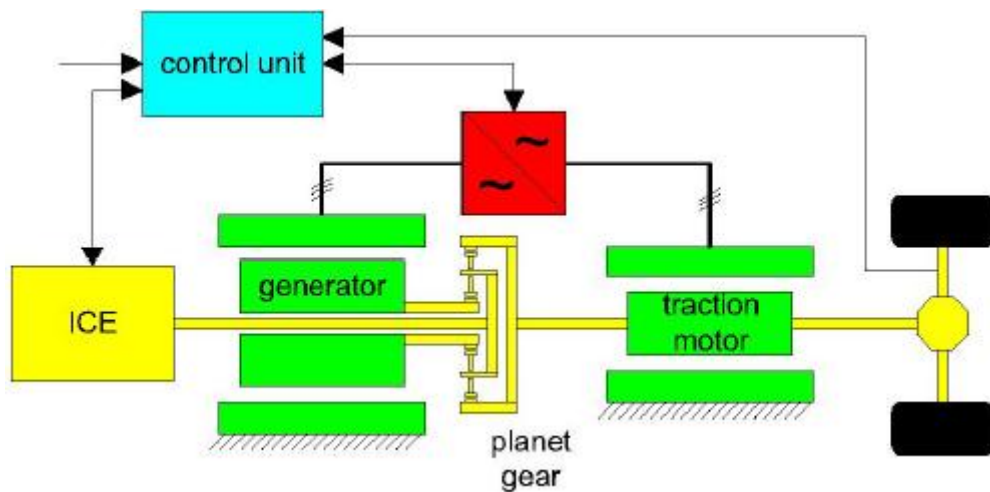
## **6 Carry out analysis of power flow and operational modes of hybrid drive with electric and planetary gear power splitter**

This part contains the measurement in laboratory and experimental results. It is mainly focused on the series hybrid electric vehicle.

### **6.1. Introduction of Hybrid Electric power divider in Hybrid electric vehicle**

Hybrid electric vehicle is a special kind of vehicle in which primary combustion engine runs a power divider. This power divider can be electric generator or planetary gear system. The working of power divider is to split to mechanical power of the engine into two parts. The splitting phenomenon is done by the three shaft of the planetary gear. Internal combustion engine operates the first shaft of the planetary gear, second and third shaft drives the generator and the car wheels respectively. In this configuration there is difference between car speed and ICE and the generator rotates with speed which is proportional to that difference. This result allows the output of ICE splits into two parts. The first is proportional to the difference between ICE and car speed, it is transformed electric energy into the generator and supplied to the motor. The second part is also proportional to the car speed and transferred directly to the car wheels by the planetary shaft. This mechanism enables to control the speed of the engine which is not dependent on the car speed to reach the minimum consumption of fuel. Figure 6.1 shows the mechanical power divider configuration.





**Figure 6.1:** HVC with mechanical power divider [28]

## 6.2. Aim of this experiment

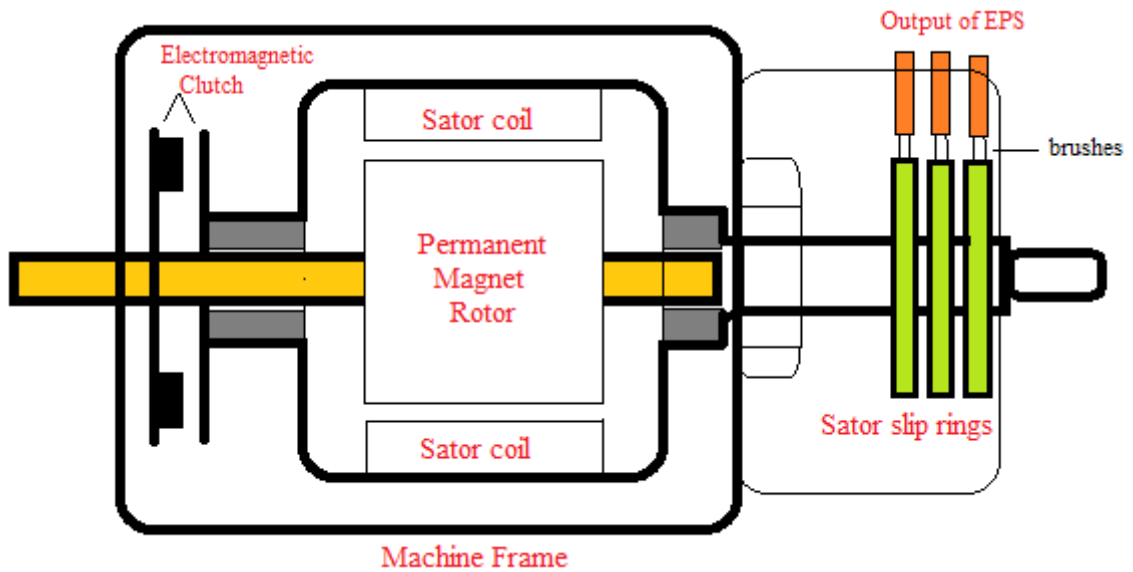
The aim of this experiment is calculate the approximate value of energy efficiency of individual components and total energy efficiency of this experimental setup. With the help of these results one can compare the energy efficiency among conventional, hybrid and electric vehicles.

## 6.3. HEV-CVUT concept of hybrid-electric propulsion system

There is an experimental setup of series hybrid vehicle in laboratory of FEE CTU (Faculty of electrical engineering at the Czech technical university).. The electric power splitter (EPS) and super-capacitor (SC) are the main characteristics of the experimental setup of hybrid vehicle. This type of technologies has been already used in Toyota Prius car which works on energy splitting from internal combustion engine (ICE). In the experimental setup of hybrid vehicle in CTU, Prague, the concept of power splitting is operated electrically by using of EPS. Conceptually, the overall weight of the vehicle is reduced by reducing the weight of one component and it is directly influenced on the reduction of fuel consumption. In this drive concept, the use of super-capacitor as technological equipment for storage of electrical energy in place of chemical battery for accumulation of breaking kinetic energy. Thus, it gives a chance to store energy without any transformation from electrical to chemical and vice- versa. Moreover, there could be a chance to eliminate the one energy transformation and it means that significant loss

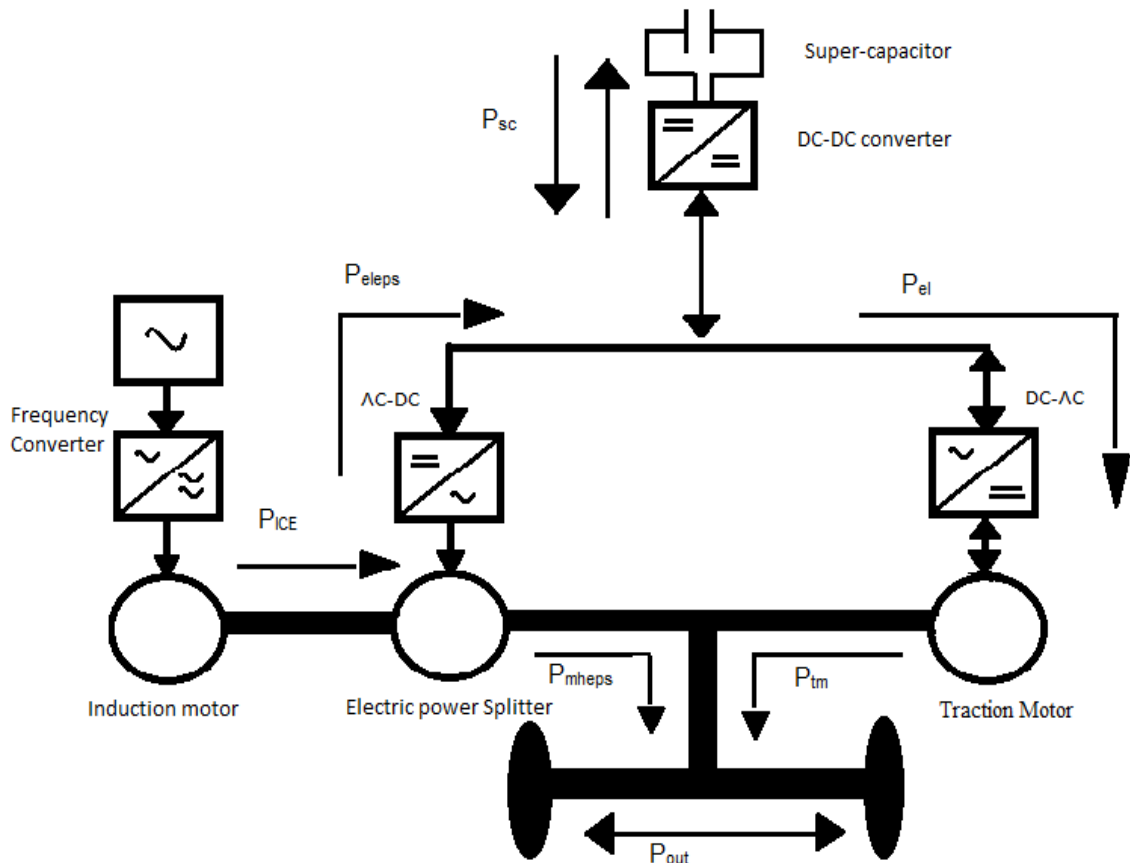
of energy transformation will be ignored. Hence it gives higher efficiency as compared to other propulsion.

The illustrative representation and power flow of the experimental setup of HEV with super-capacitor and EPS is shown in Figure 6.3. In this configuration, EPS is a kind of synchronous generator with two rotating parts i.e. one is rotating stator and other one is permanent magnet which is shown in Figure 6.2.



**Figure 6.2:** Electric power splitter

ICE is only one main power source of the vehicle which generates mechanical power  $P_{ICE}$ . The rotating stator and permanent magnet rotor are thoroughly coupled to the Traction motor (TM) and drive-shaft of ICE respectively and this transmission leads to the wheels of car and rotates with the speed proportional to the velocity of vehicles. This setup enables the ICE to drive on the most optimal revolutions during whole driving period and it behaves like a series hybrid configuration.



**Figure 6.3:** Power Flow in the configuration of HEV-CVUT

There are seven distinguished powers in this HEV system and it is shown as given below:

$P_{ICE}$  = mechanical output power of ICE on the drive-shaft

$P_{eleps}$  = electrical output power of EPS to the DC circuit,

$P_{mheps}$  = mechanical EPS output power on the stator shaft

$P_{tm}$  = mechanical output power of the traction motor (TM),

$P_{sc}$  = electrical power for charging (discharging) to the super capacitor,

$P_{el}$  = electrical power that powers the traction motor from DC circuit,

$P_{out}$  = final output power that delivers to the car wheels.

The induction motor represents the main electrical source of the vehicle and it is inserted on the rotating stator shaft of the EPS. Electric power splitter facilitates more flexible process between car wheels and ICE drive shaft because there is only one connection which is magnetic field between rotor and stator of the EPS. These two components are connected electrically through two power converter i.e. AC/DC and DC/AC via DC link. A SC is connected in series to the DC/DC converter for charging and discharging on the DC link. Mechanical power of ICE is divided into mechanical

power  $P_{mhps}$  and electrical power  $P_{eleps}$  by use of EPS. This power splitting concept depends on controlling of AC/DC converter, which controls the current flow into the stator winding of EPS. By controlling the current in the stator winding, it is important to regulate the magnetic field within the machine. By regulating the magnetic field, it enables to control the torque on the stator shaft and hence to control the mechanical power  $P_{mhps}$  of EPS. The input power ( $P_{el}$ ) of the TM is summation of generated power in electrical part of EPS ( $P_{eleps}$ ) and power from SC ( $P_{sc}$ ).

$$P_{el} = P_{eleps} + \eta_{dcdc} * P_{sc} \quad (6-1)$$

$$P_{el} = P_{eleps} + P_{dcsc} \quad (6-2)$$

Total output power ( $P_{out}$ ) to the car wheels is multiplication of transmission efficiency ( $\eta_{trans}$ ) to the summation of produced mechanical power ( $P_{tm}$ ) by TM and output mechanical power ( $P_{mhps}$ ) of EPS.

$$P_{out} = (P_{mhps} + P_{tm}) * \eta_{trans} \quad (6-3)$$

$$P_{out} = (P_{mhps} + P_{el} * \eta_{tm} * \eta_{dc-ac}) * \eta_{trans} \quad (6-4)$$

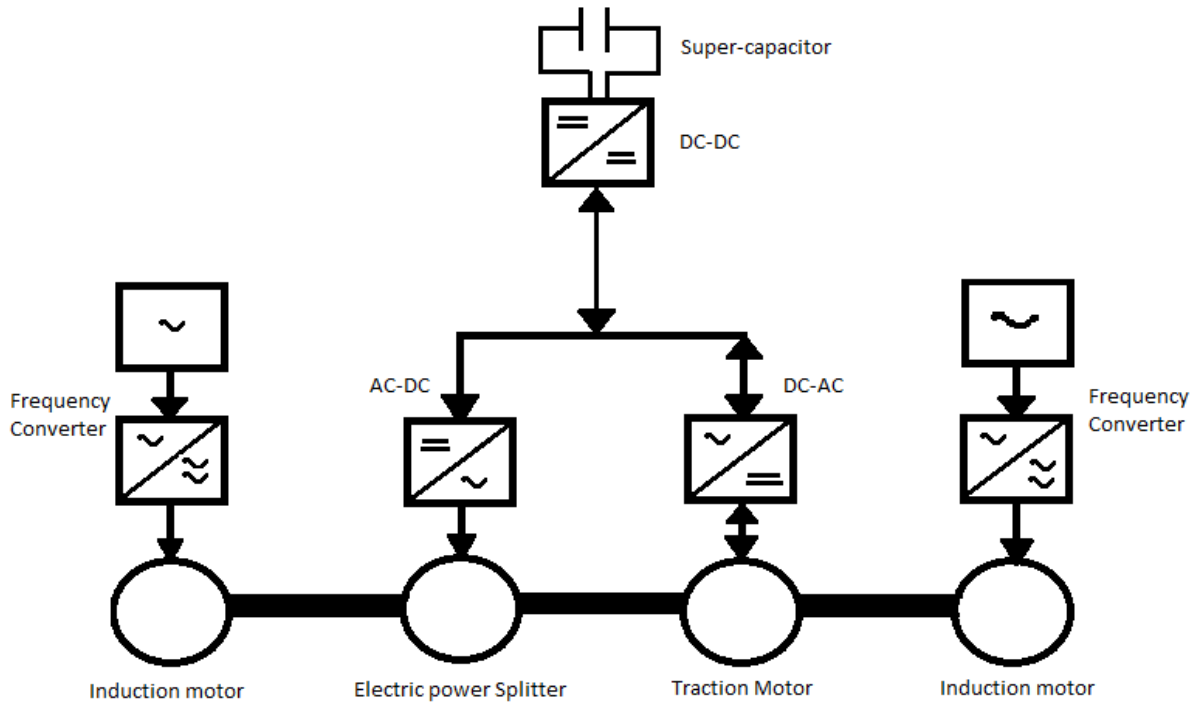
TM changes its mode of operation from motor to generator during the braking mode of car. During that process the moving vehicle acts a kinetic energy and TM generates electrical energy during generator mode and it is stored to the Sc via DC/AC converter and DC/DC converter.

This experimental setup of HEV-CVUT is complex concept and it has many power transformations and energy pathways. This setup has the similar advantages as Toyota Prius drivetrain concept as a series or parallel drivetrain structure. In HEV-CVUT experimental setup, it has only one device i.e. EPS for power splitting in place of two separate devices which is used in Toyota Prius concept. Due to this fact, there is less number of energy transformations and overall mass of the vehicle is lower and hence it shows more fuel efficient process. Super- capacitor is also implemented in this concept and it has more power density as compared to chemical battery and gives better recuperation power absorbance and energy storage unit.

#### **6.4. Experimental setup of HEV stand**

This experimental setup has been created in laboratory at department of electric drives and traction, Czech Technical University, Prague. The aim of this experimental setup is to determine the performance of individual components of HEV concepts. The block diagram of this setup is shown in Figure 6.4. The main functional units of this

experimental working stand and its individual powers of each component have been already discussed in last section.



**Figure 6.4:** Block Diagram of Experimental Setup

On this experimental setup, two regulated traction motors (TM) has been used instead of car wheels and ICE. AC induction motor works like ICE and it produced  $P_{ICE}$  power and rotation  $n_{ICE}$  on drive shaft and electrically controlled with frequency converter (FC). The working of FC is to regulate the rotation and power of AC induction motor on the basis of demand of ICE working performance. Second induction motor works as traction load (brake) which generates braking torque ( $T_{brake}$ ) on the shaft of the working regime and it is proportional to the braking resistance of the braking load. By means of this experimental working stand, it is developed a setup for testing of the hybrid electric vehicle without using any actual hybrid vehicle.

In this working regime, there are two rotating shafts and these are mechanically independent to each other. First rotating shaft is connected in between the controlled induction motor (ICE) and rotor of EPS. Second rotating shaft is connected among three equipments i.e. rotating stator of EPS, controlled induction motor (brake) and traction motor. Only magnetic field of EPS is connection in between these two rotating shafts. There are two sensors which are connected on the rotating shaft and they detect the rotation of every component. This experimental setup subsist four electrical machines

(one traction motor, two induction motors and one electric power splitter), super-capacitor, five semiconductor power control units and all required equipment, power supply and protection instruments. These four electrical machines are shown in Figure 6.5.



**Figure 6.5:** Experimental setup of four machines

Other necessary equipments such as frequency converters, power switches, control switches, power control unit (AC/DC,DC/AC and DC/DC converters), power cables which are connected with each other and put in the equipment cabinet of the working regime. This configuration is shown in Figure 6.6.



**Figure 6.6:** Other necessary equipment in this control chamber.

Nice	Mice	Feps	leps	Ueps	cosF	ldc	Udc	Nbrake	Mbrake	Seps	Peps
1500	0,71	86,7	0,27	169,2	0,7	0,25	219,2	200	1,99	80	72
1551	0,81	86,8	0,33	168,9	0,74	0,31	219,5	250	1,58	94	90
1601	0,9	86,8	0,38	165,5	0,77	0,37	214,5	300	1,76	107	109
1650	0,95	86,7	0,41	168,5	0,77	0,42	217,5	350	1,96	122	128
1701	1,05	86,8	0,47	168,3	0,79	0,48	217,3	400	2,14	136	151
1750	1,17	86,7	0,52	168,5	0,8	0,54	217	450	2,41	150	174
1798	1,33	86,9	0,59	167,8	0,82	0,62	215,9	500	2,55	168	206
1849	1,43	86,5	0,63	167,6	0,83	0,69	215,7	550	2,83	185	235
1901	1,59	86,8	0,72	167,4	0,85	0,8	214,9	600	3,04	207	273
1950	1,77	86,7	0,81	167,4	0,86	0,91	214,5	650	3,39	232	317
2001	1,95	86,7	0,89	167,3	0,87	1,02	214,1	700	3,72	259	365
2051	2,14	86,8	0,98	166,7	0,87	1,14	213,3	750	4,04	285	414
2098	2,38	86,4	1,11	166,6	0,88	1,26	212,9	800	4,38	319	476
2150	2,6	86,8	1,23	166,5	0,89	1,45	212	850	4,83	355	543
2200	2,82	86,7	1,32	166,5	0,89	1,57	211,5	900	5,07	384	607
2251	3,21	86,6	1,55	165,8	0,9	1,8	210,7	950	5,77	441	708
2300	3,55	86,8	1,71	165,8	0,9	2,05	209,6	1000	6,31	490	809
2351	3,91	86,7	1,88	165,1	0,9	2,27	208,7	1050	6,81	539	914
2404	4,32	86,9	2,09	164,7	0,91	2,53	207,4	1100	7,5	599	1037
2453	4,76	86,8	2,36	164,2	0,91	2,86	206,7	1150	8,17	667	1176
2498	5,23	86,7	2,58	163,8	0,91	3,14	205,3	1200	8,71	733	1322
2551	5,77	86,8	2,88	163,4	0,92	3,51	204,5	1250	9,65	813	1496
[rot/min]	[Nm]	[Hz]	[A]	[V]		[A]	[V]	[rot/min]	[Nm]	[VA]	[W]

Table 6.1: Measured values of 0%inclination of flat road



#### 6.4.1. Calculated values 0% inclination from the road

By using the following formulae, Power and efficiency of individual equipment in this experimental setup is computed and Table 9 shows the values of different RPM.

1. Output power  $P_{ICE}$  Internal combustion engine:

$$P_{ICE}(t) = \frac{2 \cdot \pi}{60} \cdot n_{ICE}(t) \cdot M_{ICE}(t) \quad (6-5)$$

2. Traction load braking power  $P_{brake}$ :

$$P_{brake}(t) = \frac{2 \cdot \pi}{60} \cdot n_{brake}(t) \cdot M_{brake}(t) \quad (6-6)$$

3. Output power  $P_{DC}$  in DC circuit:

$$P_{DC}(t) = U_{DC}(t) \cdot I_{DC}(t) \quad (6-7)$$

4. EPS revolution  $N_{EPS}$ :

$$n_{eps}(t) = n_{ICE}(t) - n_{brake}(t) \quad (6-8)$$

5. Power of internal combustion engine is directly transmitted to the shaft of the wheel ( $P_{epsmh}$ ):

$$P_{epsmh}(t) = \frac{2 \cdot \pi}{60} \cdot n_{brake}(t) \cdot M_{ICE}(t) \quad (6-9)$$

6. Out of total EPS power ( $P_{eps}$ ),  $P_{epsmh}$  is directly transmitted to the shaft and remaining power ( $P_{epsel}$ ) is induced into the winding of the rotating stator of the EPS through the introduction of magnetic field phenomena.

$$P_{eps}(t) = P_{epsmh}(t) + P_{epsel}(t) \quad (6-10)$$

$$P_{epsel}(t) = P_{eps}(t) - P_{epsmh}(t) \quad (6-11)$$

7. Overall efficiency [ $\eta_{HEV}(t)$ ] of HEV setup:

$$\eta_{HEV}(t) = \frac{P_{brake}(t)}{P_{ICE}(t)} \quad (6-12)$$

8. Efficiency of AC-DC rectifier [ $(\eta_{AC-DC}(t))$ ]:

$$\eta_{AC-DC}(t) = \frac{P_{DC}(t)}{P_{EPS}(t)} \quad (6-13)$$

9. Braking power ( $P_{brake}$ ) is summation from mechanical power from EPS and power generated from the traction motor ( $P_{tm}$ ).

$$P_{brake}(t) = P_{epsmh}(t) + P_{tm}(t) \quad (6-14)$$

$$P_{tm}(t) = P_{epsmh}(t) - P_{brake}(t) \quad (6-15)$$

10. The efficiency of traction is the ratio of power generated from traction motor to DC circuit power.

$$\eta_{tm} = \frac{P_{epsmh}(t) - P_{brake}(t)}{P_{DC}(t)} \quad (6-16)$$

Price	Pbrake	$\eta_{HEV}$	P <sub>de</sub>	$\eta_{ac-de}$	$\eta_{ac-de2}$	$\eta_{ps}$	Pe <sub>psmb(0)</sub>	Pe <sub>psel(0)</sub>	$(2\pi)^{0.60}$	$\eta_{E,PS}$	Pe <sub>psel/Pe<sub>psmb</sub></sub>	P <sub>tm</sub>	$\eta_{tm}$	Price-Pe <sub>psmb</sub>	$\eta_{psel}$
111,47	41,66	37,37	54,80	0,96	95,91	1300	14,9	57,1	0,105	0,65	3,8	26,8	48,9	96,6	0,59
131,49	41,34	31,44	68,05	0,99	98,90	1301	21,2	68,8	0,105	0,68	3,2	20,1	29,6	110,3	0,62
150,81	55,26	36,64	79,37	0,98	98,30	1301	28,3	80,7	0,105	0,72	2,9	27,0	34,0	122,6	0,66
164,07	71,80	43,76	91,35	0,98	98,02	1300	34,8	93,2	0,105	0,78	2,7	37,0	40,5	129,3	0,72
186,94	89,59	47,93	104,30	0,97	97,44	1301	44,0	107,0	0,105	0,81	2,4	45,6	43,8	143,0	0,75
214,31	113,51	52,97	117,18	0,99	98,56	1300	55,1	118,9	0,105	0,81	2,2	58,4	49,8	159,2	0,75
250,29	133,45	53,32	133,86	0,98	98,14	1298	69,6	136,4	0,105	0,82	2,0	63,8	47,7	180,7	0,75
276,75	162,91	58,87	148,83	0,97	97,48	1299	82,3	152,7	0,105	0,85	1,9	80,6	54,2	194,4	0,79
316,36	190,91	60,35	171,92	0,99	99,29	1301	99,9	173,1	0,105	0,86	1,7	91,1	53,0	216,5	0,80
361,26	230,63	63,84	195,20	0,99	99,29	1300	120,4	196,6	0,105	0,88	1,6	110,2	56,5	240,8	0,82
408,40	272,55	66,74	218,38	0,98	98,31	1301	142,9	222,1	0,105	0,89	1,6	129,7	59,4	265,5	0,84
459,40	317,14	69,03	243,16	0,99	98,84	1301	168,0	246,0	0,105	0,90	1,5	149,2	61,3	291,4	0,84
522,63	366,75	70,17	268,25	0,97	96,94	1298	199,3	276,7	0,105	0,91	1,4	167,5	62,4	323,3	0,86
585,09	429,71	73,44	307,40	0,99	98,62	1300	231,3	311,7	0,105	0,93	1,3	198,4	64,5	353,8	0,88
649,35	477,59	73,55	332,06	0,97	97,28	1300	265,6	341,4	0,105	0,93	1,3	212,0	63,8	383,7	0,89
756,29	573,73	75,86	379,26	0,98	97,54	1301	319,2	388,8	0,105	0,94	1,2	254,5	67,1	437,1	0,89
854,60	660,45	77,28	429,68	0,98	98,23	1300	371,6	437,4	0,105	0,95	1,2	288,9	67,2	483,0	0,91
962,14	748,42	77,79	473,75	0,98	97,82	1301	429,7	484,3	0,105	0,95	1,1	318,7	67,3	532,4	0,91
1086,99	863,50	79,44	524,72	0,97	97,24	1304	497,4	539,6	0,105	0,95	1,1	366,1	69,8	589,6	0,92
1222,12	983,40	80,47	591,16	0,98	98,03	1303	572,9	603,1	0,105	0,96	1,1	410,5	69,4	649,2	0,93
1367,42	1093,98	80,00	644,64	0,97	96,92	1298	656,9	665,1	0,105	0,97	1,0	437,1	67,8	710,5	0,94
1540,62	1262,54	81,95	717,80	0,97	96,86	1301	754,9	741,1	0,105	0,97	1,0	507,6	70,7	785,7	0,94
[W]	[W]	[W]	[W]	[%]	[rot/min]	[W]	[W]	[W]				[W]	[%]	[W]	

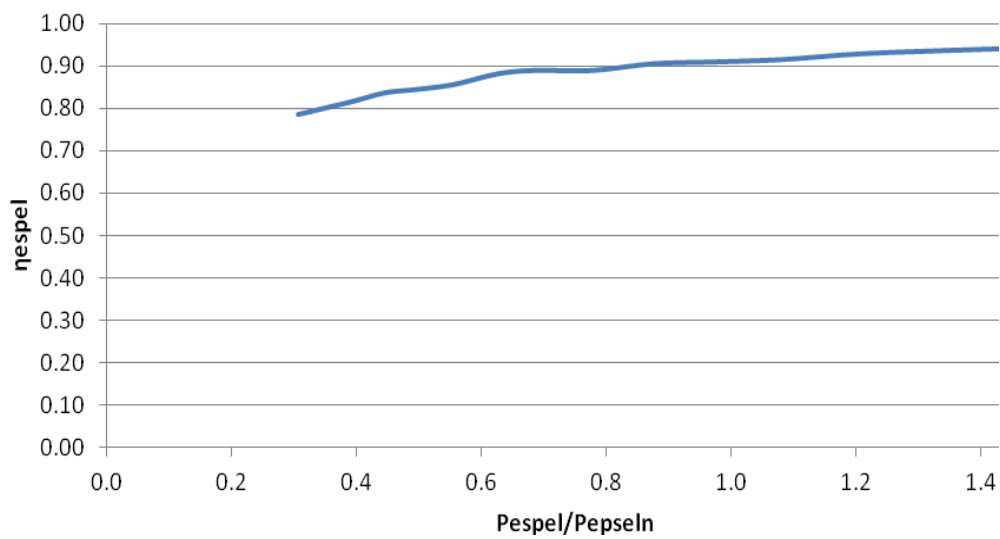
Table 6.2: Calculated values for 0% inclination of flat road

## 6.4.2. Results

### 6.4.2.1. Energy Efficiency of Electrical part of electric power splitter ( $P_{\text{epsel}}$ )

The energy efficiency of electrical part of EPS is defined by the calculated part of output power of electric EPS ( $P_{\text{epsel}}$ ) and shown in Figure 6.7. The rated power of machine of real vehicle is higher the experimental setup of HEV-CVUT. Hence, energy efficiency is the function of the ratio of relative rated power of EPS machine.

$$\eta = f \frac{P_{\text{epsel}}}{P_{\text{epseln}}} \quad (6-17)$$



**Figure 6.7:** Energy efficiency of electric part of EPS

### 6.4.2.2. Energy efficiency of mechanical part of the EPS ( $P_{\text{epsmh}}$ )

The energy efficiency of mechanical part of EPS is almost of 97% because there is only one power loss i.e. bearing loss during the transmission from EPS mechanical to car wheels.

### 6.4.2.3. Energy efficiency of Traction motor (TM)

The nominal power of traction motor is 3 kW. To plot the graph of energy efficiency of traction motor is the ratio of the calculated power of the traction motor during the experiment to the nominal part of the traction motor.

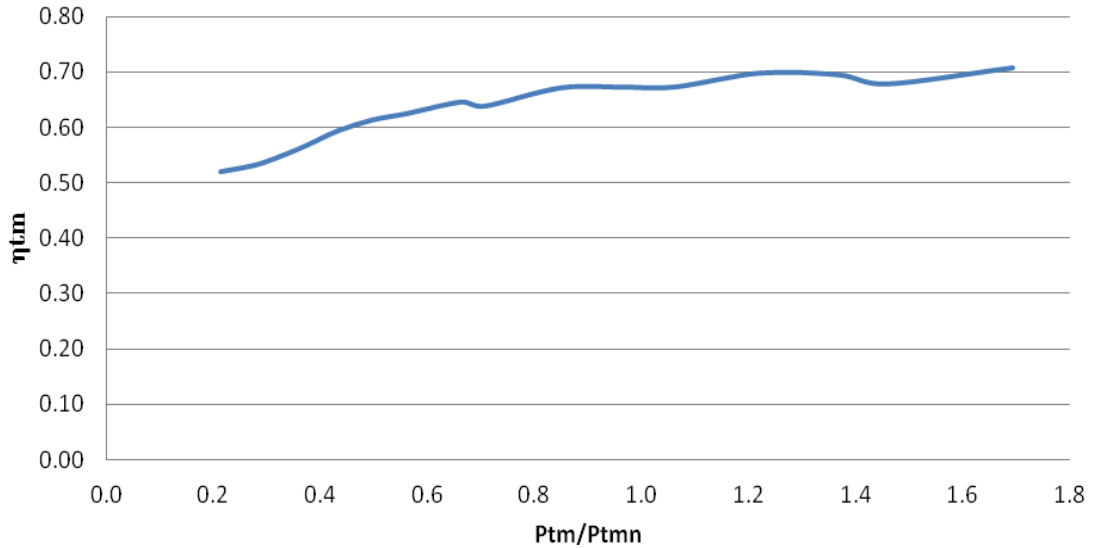


Figure 6.8: Energy efficiency of TM

### 6.4.2.4. Energy efficiency of AC-DC power converters

The efficiency of AC-DC converter and DC-AC is almost same and it is calculated on the basis of the measured values of experiment and shown in Figure 6.8.

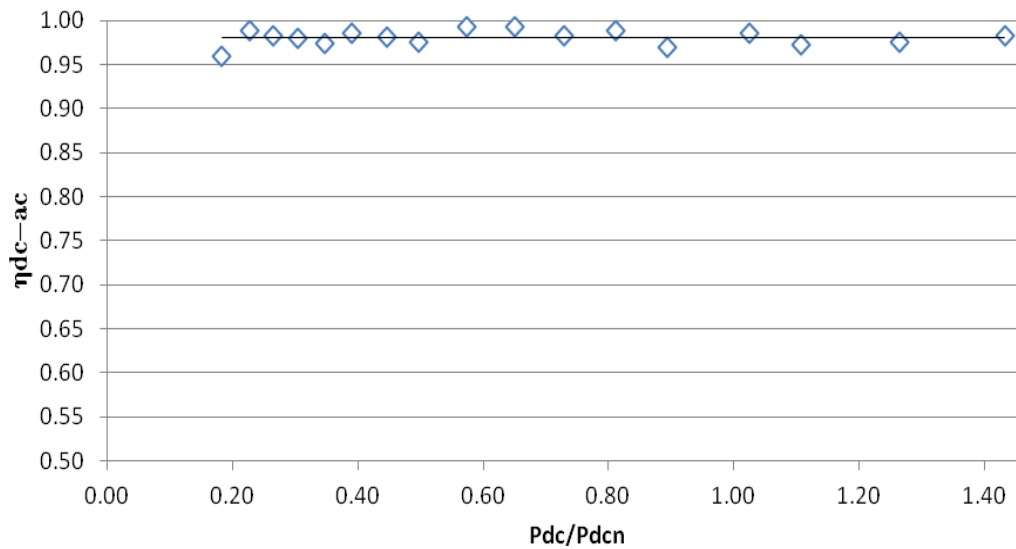


Figure 6.9: Energy efficiency of AC-DC converter

#### 6.4.2.5. Overall efficiency of HEV-CVUT

Total efficiency of HEV-CVUT is the multiplication of average efficiency of AC-DC converter, average efficiency of traction motor and average efficiency of electrical and mechanical of EPS and it is given below:

$$\eta_{overall} = \mu\eta_{tm} \cdot \mu\eta_{AC-DC} \cdot \mu\eta_{epsel} \cdot \mu\eta_{epsmh} \quad (6-18)$$

$$\eta_{overall} = 0.57 \cdot 0.98 \cdot 0.82 \cdot 0.97$$

$$\eta_{overall} = 0.45$$

## 7. Conclusion

The transition from the currently dominating internal combustion engines towards alternative engines such as hybrid and electric engines is one of the major challenges for the automotive sector and the nations all over the world to solve the problem of energy demand and greenhouse gas emission globally.

The closer look at the life cycle assessment of the three propulsion concept shows that a detailed assessment of the energy process (Well-to-Tank) and vehicle process (Tank-to-Wheel) has to be done to get a precise statement concerning energy demand and greenhouse gas emission of each type of drivetrain. Besides that, there are many factors which should be considered such as energy density of the different types of fuels, batteries and fuel cells. This parameter has a big influence on the efficiency of the type of drive. The comparison showed that the fossil fuels have the highest volumetric energy density and specific energy ahead of the fuel cells and gaseous fuels. The lowest is given by the batteries whereby there are also variations between the different types of batteries, meaning the lithium-ion batteries have the highest value.

During the measurement of the energy demand and emissions of the different drives in the Tank-to-Wheel process, it is also important to consider the factor driving behavior in the urban and extra-urban driving cycles. Moreover, the determination of efficiency depends on the different forces which have an influence on the vehicle dynamics and the energy consumption respectively. The car manufacturers already realized this effect very early and have adjusted over the last decades the body construction with a focus on an improved aerodynamic design and lightweight construction by using material mix of

steel with aluminum or carbon. Although, there is not much scope left to further big improvements.

The Tank-to-Wheel analysis shows that the electric vehicle has the highest efficiency with up to 90% followed by hybrid up to 60% and the poorest is shown by the combustion engine which ranges between 18-30%. However, there are still some obstacles concerning electric vehicle such as the actual greenhouse emission during the generation of electricity from the primary energy sources. The electric drive has only the lowest emission in case of the use of 100% renewable resources. At the moment, this status is not given because the European energy mix is still more dependent on conventional resources such as brown and black coal and crude oil. These are the main driver for the greenhouse gas emission. This means that the electric drive is in reality not such environmental-friendly as it should be.

Within the diploma thesis it was also calculated the energy demand of an electric drive. Based on average electricity price at 100 km compared to the fuel costs of a combustion drive it is shown that the costs of the last-mentioned are 2.5 times higher than these of an electric drive.

The practical part of the diploma thesis contains the measurement in laboratory and experimental results of a hybrid electric power splitter in a hybrid electric vehicle. This is based on the experimental setup of series hybrid vehicle in the laboratory of the electrical faculty at the Czech Technical University. The electric power splitter (EPS) and super-capacitor are the main characteristics of this experimental setup of hybrid vehicles. The result the overall efficiency of the HEV-CVUT is 45% which confirms the statement, that the efficiency of hybrid drives ranges between 40-50%.

The assessment of the three drivetrain shows that each drive has its specific challenges. On the one hand, the electric drives are burdened by the European energy mix, the heavier engine in comparison to the combustion engine, high initial costs, the limited range and the poor infrastructure. Additionally, it remains open how long the lithium reserves will be available to cover this extraordinary demand for the constantly rising battery production. On the other hand the combustion engines have the poorest efficiency and burden the environment most heavily. This can be resolved by using

alternative fuels, but this is also a limited option. Hence, currently we are on a transition market and not on a replacement market: the combustion, hybrid and electric vehicle will exist in parallel. In the mid-term it can be expected that the hybrid concept will be the dominant and most suitable option instead of conventional vehicle. However, in the long-term future, if we are able to resolve the issues of electric vehicles, then they might be the best option among the other propulsion concepts.



## Abbreviations

AC Power	Active Power
BEV	Battery electric vehicle
CNG	Compressed natural gas
DC Power	Direct Power
ICE	Internal combustion engine
EPS	Electric power splitter
EUDC	Extra-urban driving cycle
EU energy mix	European energy mix
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
HEV	Hybrid electric vehicle
HEV-CVUT	Hybrid electric vehicle - České Vysoké Učení Technické
KERS	Kinetic energy recuperation system
NEDC	New European Driving Cycle
PHEV	Plug-in hybrid vehicle
TM	Traction motor
TtW	Tank-to-Wheel
UDC	Urban driving cycle
WLTP	World Harmonized Light Vehicle Test Procedure
WtT	Well-to-Tank
WtW	Well-to-Wheel
GHG	Green house gas

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