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Potentials of Low-Carbon Drive Concepts for Future Mobility Regarding their Global Warming Potential in Relation to Legislative Climate Programs in Europe and China

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Alexander Rust

February 2021

Statutory Declaration

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Abstract

Mobility is a topic that affects almost everyone on this planet. A proven technology, which has already undergone more than 100 years of development, is the automobile. Operated by fossil fuels, the traditional automobile is a very well-engineered technology, but the main disadvantage about it are the emitted pollutants and greenhouse gases. With the progress of climate change and air pollution in many cities, voices have become louder in recent decades to change mobility in the future. By signing the Paris Agreement, a milestone was set for many countries to fight climate change. Additionally, the introduction of stricter emissions legislation practically forced car manufacturers to push the development of new technologies.

This thesis addresses the potential of different low-carbon drive concepts to reduce the carbon footprint compared to conventional drive technologies. An overview of the resulting greenhouse gas emissions over the entire life cycle of the vehicles will be given. Due to the strong dependence of the amount of those emissions on the location where a vehicle is produced, operated, and recycled, the European Union and China will be contrasted.

At the beginning, the topic is briefly introduced and the climate programs within their goals of the European Union and China, as well as the United Nations, are explained in more detail. Furthermore, the global situation regarding greenhouse gases is discussed and the latest emissions legislations are presented. Subsequently, vehicles with the following drive technologies are discussed in detail: Electric motor, internal combustion engine, hybrids and fuel cell systems. The life cycle of the vehicles is broken down into the phases, namely vehicle production, fuel production, use-phase and end-of-life, and the greenhouse gases produced in these phases are displayed. The results are based on numerous studies and own calculations. For a clear presentation, the overall results of the individual drive concepts are compared in three different scenarios. Scenario 1 represents the current situation, or the starting point, Scenario 2 provides an outlook for the reduction of carbon footprint by 2030, and Scenario 3 illustrates the best-case scenario that has the highest reduction potential. All drive concepts are analyzed in each scenario. In addition, the possibilities and necessary changes to integrate these low-carbon drive concepts into our mobility systems are discussed. Finally, new mobility concepts and other influencing aspects are also demonstrated and an outlook for the future is given.

Kurzfassung

Mobilität ist ein Thema, das praktisch jeden Menschen dieser Erde betrifft. Ein hierfür bewährtes Mittel, das bereits eine Entwicklung von über 100 Jahren hinter sich hat, ist das Automobil. Betrieben mit fossilen Kraftstoffen ist das Automobil eine sehr ausgereifte Technologie, die jedoch den Nachteil mit sich bringt, dass bei der Verbrennung der fossilen Kraftstoffe Schadstoffemissionen und Treibhausgase ausgestoßen werden. Aufgrund des Voranschreitens von Klimawandel und Luftverschmutzung in vielen Städten wurden in den letzten Jahrzehnten die Stimmen lauter, die Mobilität künftig zu verändern. Mit der Unterzeichnung des Pariser Klimaabkommens wurde für viele Länder ein Meilenstein gesetzt, gegen den Klimawandel anzukämpfen. Zusätzlich hat die Einführung strengerer Abgasgesetzgebungen die Automobilhersteller in die Pflicht genommen, die Entwicklung von neuen Technologien voranzutreiben.

Diese Arbeit befasst sich mit den Potentialen unterschiedlicher alternativer Antriebskonzepte für Automobile, den Ausstoß von Treibhausgasen im Vergleich zu herkömmlichen Antriebstechnologien zu verringern. Es soll dabei ein Überblick über die entstehenden Treibhausgasemissionen über den gesamten Lebenszyklus der Fahrzeuge gegeben werden. Aufgrund der starken Abhängigkeit des Ausstoßes an Treibhausgasen vom Standort, wo ein Fahrzeug produziert, betrieben und recycelt wird, werden die Europäische Union und China gegenübergestellt.

Zu Beginn wird kurz in das Thema eingeführt und anschließend werden die Klimaprogramme der Europäischen Union und Chinas, sowie auch der Vereinten Nationen genauer erläutert und deren Ziele dargestellt. Des Weiteren wird auf die globale Ausgangssituation in Bezug auf Treibhausgase eingegangen und die neuesten Abgasgesetzgebungen vorgestellt. Im Anschluss werden Fahrzeuge mit folgenden Antriebstechnologien im Detail behandelt: Elektromotor, Verbrennungsmotor, Hybride und Antriebssysteme mit Brennstoffzellentechnologie. Dabei wird der Lebenszyklus der Fahrzeuge auf die Phasen Fahrzeugproduktion, Kraftstoffproduktion, Nutzung und Lebensende aufgeschlüsselt und die dabei entstehenden Treibhausgase dargestellt. Die Ergebnisse basieren auf zahlreichen Studien und eigenen Berechnungen. Für eine anschauliche Darstellung werden die Gesamtergebnisse der einzelnen Antriebskonzepte in drei verschiedenen Szenarien verglichen. Dabei stellt Szenario 1 die aktuelle Situation, beziehungsweise den Ausgangspunkt dar, Szenario 2 gibt einen Ausblick für die Verringerung der Treibhausgase bis 2030 und Szenario 3 stellt den besten Fall dar, um die Treibhausgase maximal zu reduzieren. In jedem Szenario werden alle Antriebskonzepte analysiert. Des Weiteren wird über die Möglichkeiten und erforderlichen Änderungen diskutiert, um diese alternativen Antriebskonzepte in unsere Mobilität zu integrieren. Abschließend werden neue Mobilitätskonzepte und andere einflussnehmende Aspekte demonstriert und es wird ein Ausblick zu zukünftigen Entwicklungstrends gegeben.

Contents

Abbreviations

AC	Alternating Current
AI	Artificial Intelligence
ASM	Asynchronous Machine
AT	Automatic Transmission
ATM	Automated Teller Machine
BEV	Battery Electric Vehicle
CARB	California Air Resources Board
CCS	Carbon Capture and Storage
CNG	Compressed Natural Gas
CNY	Chinese Yuan
DC	Direct Current
DCM	Direct Current Machine
DMFC	Direct-Methanol Fuel Cell
DIN	Deutsches Institut für Normung (German Institute for Standardization)
EC	European Commission
ECU	Engine Control Unit
EM	Electric Motor
EN	Europäische Norm (European Standard)
EOL	End-of-Life
EPA	Environmental Protection Agency
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cells and Hydrogen
FYP	Five-Year Plan
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential

HEV	Hybrid Electric Vehicle
HF	Hybridization Factor
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life-Cycle-Analysis
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
MHEV	Mild Hybrid Electric Vehicle
MIC	Made in China
MT	Manual Transmission
NMC	Lithium Nickel Manganese Cobalt Oxide
NEDC	New European Driving Cycle
NEV	New Energy Vehicle
NoVA	Normverbrauchsabgabe (Standard Consumption Tax)
OEM	Original Equipment Manufacturer
PC	Passenger Car
PEF	Product Environmental Footprint
PHEV	Plug-in Hybrid Electric Vehicle
PM	Particulate Mass
PEMFC	Proton-Exchange Membrane Fuel Cell
PN	Particle Number
PSM	Permanent Magnet Synchronous Machine
PV	Photovoltaic
RDE	Real Driving Emissions
SDG	Sustainable Development Goals
SMR	Steam Methane Reforming
SRC	Short Rotation Coppice

SRM	Switched Reluctance Machines
SUMP	Sustainable Urban Mobility Plan
TTW	Tank-to-Wheel
TUG	Graz University of Technology
UN	United Nations
USA	United States of America
VW	Volkswagen
WLTC	Worldwide Harmonized Light Duty Test Cycle
WTT	Well-to-Tank

Symbols

Parameters and Constants

a	Calculated factor
M	Fleet averaged mass
M0	Reference mass (based on the European fleet averaged mass of three previous years)
Target	Fleet consumption target

Chemical Symbols

CO	Carbon Monoxide
CO_2	Carbon Dioxide
CH_4	Methane
HC	Hydrocarbons
HFC	Hydrofluorocarbons
Li-Ion	Lithium-Ion
Ni-Cd	Nickel Cadmium
Ni-MH	Nickel-Metal Hydride
NMHC	Non-Methane Hydrocarbons
NO_x	Nitrogen Oxides
N_2O	Dinitrogen Monoxide
NF_3	Nitrogen Trifluoride
Pb-Acid	Lead-Acid
PFC	Perfluorocarbons
SF_6	Sulfur Hexafluoride
SO_2	Sulphur Dioxide
THC	Total Hydrocarbons

Units

g	Gram
kg	Kilogram

km	Kilometer
kW	Kilowatt
kWh	Kilowatt Hours
L	Liter
mg	Milligram
MJ	Megajoule
MW	Megawatt
t	Ton
#	Number

1 Introduction

The mobility sector is on the verge of a trend reversal, with new technologies entering the market. The underlying idea is to focus on counteracting climate change and reducing air pollution. Whether new drive technologies are actually better for the environment is analyzed in many studies. However, the results of these studies vary widely. This is mainly due to the fact that a life cycle analysis of different propulsion technologies is required in such a study, and this allows for a lot of degrees of freedom regarding the considered data and the interpretation of results. Therefore, this thesis focuses on comparing different studies on life cycle assessment of various propulsion systems, identifying the differences, and deriving results for further calculations. In this regard, the focus lies on the European mobility sector, but comparisons are also made with the Chinese market in view of boundary conditions and market behavior. To understand the results in a broader and realistic context, it is necessary to also discuss the legislations systems and other factors that contribute to decarbonize the mobility sector in relation with the drive concepts.

As two important markets in automotive business, Europe and China are hardly comparable in many respects, but they are nevertheless pursuing some similar goals, especially with regard to the mobility sector. This is reflected, for example, in emissions legislations, where China uses European Union legislation as a basis for defining its own legislation. Furthermore, China is the largest automobile producer and has the largest automotive market in the world in the meantime. For this reason, the Chinese automotive industry is also growing steadily. Although the European automotive industry has proven itself worldwide, China is one of the pioneers when it comes to electromobility. Thus, both are major players in the mobility field, and therefore it will be interesting to compare the drive concepts within their own legal and technological context.

1.1 Relevance of the Topic

Climate change is progressing and possible solutions are being researched everywhere. The mobility sector makes a significant contribution to the global greenhouse gas emissions and consequently is in transition. For the automotive industry, electrification is proposed as one solution, but improvements to the conventional internal combustion engine (ICE) are also constantly being worked on. Furthermore, a lot of different propulsion systems and fuels are in development and could be the right concept to face the problem of global warming, like fuel cell engines or synthetic fuels.

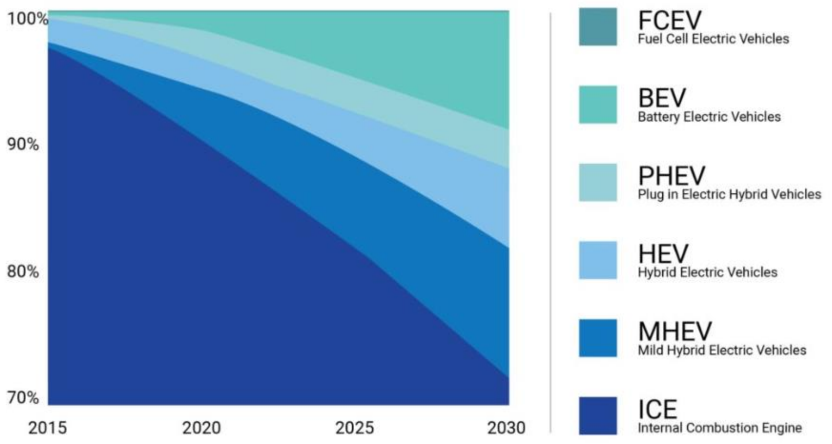

Figure 1 – Prognosis of Global Powertrain Market Share 2015-2030 [1]

Figure 1 shows a prediction of the global powertrain market share from 2015 to 2030. The forecast up to 2030 shows that the share of ICEs might be over 70%. Of course, this development largely depends on future legislations, but it can be assumed that the combustion engine will not become extinct in the next few years. Another interesting aspect in ***Figure 1*** is that fuel cell electric vehicles (FCEVs) practically do not appear in the graphics (<1%). This is since the costs, large scale applications and the necessary infrastructure including hydrogen production are still insufficient. However, future developments will make the fuel cell as a propulsion technology interesting and applicable [1, 2].

A forecast to 2030 for the European market is shown in ***Figure 2***, which differs significantly from the global point of view. In this scenario the share of newly sold ICEVs in Europe until 2030 will be under 10% and hybrid electric vehicles (HEVs) and mild hybrid electric vehicles (MHEVs) will make up the largest part. The only analogy with the global scenario is that FCEVs will not play a significant role in Europe for the next ten years either. The idea behind this European scenario is that in order to be able to comply with European legislation, such a development is necessary. The current value for the fleet consumption of new vehicles is 95 gCO_2/km [3] but this target will decrease significantly in the coming years to meet the climate goals. It can be assumed that almost every new vehicle until 2030 will contain some kind of electrification.

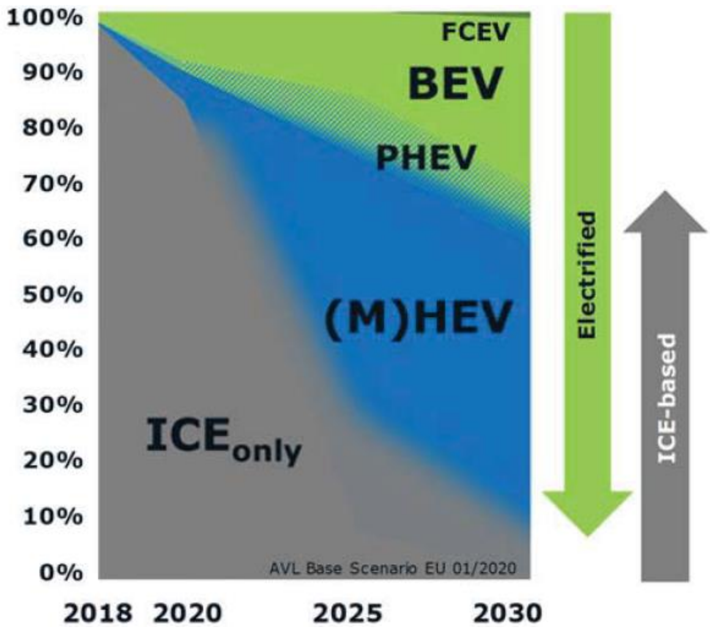

Figure 2 - Future Technology Scenario in Europe [4]

A point often overlooked regarding greenhouse gas emissions in the automotive industry is electricity production. For the use-phase of almost every low-carbon drive technology, a huge amount of electricity is necessary. Nuclear, gas and coal-fired power plants are commonly used in Europe and China, while hydro, wind and solar power plants would be the far more environmentally friendly methods of generating electricity. ***Figure 3*** shows the share of energy from renewable sources in the EU Member States. The 2020 target for the European Union is to reach 20% renewable energies of gross final energy consumption [5]. This goal is rather low when one thinks that in the future only low-carbon technologies should come onto the market and that they will need a lot of electrical energy. Without the energy transition, fighting climate change will not be possible. But anyway, a country like Sweden is one of the pioneers in terms of utilizing renewable energies, while a lot of other countries in the European Union limp behind. A similar depiction of the renewable energy share for the provinces of China is shown later on in ***Figure 7***.

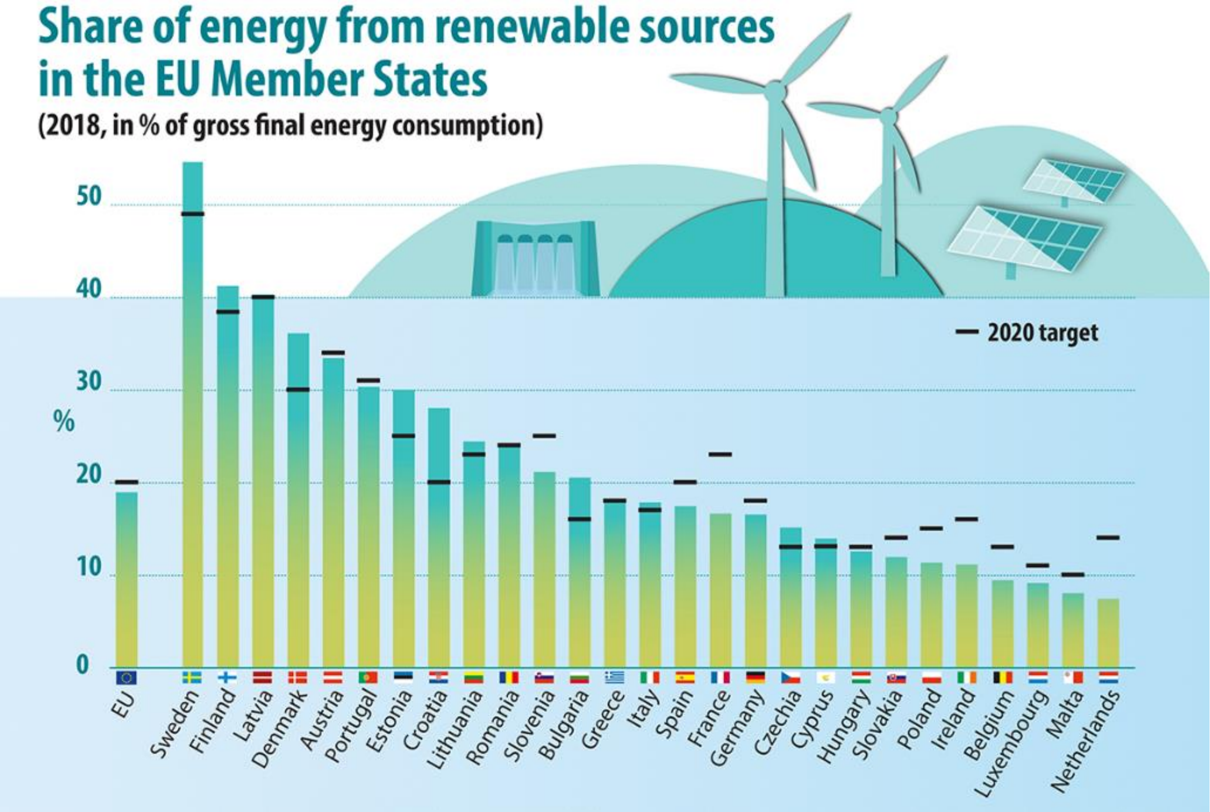

Figure 3 - Share of Energy from Renewable Sources in the EU Member States [5]

Nevertheless, the mining of raw materials and especially the manufacturing of the vehicles must also become much more sustainable. Furthermore, recycling plays a very important role for future developments. The entire vehicle life cycle, also called “Cradle-To-Grave” is shown in ***Figure 4***. The whole process starts with the “Raw Material Extraction” and/or the reuse of old materials, continues with the “Manufacturing”, is followed by the “Use-Phase” and ends with the “End-of-Life Recycling”. To get a complete approach to the entire vehicle life cycle, the fuel generation (Well-to-Tank) has to be added (also shown in ***Figure 4***). The ecological impact can only be reduced to a minimum if the entire vehicle life cycle is sustainable and low carbon oriented.

The European Union has therefore published the so called “Product Environmental Footprint (PEF) Guide”. This guide stipulates the mandatory disclosure of a carbon footprint for various products. Furthermore, the guide defines how PEF studies should be carried out including the boundaries, the goals, the scope, and the interpretation of the results of the studies. Compared to the vehicle life cycle, as shown in ***Figure 4***, the PEF Guide defines similar stages:

- Raw material acquisition and pre-processing
- Capital goods: linear depreciation shall be used
- Production
- Product distribution and storage
- Use stage
- Logistics
- End-of-life

Regarding all these points, the environmental effects should be considered in a PEF Study. A more detailed breakdown of the individual phases can be found in the ensuing source [6]. Since an LCA is quite similar to a PEF study, a conventional LCA approach is used for further analysis in this thesis.

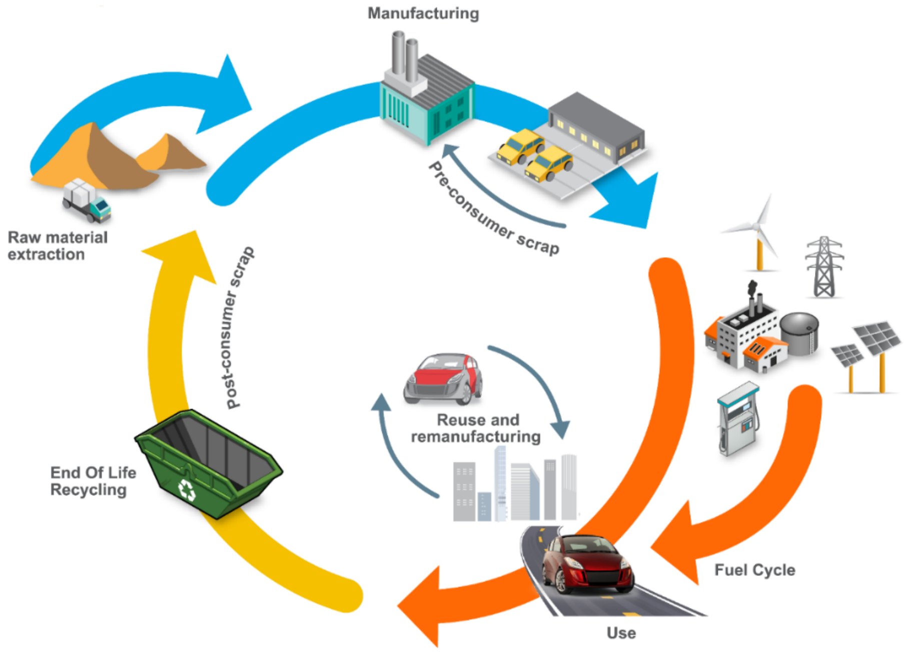

Figure 4 - Vehicle Life Cycle [7]

1.2 Objectives

The main goal of this thesis is to show the potential of low-carbon drive concepts for lowering the carbon footprint in the mobility sector under holistic consideration of the product life cycle. Since this topic is extremely extensive, the thesis focuses on concepts applicable for passenger cars. Due to the close connection of the development of the mobility sector to legislative boundary conditions, legislative climate programs of the EU and China should also be analyzed. Additionally, the global situation concerning greenhouse gases is to be shown. Regarding the drive concepts, the individual phases of the life cycle are to be analyzed in terms of climate gases. After a comprehensive analysis of existing literature, the potential for reducing greenhouse gases for each phase of the life cycle must be carried out for both, the EU and China. The bottom line is to then compare the different low-carbon drive technologies with each other and make a statement about suitability. Finally, the possibilities and the necessary changes for integrating these technologies into the mobility sector should be discussed and an outlook to future developments should be given.

1.3 Structure

Due to the fact that this thesis is part of the double degree program between Graz University of Technology and Tongji University Shanghai, it focusses on the comparison of the situation in the European Union and China.

At the beginning in Chapter 2, the legislative climate programs of the EU and China are analyzed, and a comparison is carried out. This comparison should also demonstrate the different starting points of the

EU and China. To see a global approach of climate goals, the relevant parts of the United Nations Sustainable Development Goals are also presented.

Subsequently, Chapter 3 displays the global situation regarding greenhouse gases. Both, the breakdown of the individual greenhouse gases and the origin are illustrated. For the origin, three views are depicted, namely the total emission per country, the per capita emissions of these countries and the emissions divided by sectors. In the last part, the emissions legislations of the EU and China are presented and other LCA-related regulations are discussed.

The most comprehensive part of this thesis is Chapter 4, which covers investigations of low-carbon drive concepts. Divided into subsections, the life cycle phases of Battery Electric Vehicles (BEV), Internal Combustion Engine Vehicles (ICEV), Hybrids (HEV/PHEV) and Fuel Cell Electric Vehicles (FCEV) are elaborated based on various studies. Build on this, the drive concepts are then contrasted in three scenarios. Scenario 1 represents the starting point for each concept operating with the most common fuels in 2020, Scenario 2 gives an outlook to the development of these concepts until 2030 and Scenario 3 represents the best cases for all drive concepts.

In Chapter 5, the possibilities and necessary changes for achieving a high global warming potential (GWP) reduction are discussed. This mainly concerns 100% renewable electricity generation, improvement of process and technology development, creating the necessary infrastructure, introduction of further legislations, implementing of new mobility concepts and other influencing aspects.

Finally, Chapter 6 gives an outlook to low-carbon drive concepts for the future.

1.4 Methodology

The basic structure of this thesis is built on a comprehensive literature review to extract life cycle results for the various drive concepts throughout their different life cycle stages. Based on this information and own assumptions regarding the current and future development of the technologies, as well as other influencing factors, calculations are made to demonstrate the life cycle emissions of the drive concepts under different scenarios.

Chapter 2 and Chapter 3 represent facts, goals and figures on climate programs, greenhouse gases, and emissions legislations. The main part of this thesis comprises Chapter 4, which figures out the potential for reducing greenhouse gases of passenger cars with different drive concepts in an LCA context. For this purpose, existing life cycle analyses from the literature are used.

Due to a high level of flexibility for conducting an LCA, the reviewed studies are analyzed for comparability and adjusted for further calculations if necessary. Since there are many points of attack in this respect, primarily the main parameters (e.g. vehicle mass, battery capacity, vehicle power, energy intensity of industry, electricity mix) of these studies are compared. After successful analysis of the individual phases of the life cycle, these are summarized and presented in various scenarios.

The different scenarios are intended to reflect the current starting point on the one hand, and future developments on the other. Regarding the current starting point, the most recent data including newest technologies is chosen for the representation. For future developments, literature is used as far as available, and missing parameters are assumed if required. The selection of data used from the literature is based on the highest potential to reduce GHG emissions, especially for the best-case scenario. For the presentation of the reduction potential by 2030, own assumptions are based on a 5% improvement for conventional technologies (e.g. gasoline/diesel production and consumption) and on a 10% improvement for alternative technologies (e.g. hydrogen production and consumption, e-fuel production, battery energy density, electricity consumption). Similarly, these improvements are increased to 10% for conventional technologies and 20% for alternative technologies for the best-case scenario. The reason for the difference in the improvement potential is due to the fact that conventional technologies are already very well-engineered and alternative technologies still have more potential for further improvements.

In Chapter 5, other influencing factors are identified of how to achieve a high GWP reduction by addressing the necessary elements to achieve the highest reduction potential. These include not only technological aspects as demonstrated in the scenarios, but also social aspects.

In the last part, based on the analysis, a rough outlook of how low-carbon drive concepts might look like in the future is described and discussed.

2 Legislative Climate Programs

Many countries and associations have developed climate programs to face against climate change and increasing environmental pollution. These climate programs draw attention to the existing grievances and solutions for the future are made. The highest international level climate program is the Paris Agreement [8]. The Paris Agreement is the first comprehensive and legally binding global climate change agreement and was signed at the Paris Climate Change Conference (COP21) in December 2015. To achieve the objective of the Paris Agreement, a maximum global temperature increase of 2°C, there are a lot of different approaches. This chapter deals with the mobility-related parts of the European and Chinese climate programs. In order to show a global approach, the UN's Sustainable Development Goals are mentioned, too.

2.1 European Green Deal

The EU is combating climate change through aspiring policies within its own boarders and through close cooperation with international partners. The EU's flagship in relation to climate action is the European Green Deal – a measures package ranging from reducing greenhouse gas emissions, investments into elite research and innovation, to upkeeping Europe's natural environment. The European Green Deal essentially follows three temporal goals [9]:

- 2020 climate & energy package
- 2030 climate & energy framework
- 2050 long-term strategy

These mean a 20% cut in greenhouse gas emissions from 1990 levels, 20% of EU energy from renewable energy sources and 20% improvement in energy efficiency, are the three key targets of the 2020 climate & energy package. Each country in the EU has its own guidelines, which are tailored depending on their initial situation. The national emission reduction targets differ according to national wealth from a 20% cut to a 20% increase and the national renewable energy targets vary from 10% (Malta) to 49% (Sweden) to reflect the different starting points [10].

For the 2030 climate & energy framework the EU increased the three key targets from the 2020 package. The greenhouse gas emissions cut should reach at least 40% from 1990 levels, the renewable energy share should at least increase up to 32% and the energy efficiency improvement has to reach at least 32,5%. Depending on the situation, these goals can still be adjusted over the course of the years, as it has been proposed in 2020 to increase the greenhouse gas emissions cut from 40% to at least 55% until 2030. In this regard, all three pieces of climate legislation will be updated until June 2021, when the Commission will come forward with new proposals [11].

With the 2050 long-term strategy the EU aims to be the first climate-neutral association worldwide. This objective forms the core of the European Green Deal and pursues efforts to exceed the goal of the Paris Agreement from a global temperature increase of 2°C to 1,5°C. There are several parts that will be an issue – from the power sector to industry, mobility, buildings, agriculture and forestry. On March 4th, 2020, as part of the Green Deal, the Commission proposed the first European Climate Law that legally anchored the goal of climate neutrality by 2050 [12].

The European Green Deal is of course much more extensive than these three temporal goals and there are many aspects that have to be considered when implementing it. For instance, it is a difficult task to reconcile economic growth with a reduction in greenhouse gas emissions. However, the past, as pictured in ***Figure 5***, shows that the European Union successfully decoupled that in the period from 1990 to 2017. With a gross domestic product (GDP) growth of 58%, greenhouse gases were reduced by 22%. This trend must be strengthened in the coming years in order to achieve the 2050 objective of carbon-neutrality [13].

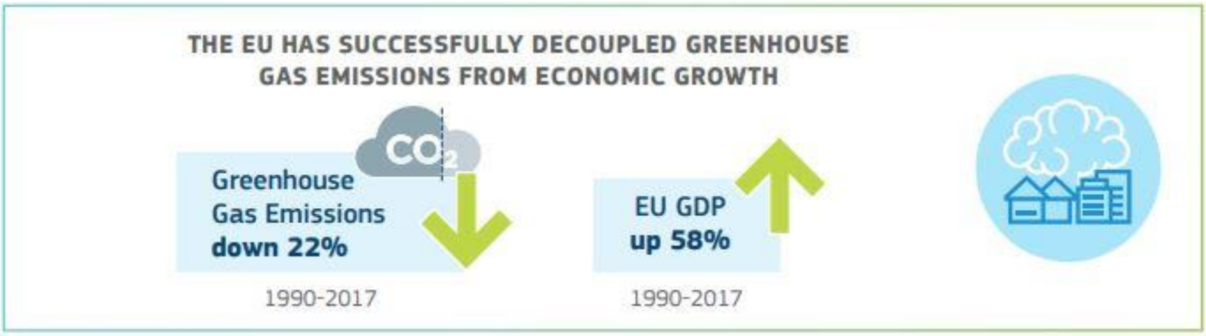

Figure 5 - EU GDP vs. Greenhouse Gas Emissions [13]

Between October 24th and November 07th, 2018 the "Future of Europe" survey was carried out. One of the results of this survey was that 93% of the European citizens believe climate change to be caused by human activity and 85% affirm that economic growth and new jobs can be created by fighting climate change and using energy more efficiently [14]. The result of this study is great for the progress of the European Union. Because legislators alone cannot fight climate change, the entire population must get involved and have the right attitude towards it.

2.1.1 Road to Climate Neutral Economy

The European Union, as a global leader in terms of climate action, has set strategic priorities to achieve all their visions by 2050. As shown in ***Figure 6***, the "Road to Climate Neutral Economy" presents a way to achieve climate neutrality through a fair transition including all branches of industry. It starts with the decarbonization of energy production, affects the whole mobility sector, is intended to promote energy efficiency, needs smart connections, modernizes industry and economy, renews agriculture and ends with the reduction of CO_2 that is already in our atmosphere. All these areas, except for agriculture, have a direct impact on the automotive industry. But if one takes biofuels into account, agriculture has an impact, too. All things considered, one can see that changes in the mobility sector can be precipitated by many different adjusting screws, especially if the entire life cycle of the vehicles is considered. However, achieving a climate neutral economy by 2050 is feasible from a technological, economic and social point of view, but it requires profound social and economic changes within one generation [13].

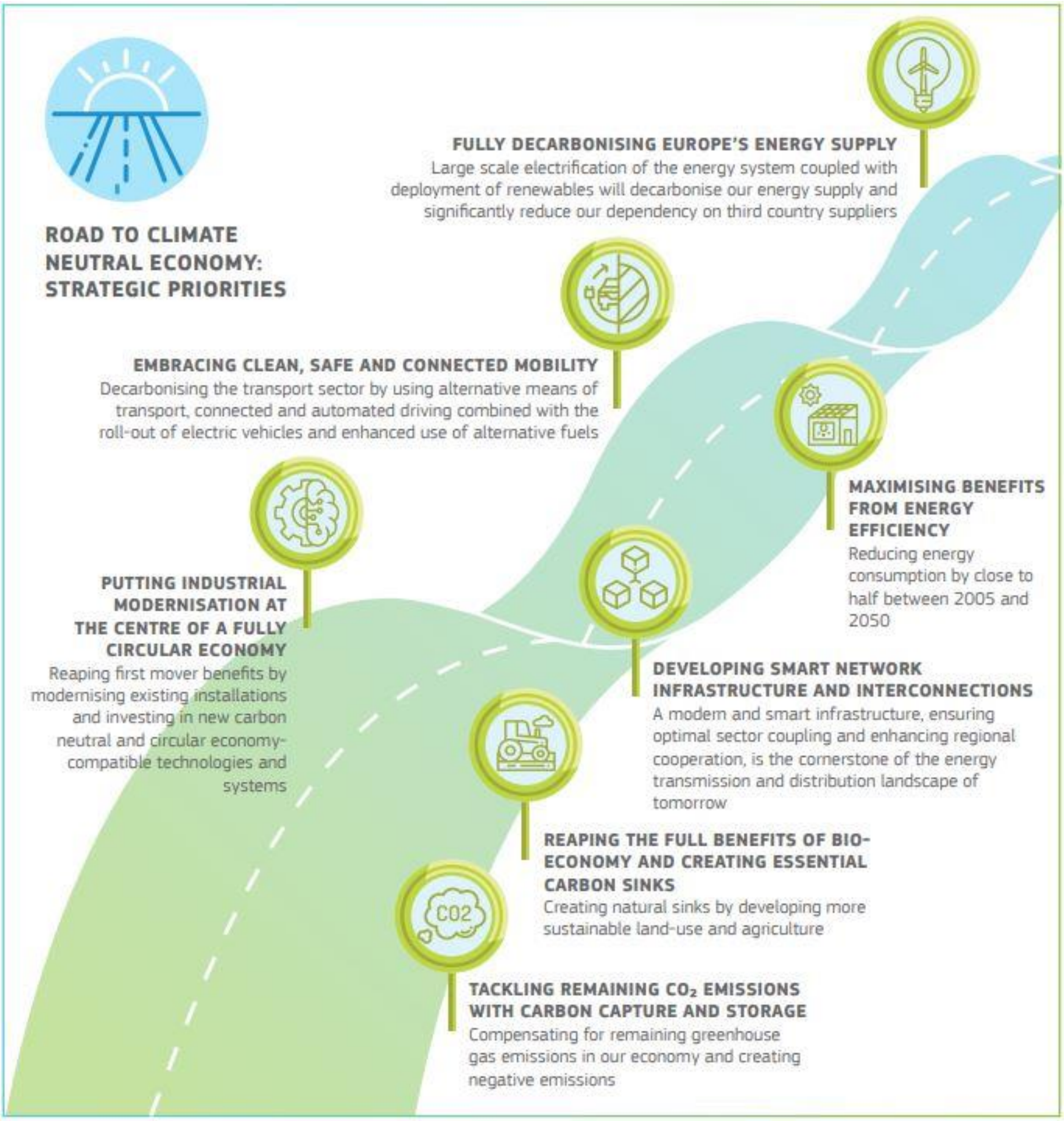

Figure 6 - Road to Climate Neutral Economy: Stratetic Priorities [13]

2.1.2 Regulatory Framework for Low-Emission Mobility

As part of the Green Deal, the mobility sector must change sustainably. The transition to low-emission mobility, respectively zero-emission mobility, while the transportation sector is constantly expanding, starts with a transport system that is more efficient than before. Furthermore, alternative technologies must prevail, especially to be able to move on from the dependence on imported oil. This also presents an opportunity for innovation and job creation in the field of alternative energy. All of this is summarized in the regulatory framework for low-emission mobility and therefore is divided into three parts [15]:

- Optimizing the transport system and improving its efficiency
- Scaling up the use of low-emission alternative energy for transport
- Moving towards zero-emission vehicles

The first part regarding the transport system and its efficiency deals with digital mobility solutions, fair and efficient pricing in transport and multi-modality. Mobility is getting more and more digital and these digital technologies support efficiency and can make transport safer and more inclusive. Intelligent transport systems for cargo or automated driving technologies for passenger cars are two brilliant examples. In addition, the EU wants to change the electronic tolling system across the whole union to a distance-based charging system. This change should reflect better the polluter-pays and user-pays principles. Equally important are the ambitions of promoting multi-modality. The main goal is to make low-emission transport modes more attractive [15].

The second part regarding low-emission alternative energy deals with an effective framework for low emission alternative energy, the roll-out of infrastructure for alternative fuels, and interoperability and standardization for electro-mobility. About 94% of the overall energy needs in the transport sector depend on imported oil, which is higher than in any other sector. As a matter of fact, alternative energy has to be developed further for a long-term decarbonization. Of course, the individual solutions depend heavily on their application. But alternative solutions must be found for each branch of the transport sector. For internal combustion engines, the Commission has already determined that food-based fuels will only play a limited role in decarbonization and that public support for that cause will expire in 2020. Rather, it is advanced biofuels that represent an alternative solution. However, from today's perspective, these are not yet competitive and will therefore be further developed in the years to come. In the same way the infrastructure for alternative fuels has to be rolled-out. It must be possible to fill up with fuels/energy such as electricity, natural gas and hydrogen across the board. Filling and loading times as well as costs play decisive roles for the end consumer. Therefore, the ultimate objective is to make electric vehicle charging as easily as filling the tank during a car journey across Europe. Due to the high-power demand of superchargers, the necessary infrastructure must be upgraded. For this reason, interoperability and standardization for electro-mobility are of great importance. While there are already standardized charging plugs for cars, electric buses and motorcycles are next in line. Furthermore, standards for inductive charging still have to be developed. Another point is the real-time availability of the charging stations as well as a uniform European payment method for the charged electricity [15].

The third part regarding zero-emission vehicles deals with improvements in vehicle testing to regain trust of consumers, a post-2020 strategy for cars and vans, and a post-2020 strategy for lorries, buses and coaches. The road to zero-emission vehicles will still be a long one and, in addition to alternative propulsion technologies, also includes improving the internal combustion engine. To this end, the European Union is constantly working out new emissions legislations. The currently valid Euro 6d legislation includes both the conversion of the test cycle used from the NEDC to the WLTC, which is much more dynamic than its predecessor, and the introduction of Real Driving Emissions (RDE) test procedures in order to obtain a better comparison with the actual use of the vehicles. In the post-2020 strategy for cars and vans the EU is working on new legislations, especially regarding fuel consumption. The fleet consumption must be reduced further, which is achieved above all with low-emission vehicles and zero-emission vehicles. For this, the EU assumes the goal of better informing the population about the current status and the benefits of electric vehicles in order to get people to rethink [15].

All things considered, there is still a critical issue in the actual legislation. Electric and fuel cell cars are still considered carbon-free, which does not reflect the reality. To draw a better comparison to conventional technologies the EU should consider the fuel cycle in their emissions legislation. It would be even better to consider the entire vehicle life cycle, but this is difficult to implement due to the difficulty of obtaining data and the very different procedures in production- and end-of-life phases. Anyway, it would be much more transparent and inclusive if fuel and electricity production is also considered in the legislation.

2.2 China's Legislative Climate Programs

China, the largest developing country, measures by different standards and scales than the European Union. Nonetheless, China is also trying very hard to meet its specified targets for climate change and an increase in living standards. To do this, they draw up a new plan for social and economic development every five years. In addition, China launched the "Made in China 2025" initiative to foster future developments. Until now, China has already lifted about 700 million people out of poverty through economic growth and is always working to lift the remaining 50 million people out of extreme poverty. Furthermore, they integrated the 2030 Agenda of the United Nations in their 13th Five-Year-Plan. A lot of goals from this agenda were already achieved, for instance the energy intensity and therefore the carbon dioxide emissions decreased 3,1% in 2018 and 4% in 2019. Additionally, the "Ant Forest" project was launched in 2016 on the Alipay app, which mobilized 500 million users to reduce their CO_2 footprint. In this regard, 122 million trees have been planted and therefore 7,92 million tons of CO_2 have been reduced [16].

2.2.1 13th Five-Year Plan (2016 – 2020)

On March 17th, 2016 the State Council published the full text of the 13th Five-Year Plan. The main objectives are [17]:

- Finishing of the transition towards a moderately prosperous society
- Maintain a medium-high rate of growth
- Achieve significant results in innovation-driven development
- Improve standards of living and quality of life
- Improve the overall caliber of the population and the level of civility in society
- Achieve an overall improvement in the quality of the environment and ecosystems
- Ensure all institutions become more mature and better established

As one can see, the 13th FYP includes a mixture of goals and policies spread over economic and social development. The massive economic growth has a bearing on the mobility sector. One major factor to ensure economic growth and the achievement of a moderately prosperous society is urbanization. That means the infrastructure had to expand significantly over this period. In addition to the new International Airport of Beijing, which recently opened, about 50 new airports are part of the plan. Furthermore, the plan foresees 30.000 km of additional high-speed trains, 30.000 km of new highways, more than 150.000 km of roads in rural areas, exalting city cluster and urban transport as well as a lot of projects in the energy sector. "Going Green" is another key factor in the 13th FYP, which is so far called "greenest" compared to the older ones. This is exemplified by promoting a cleaner and greener economy through vigorous dedication to environmental management and protection. The government is also planning to set up cross-regional environmental protection and law enforcement agencies to oblige companies to self-monitor emissions and disclose information about compliance with environmental regulations, and to establish a national market for carbon-trading [17, 18].

A key issue that is included in almost every legislative climate program is industrial energy efficiency. For example, the crude steel production efficiency in China increased by 4,13% from 2010 to 2015 and by 3,45% from 2015 to 2020. Since steel is a key component of every automobile, increasing production efficiency naturally helps to reduce CO_2 emissions [19].

Not every objective of the 13th FYP has been achieved successfully. For instance, the provincial targets for the installation of renewable energies (as shown in ***Figure 7***) have only been achieved partly. The six provinces who have achieved the goal are Tianjin, Fujian, Zhejiang, Guangxi, Guangdong and Shandong. All other provinces failed their targets, some of them with a huge gap like the Inner Mongolia, Xinjiang, Yunnan and Sichuan. For the further development of China regarding to the energy transition, it is important that all provinces achieve their goals in the future.

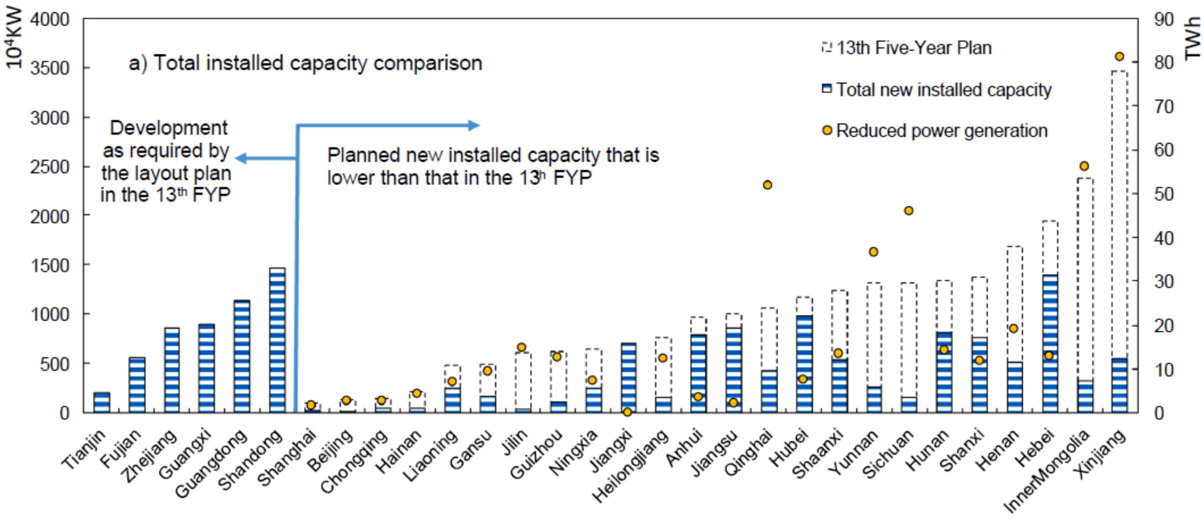

Figure 7 - Renewable Energy - Total installed Capacity compared to 13th FYP [20]

2.2.2 14th Five-Year Plan (2021 – 2025)

The 14th FYP has not yet been published to the time of writing this thesis, but there are already tendencies as to which focuses it will deal with. First of all, a few facts that set the starting point for the 14th FYP [21]:

- The energy consumption per unit of GDP in 2019 decreased by 13,2% compared to 2015
- The utilization rate of recycled water in cities nationwide reached 22,1% in 2019
- The area of construction land used per unit of GDP decreased from 2016 to 2018 by 14,4%
- In 2019, the proportion of sections with good surface water quality in the country was 74,9%, an increase of 8,9% compared to 2015
- The import volume of solid waste in 2019 decreased by 40,4% compared to 2018

The main goal for the 14th FYP is to further promote green, circular and low-carbon development. This is also integrated into the preparation of various special plans. Profound changes in the national and international environment make it urgently necessary to accelerate the promotion of green cycle low-carbon development. One example for this is the plan to call for half of the vehicles to be electric or fuel-cell powered, and the other half hybrid by 2035. Nevertheless, China's green cycle and low-carbon development still faces some problems and shortcomings. Inadequate understanding, unbalanced development and uneven overall utilization of energy resources represent some examples. For the 14th FYP, head of state Xi Jinping has laid down a few basic principles. First, they have to stick to problem orientation, which is the starting point of the research and development policy. The working point is therefore on the most important contradictions and problems. Second, they should follow the bottom-line thinking method. Preparing for disadvantages, strive for the best result, be prepared for the troubles, not panic, and firmly grasp the initiative belong to that. Third, they must adhere to local conditions. That means, it is necessary to adjust und improve regional policies in accordance with objective economic laws. Finally, they have to adhere to the government role and the market action. Xi Jinping pointed out that more attention should be paid to making the market a decision in resource allocation [21, 22].

2.2.3 Made in China 2025

China wants to catch up with the world's strongest economies. The government has therefore launched an ambitious plan to bring the country to the top in terms of technology as well. Where manual labor currently provides the bulk of value creation, automated production is set to dominate in the future and turn the country into an industrial superpower. Already in 2015, China was one of the world’s industrial engine rooms. The industrial sector contributed more than 40% to economic growth, and at the same time 90% of all exported goods were industrial products. In the case of future goods such as computers and cell phones, between 80% and 90% of the goods produced worldwide were manufactured in China. In the mobility sector, too, a significant contribution was manufactured in China, namely 28% of cars and 41% of ships. But China was still a country where most production is done by hand. The automation rate in production was far below the rate of European industrialized countries or even China's East Asian competitors such as South Korea [23].

To change this, the “Made in China 2025” program was launched. The main goal of this program is to be the world’s leading manufacturer of core technologies, such as high-speed rail, telecommunications, and power equipment and to be at least second or third in the sectors robotic, high-end automatization and new energy vehicles. ***Figure 8*** shows the ten strategic economic sectors of MIC 2025. From these ten sectors, one can clearly see that the mobility sector plays a significant role in this project. However, this program is divided into three milestones: become major manufacturing power until 2025, become global manufacturing power until 2035 and become leading manufacturing superpower until 2049. The goal of 2049 is based on the fact that China will celebrate its 100th anniversary in that year. Additionally, some of China's climate targets are based on developments set in MIC 2025. For example, China’s goal to have the latest peak of CO_2 emissions in 2030 relies on MIC 2025 goals in energy saving & new energy vehicles and new materials, such as batteries [22–24].

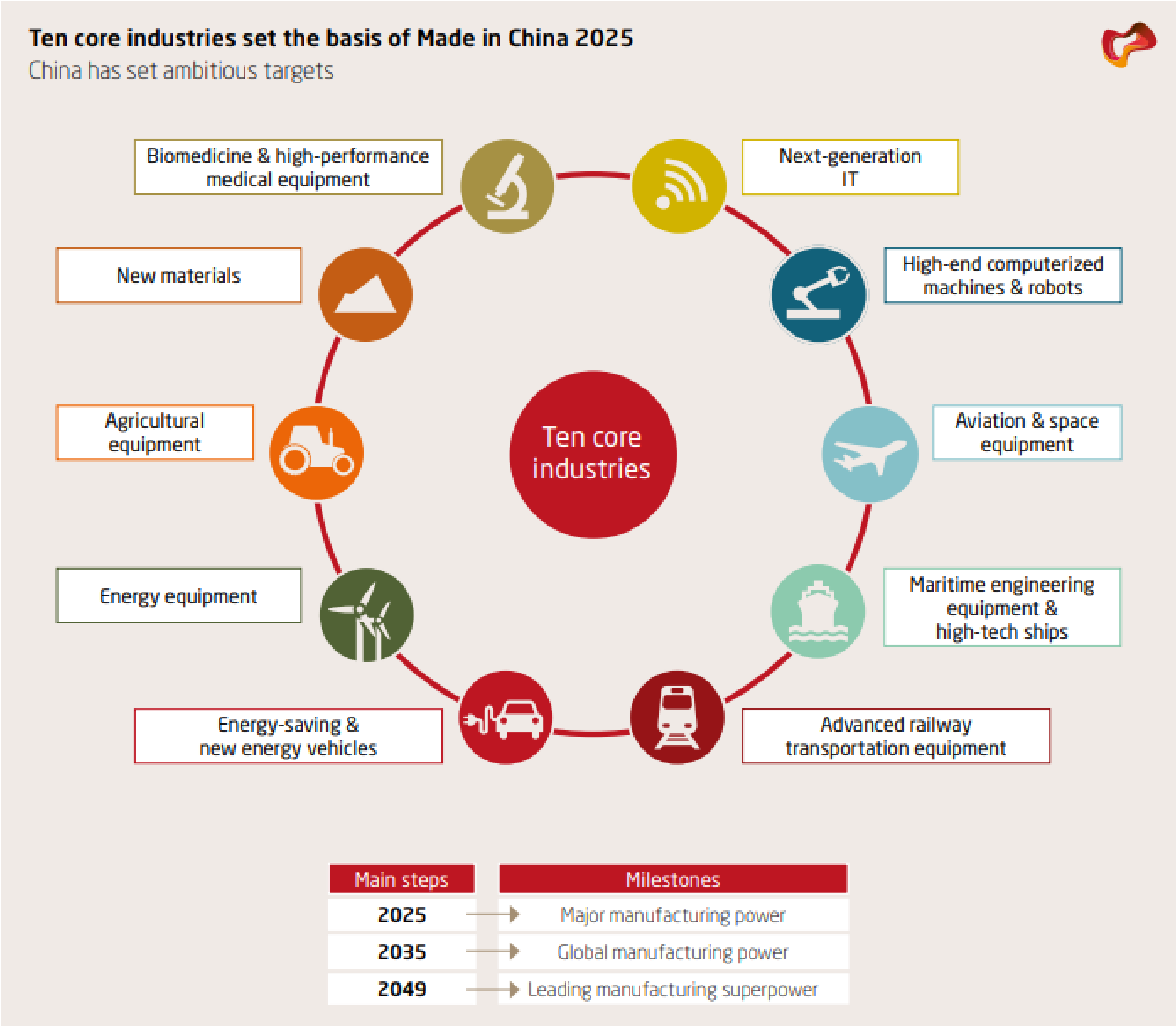

Figure 8 - Made in China 2025 [24]

2.3 United Nations - Sustainable Development Goals

The United Nations, as an international organization, is very committed to sustainable development and has therefore launched the 2030 Agenda for Sustainable Development. This agenda includes 17 sustainable development goals, which are shown in ***Figure 9***, and 169 associated targets. The main objective is that all countries, acting in collaborative partnership, will implement this agenda and therefore poverty, seen as the greatest global challenge, should be decreased and planet earth should be healed and secured.

Figure 9 - United Nations - Sustainable Development Goals [25]

The Sustainable Development Goals are aimed very much at all areas of human life, including the mobility sector. However, in contrast to the European Green Deal, there are no specific proposals for solutions to individual problems; rather, goals are set that are to be achieved. Two of these 17 goals have a huge impact on the mobility sector, namely Goal 7 and Goal 13. The UN aims to change the energy sector with five specific targets:

7.1 By 2030, ensure universal access to affordable, reliable and modern energy services

7.2 By 2030, increase substantially the share of renewable energy in the global energy mix

7.3 By 2030, double the global rate of improvement in energy efficiency

7.a By 2030, enhance international cooperation to facilitate access to clean research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology

7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small islands developing states and landlocked developing countries, in accordance with their respective programs of support

(United Nations – Transforming our World: The 2030 Agenda for Sustainable Development)

As one can see, these targets are similar to the European Green Deal with the only difference that they should be reached globally. Regarding Goal 13 (climate action) the Agenda 2030 differs a lot to the Green Deal. The European Green Deal is kind of a solution to the Sustainable Development Goals. The focus of the SDGs lies on integrating climate change measures into policies and support and promote developing countries. Moreover, people should be better educated about climate change and countries should be better prepared against natural disasters [26].

2.4 Comparison of Climate Programs

Due to the different starting points of the EU and China, their climate goals also differ significantly from each other. In common is, however, that both the EU and China are working in their own way to make the future more climate friendly. The two have also committed to meet the UN's climate goals. Only the approaches to fulfil the different goals differ significantly from each other. In this regard, the formulation of the goals and their implementation take place in very different ways. A main problem in the EU, for example, is that all member states have to decide together on future goals, while in China this is decided by the government alone. Therefore, the implementation of various goals in China is easier than in the EU. Nevertheless, the EU assumes the stricter goals. To sum up, in China the holistic development of the state is always emphasized, of which the climate goals are one part. In Europe, by contrast, economic, social and climate goals are considered separately from one another.

Table 1 shows the main goals that should be achieved by the end of 2020. In China, the main aim is to reduce both total energy consumption and emissions of CO_2 and particulates, although the specific targets for emissions of PM2.5 have in some cases not been achieved. This means that in some cities in China the limit values for PM2.5 have been exceeded too often. Above all, Europe is trying to reduce its greenhouse gas emissions. This is achieved through new emissions legislation, the installation of renewable energies and more efficient energy generation. The comparison of the exhaust gas legislation valid in 2020 is dealt with in more detail in ***3.2***.

Table 1 - 2020 Goals
Own table - data obtained from [10, 18, 27, 3]

2020	European Union	China
Emissions	20% cut in greenhouse gas emissions from 1990 levels (< 3,38 billion tCO_2eq)	Reduction of carbon-dioxide emissions per unit of GDP by 45%
		Reach specific PM2.5 targets
PC Fleet Fuel Consumption	95 gCO_2/km basis: NEDC	118,5 gCO_2/km (gasoline) basis: WLTC
Energy Sector	20% of EU energy from renewable energy sources	15% of non-fossil share of primary energy consumption
		Reduction of total consumption of primary energy to less than 5 billion tons of standard coal
	20% improvement in energy efficiency	Reduction of energy consumption per unit of GDP by 15%

For the goals up to 2030, as shown in ***Table 2***, the EU and China are quite similar in terms of content, although the formulation of the goals is different. The emission of greenhouse gases, especially CO_2, should be massively reduced and renewable energies should be on the advance. While China would like to get to -60 to -65% from the 2005 level of carbon intensity, a reduction of 40% from the 1990 level is fixed in Europe. But there was recently proposed that the target will be increased up to a 55% reduction. However, experts warn that this goal might not be achieved. China wants to focus on innovations by 2030 and increasingly incorporate technology into the process. A big topic for both is the expansion of the infrastructure for New Energy Vehicles (NEVs). The development of the infrastructure goes hand in hand with the development of renewable energies, otherwise it would make little sense [28–31].

Table 2 - 2030 Goals
Own table - data obtained from [11, 28–31]

2030	European Union	China
Emissions	40% cut in greenhouse gas emissions from 1990 levels (< 2,54 billion tCO_2eq) (<1,90 billion tCO_2eq in the case of the new target of a 55% cut)	Carbon Intensity: -60 to -65% below 2005 & latest maximum of absolute CO_2 emissions in 2030
Energy Sector	32% renewable energy share	20% share of non-fossil fuels in primary energy consumption
		Improving fossil-fuel efficiency
		Increasing the share of clean energy consumption, so that non-fossil fuels and natural gas become the main energy sources
	32,5% improvement of energy efficiency	Ensure universal access to affordable, reliable, sustainable and modern energy services
		Increase energy efficiency by using big data & AI
		Advance low-carbon and green urbanization models
Infrastructure	Propose a sustainable product policy legislative initiative	Accelerate the improvement of a safe, efficient, smart, green and interconnected modern network of infrastructure
	Roll-out infrastructure for alternative fuels	Innovation driven development

For 2050 there are of course no concrete goals that could be titled with numbers today, but both the EU and China are pursuing a vision. The European Union wants to be climate neutral by 2050 and China wants to develop to a great modern socialist country, as shown in ***Table 3***.

Table 3 - 2050 Vision
Own table - data obtained from [12, 32]

2050	European Union	China
Vision	Climate neutrality	Build a great modern socialist country

3 Greenhouse Gas Emissions

The atmosphere on our planet consists of various gases that are linked to form a complex chemical system via a variety of functions and processes. Anthropogenic emissions threaten the atmospheric equilibrium in two main ways: greenhouse gas emissions lead to an increase in global temperature and the classic air pollutants are not only responsible for acidification and eutrophication of ecosystems, but also for endangering human health. Both pose major challenges for the automotive industry. The Kyoto Protocol names six greenhouse gases: Carbon Dioxide (CO_2), Methane (CH_4), and Dinitrogen Monoxide (N_2O) as well as the fluorinated greenhouse gases (F-gases): Hydrofluorocarbons (HFC), Perfluorocarbons (PFC), and Sulphur Hexafluoride (SF_6). Since 2015, Nitrogen Trifluoride (NF_3) is also included [33].

Furthermore, greenhouse gas emissions are largely responsible for climate change, which will change the life of our and the following generations. Dry areas, water shortages and mass migration are just some of the consequences that can be expected. To prevent this from happening, our lives must change significantly towards sustainability and governments around the world have to work on the common problem of climate change. The current situation regarding greenhouse gas emissions is explained in more detail in the following diagrams. All GHG emissions data shown refer to the unit CO_2 equivalent.

3.1 Current Situation

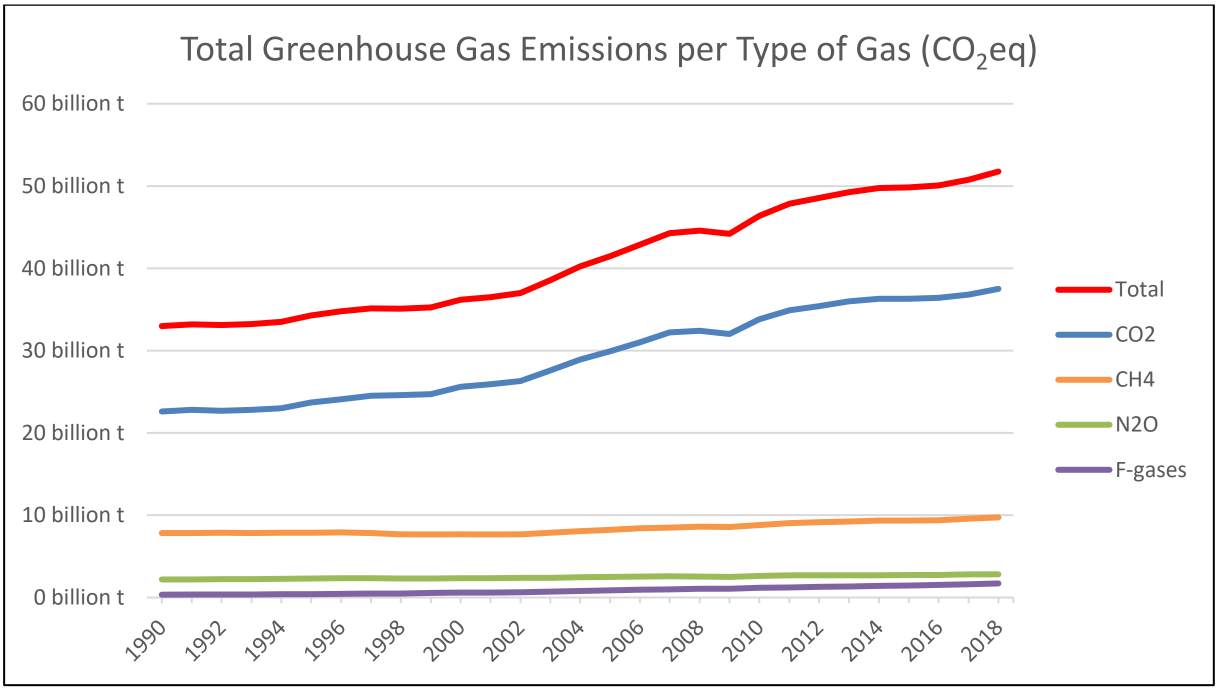

Figure 10 - Total Greenhouse Gas Emissions per Type of Gas (CO_2eq)
Own figure - data obtained from [34]

As shown in ***Figure 10***, CO_2 is the most common greenhouse gas with a total mass of 37,5 gigatons in our atmosphere in 2018. The main drivers for CO_2 are the combustion of coal, oil and natural gas. The second most common greenhouse gas is CH_4, which mainly contributes from cattle breeding. But also the production of natural gas and oil as well as coal mining are relevant contributors. The concentrations of all other climate gases are negligible compared to CO_2 and CH_4, which does not mean that they can be neglected. The low concentrations are mainly due to legislation in many countries that prohibit the use of fluorocarbons. Given these points, it can be deduced that the mobility sector makes a significant contribution to global greenhouse gas emissions, which is also shown in ***Figure 13*** [34].

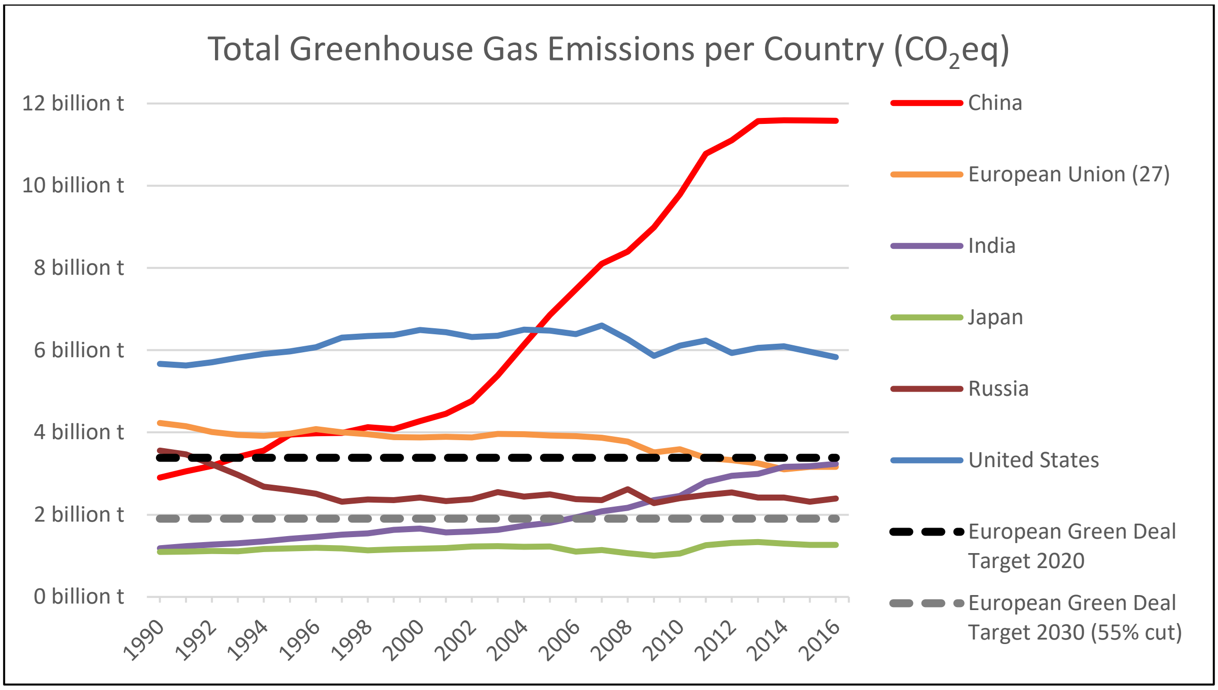

Figure 11 - Total Greenhouse Gas Emissions per Country (CO_2eq)
Own figure - data obtained from [35]

The countries with the largest total emissions of greenhouse gases worldwide are shown in ***Figure 11***. Shown as the orange graph in the diagram is the EU with its 27 member states. This plot displays China as the country with the most total greenhouse gas emissions, emitting almost twice as much as the United States of America. While the total GHG emissions in most countries have decreased in recent years, a significant increase can be seen for China and India. This is due to the fact that these two countries are fast developing countries and have experienced a massive economic boom. This is also caused by the rest of the world, which has masses of goods produced in these countries for low wages. If one were to add up the total greenhouse gases since records began, one would clearly see that Europe has emitted more than China, since Europe is already past its development period and China is just in the middle of it. However, within the framework of the UN's Sustainable Development Goals, China guarantees that the latest maximum of CO_2 emissions may take place in 2030. But developments suggest that China is ahead of its goals and that the maximum can be expected earlier.

Figure 12 shows a slightly different representation, namely the greenhouse gas emissions per capita for the same states as in ***Figure 11***. Since the data for ***Figure 12*** was obtained from two different sources and no data is available for the EU-27 before 2000, they are presented in a shorter time window. Now, the diagram obtained before is reversed and per capita the USA emit twice as much GHG emissions as China. This can be traced back to the population, where China with 1,4 billion inhabitants clearly outweighs the USA with 330 million inhabitants. Another important fact is the difference in the slope of the curves of the USA and Russia in ***Figure 11*** and ***Figure 12***. While the total GHG emissions of these two countries have remained more or less constant over the past few years, per capita emissions have fallen. In the USA this is due to population growth, but the population of Russia remained almost constant. It can be concluded Russia has actually reduced its GHG emissions. As one can see, it is very difficult to portray one country as the worst, because it always depends on the point of view. The fact is, however, that China and the USA are among the biggest climate sinners on earth. But the EU has to take its own share too, as the per capita emissions are very high, derived from the high living standard.

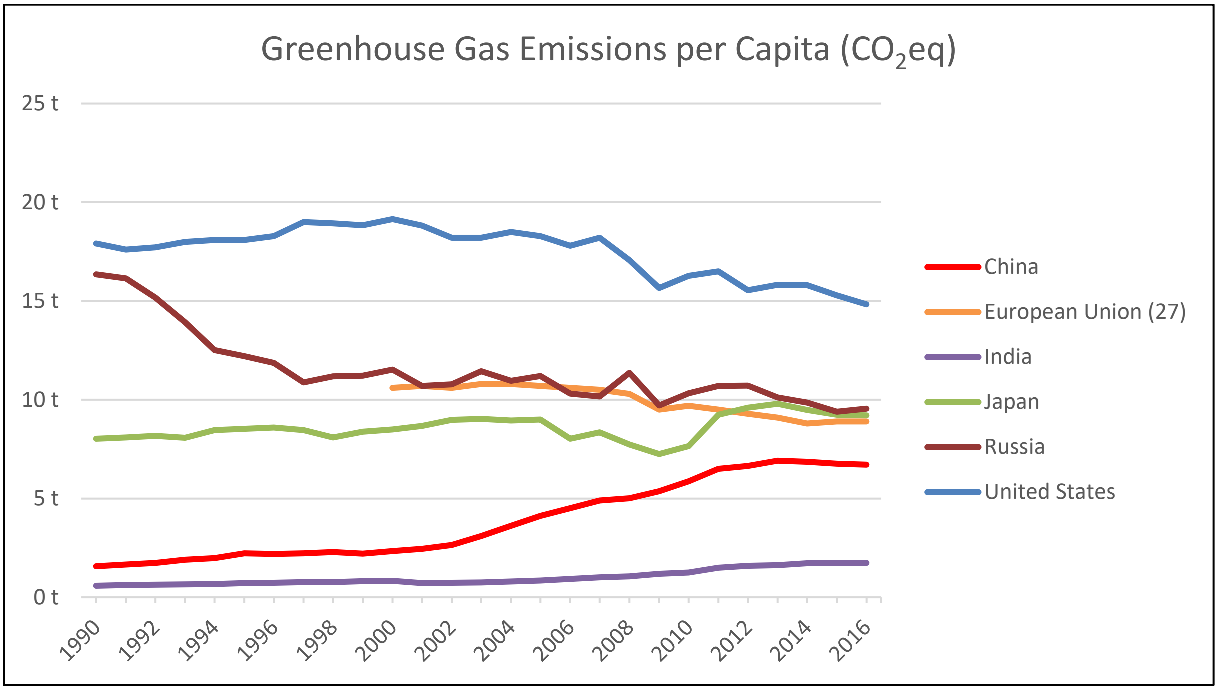

Figure 12 - Greenhouse Gas Emissions per Capita (CO_2eq)
Own figure - data obtained from [35, 36]

In ***Figure 13*** the greenhouse gas emissions emitted worldwide are broken down by sector. Electricity & Heat represent by far the largest share because it is needed for living. Through energy transition and sustainable heat technologies, these emissions have a great potential to decrease in the future. The second most common sector regarding GHG emissions is the transport sector, which almost constantly increased in the last decades. Without a technology change in this sector, this trend will continue. This makes it even more important to develop low-carbon drive technologies and bring them onto market. Manufacturing & Construction and Agriculture do make up almost the same share of total GHG emissions. The share of these sectors can also be significantly reduced with sustainable developments and a reduction in meat and dairy consumption. Land-Use Change and Forestry also still account for a significant proportion. This is mainly due to the deforestation of rainforests, especially for the production of palm oil, which is unfortunately still being carried out. One ray of hope at the end of the tunnel are palm oil-free products, which are increasingly found in supermarkets these days. All other sectors play a rather minor role, although the goal must be to reduce emissions in these sectors as well.

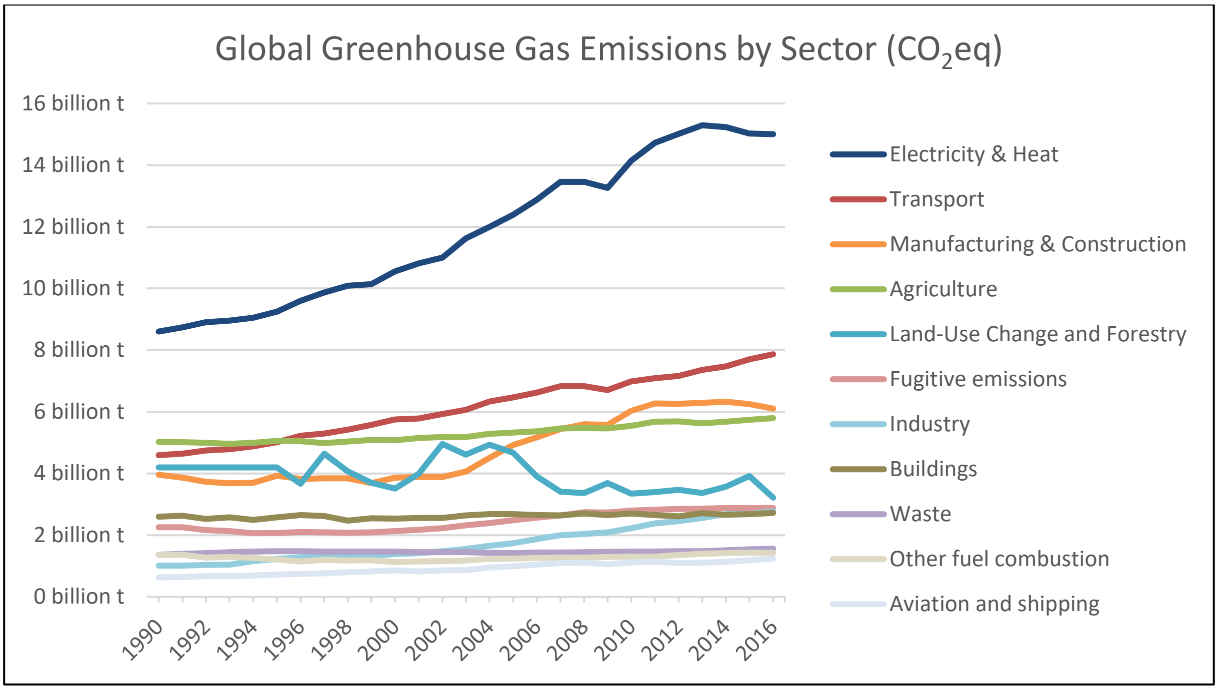

Figure 13 - Global Greenhouse Gas Emissions by Sector (CO_2eq)
Own figure - data obtained from [37]

If one were to look at the same representation as in ***Figure 13*** in a country-specific manner, the scenarios are completely different in some cases, as shown in ***Figure 14***. Electricity & Heat is at the top of overall emissions almost everywhere. But behind that Transport is one of the frontrunners in the EU and especially in Austria where it comes first. In China it is Manufacturing & Construction and Industry that lead behind Electricity & Heat and are jointly responsible for the high GHG emissions. In the final analysis, one can say that the order of the sectors varies depending on the country and the circumstances, but in almost all countries the same five or six sectors are represented at the top.

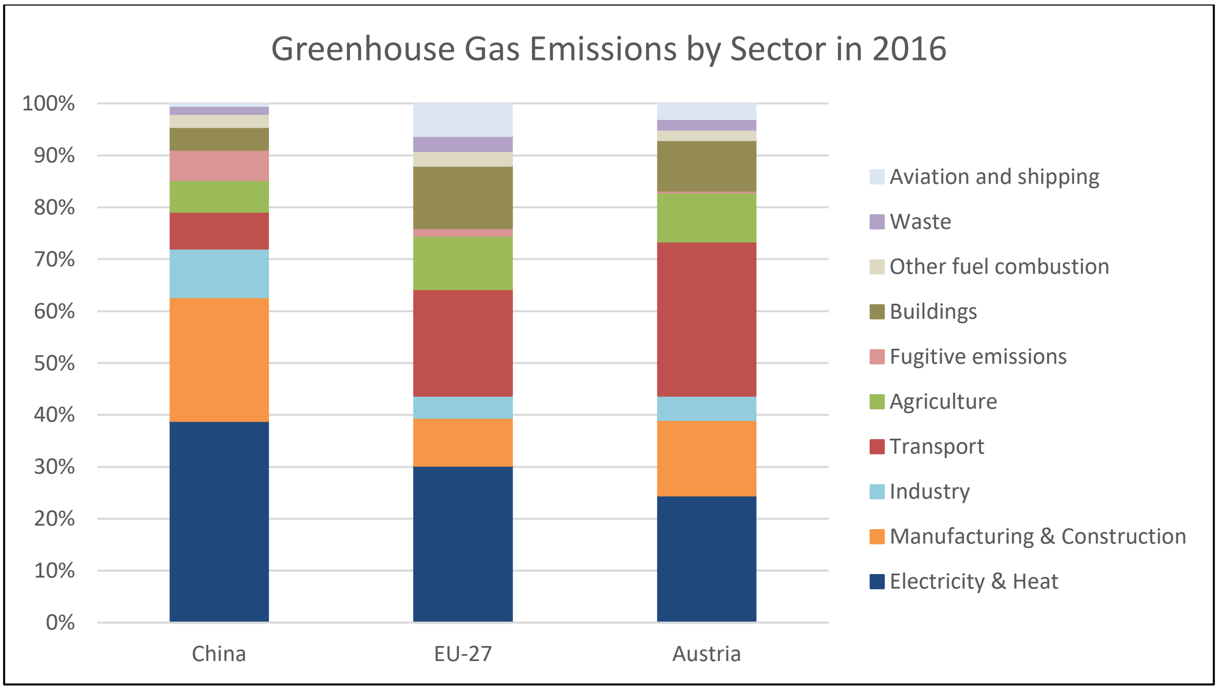

Figure 14 - Greenhouse Gas Emissions by Sector in 2016
Own figure - data obtained from [37]

3.2 Comparisons of Emissions Legislations

To reduce the greenhouse gas emissions as well as pollutant emissions, there are various legislations, especially for the transport sector. Different countries or associations, like the EU, have their own emissions legislation. As already mentioned, these regulate the emission of pollutants and greenhouse gases and range from motorcycles, cars, and commercial vehicles to ships, airplanes and others. The best-known – and most important because they cover the main markets – legislations are those of the EU, the USA, China and Japan. The USA even has two different institutions that make legislation, namely Environmental Protection Agency (EPA) and California Air Resources Board (CARB). But other countries such as Brazil, India, the Russian Federation and South Korea also have their own emissions legislations, whereby they are very much based on the best-known legislations mentioned above. In the following, only the currently valid and future planned legislations of the EU and China are dealt with. Every legislation is based on one or more test cycles to determine whether the applicable limit values are observed. Depending on the legislation, the NEDC, WLTC and RDE come into play in Europe as well as in China [3].

3.2.1 Fuel Consumption

The fleet consumption is regulated in the legislation of both the EU and China and is concerned to the fleet of newly sold (registered) cars of a defined car manufacturer in the specific market within one year. However, it only affects vehicles that emit CO_2 during operation. All other vehicles are considered CO_2-free in the legislation. And exactly this kind of regulation portrays a disadvantage for b-fuels and e-fuels, because the CO_2 emissions, emitted during combustion of these fuels were already saved before from the atmosphere (e.g. crops, power-to-liquid) or from other processes (e.g. waste stream, CCS).

The specific targets in the EU and China differ a little in their value and their calculation. What they have in common, however, is that the specific goal depends on the vehicle mass and the type of the vehicle. In the EU, the formula ***(3.1)***, shown below, is used to calculate the weight-dependent CO_2 emission limit, while in China there is a fixed limit for certain weight ranges.

$$CO_2 = Target + a * (M - M0) \qquad (3.1)$$

The parameters of the formula, which are described in detail at the beginning in ***Symbols***, are defined in ***Table 4***. From 2015 to 2019 the fleet consumption target in the EU was 130 gCO_2/km and from 2021 on it is 95 gCO_2/km with 95% fleet phase-in in 2020. The NEDC was previously used to check consumption in Europe, but the WLTC is now being used – in this way, the 95 gCO_2/km defined in the NEDC are increased to correspond with the higher load and dynamics in the WLTC. The publication of the exact increase of the fleet consumption target, based on NEDC, is planned for 2021, but an increase of about 20% is assumed. This corresponds to a fleet consumption target of about 115 gCO_2/km, based on the WLTC [38]. Starting 2021, manufacturers will have individual CO_2 reference targets based and measured on WLTC adapted to 14°C. The formula for calculating the specific targets will also change significantly by 2030 but will not be explained in more detail in this thesis. In China, the average fleet consumption value in 2020 is 5 L/100km, which corresponds to emissions of 120 gCO_2/km for gasoline engines measured in the WLTC. This puts China slightly behind the EU in terms of vehicle fuel consumption [3].

Table 4 - Parameters of the Fleet Consumption Formula in the EU for PC
Own table - data obtained from [3]

Vehicle type	**Years**	**a** gCO_2/km / kg	**Target** gCO_2/km	**M0** kg
Passenger Cars	2019	0,0457	130	1392,88
	2020	0,0333	95	1392,88

The graphic representation of the limit values described above is shown in ***Figure 15***. In Europe, the limit value depends solely on the vehicle mass and the parameters of the formula ***(3.1)***, while in China a distinction is made between manual and automatic transmission. Since the unit L/100km is used in Chinese legislation, the values for the representation in ***Figure 15*** are multiplied by a constant value of 23,7 [39]. This constant is based on the composition of gasoline and thus represents an equivalence to the fuel consumed, especially because mainly gasoline vehicles are used in China. The value of the constant can vary slightly depending on the source. If one compares Europe with China corresponding to the WLTC, one finds that Chinese legislation is oriented similarly to European legislation, with the prescribed value being somewhat higher. It is important to note that the straight lines have an incline of less than 45 degrees, which means that the higher the vehicle weight, the lower the limit relative to the average value. This applies for both Europe and China.

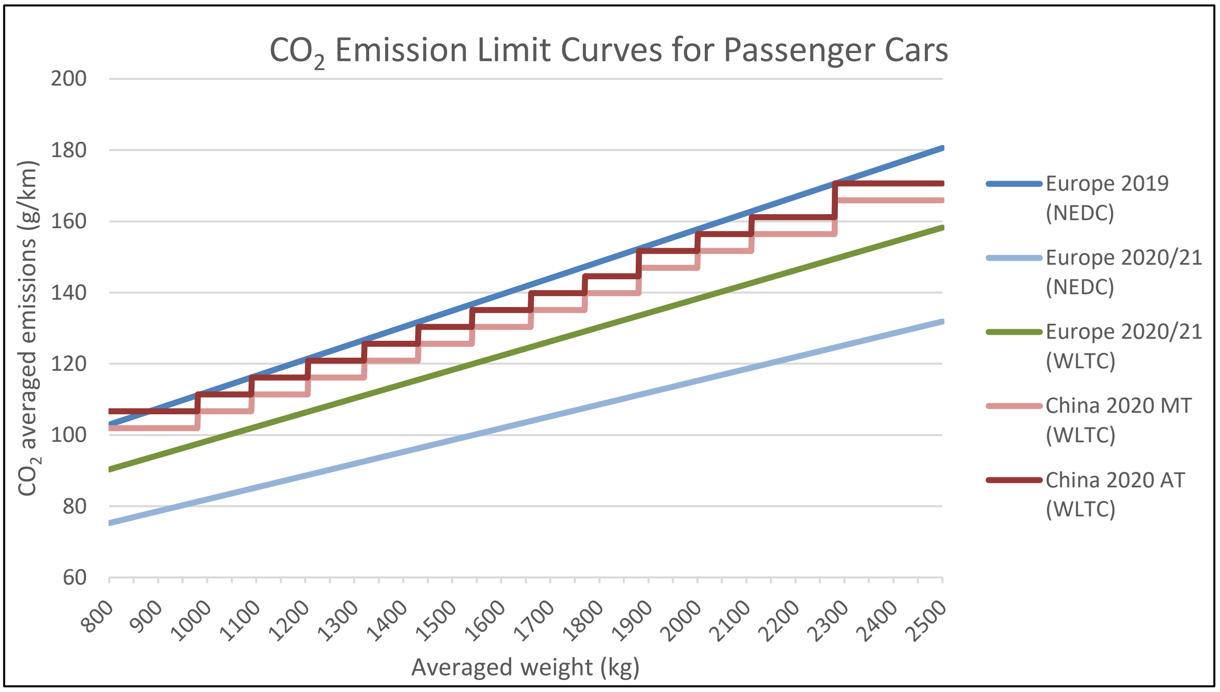

Figure 15 - CO_2 Emission Limit Curves for Passenger Cars
Own figure - data obtained from [3]

3.2.2 Air pollutants

Since not only climate change but also air pollution is a major problem, the pollutant emissions of all vehicles with internal combustion engines are also regulated. The diesel scandal [40] recently showed how important a clearly defined regulation of pollutants is for the environment. In this scandal, OEMs exemplary implemented software in the engine control unit (ECU) that detected the difference between driving on the chassis dyno and driving on the road and accordingly modified the exhaust aftertreatment to save AdBlue while still complying with emissions legislation in the test cycle. Another example are the big cities in China such as Shanghai, where air pollution is very often above the limit value and thus the air inhaled is harmful to health. But Austria, for example, is also struggling with air pollution. In the greater area of Graz there is a limit of 100 km/h on motorways if the fine dust value tends to exceed the limit value or has already exceeded it. For all these reasons and many more, the pollutant emissions from vehicles are regulated.

If one compares the EU and China, as shown in ***Table 5***, one finds that the starting point is reversed in comparison to the regulation of fuel consumption. In Europe, the EU 6d legislation has been in force since January 2020 and in China the China 6a legislation since July 2020. These two legislations are identical in their permissible limit values for gasoline engines except for the carbon monoxide value. This value is 30% lower in China than in Europe. This comparison does not match for diesel engines, as HC and NO_x are regulated together in Europe. Due to the fact that mainly gasoline vehicles are sold in China, the comparison of the diesel legislation with Europe is no longer relevant. If one goes a step further and considers future emissions legislation, China has already laid the foundation with the China 6b legislation, which will be introduced in July 2023, while there is still no agreement in Europe on the introduction and regulation of the Euro 7 legislation. In China, with the introduction of the new legislation, all limit values will be lowered, sometimes halved, except for the number of particles [3]. But in Europe there will soon be an agreement on the new legislation. Experts already suspect that under the Euro 7 legislation diesel and gasoline engines are subject to the same limit values as is the case in China anyway, and that the NO_x limit value could be about 35 to 20 mg/km, which will be a huge challenge for the automotive industry [41].

Table 5 – Comparison of Emissions Legislations
Own table - data obtained from [3]

	Positive Ignition			**Compression Ignition**		
	EU 6d	China 6a	China 6b	EU 6d	China 6a	China 6b
CO [mg/km]	1000	700	500	500	700	500
THC [mg/km]	100	100	50	-	100	50
NMHC [mg/km]	68	68	35	-	68	35
NO_x [mg/km]	60	60	35	80	60	35
HC + NO_x [mg/km]	-	-	-	170	-	-
PM [mg/km]	4,5	4,5	3,0	4,5	4,5	3,0
PN [#/km]	$6*10^{11}$	$6*10^{11}$	$6*10^{11}$	$6*10^{11}$	$6*10^{11}$	$6*10^{11}$

3.2.3 LCA-related Regulations

Instead of emissions legislations, there are also other regulations in both the EU and China regarding the life cycle stages of a vehicle to make them more sustainable and therefore reduce GHG emissions. Eco-design, for instance, plays a very important role in automotive developments. The aim of eco-design is a recycling-oriented product development using materials and designs suitable for recycling. Additionally, dismantling plans are also provided. In the EU, for example, only vehicles that are reusable and/or recyclable to a minimum of 85% by mass and are reusable and/or recoverable to a minimum of 95% by mass may be registered [42–44]. Furthermore, the recycling process itself becomes increasingly important. In this regard, car manufacturers are obligated to take back vehicles after reaching their end-of-life und recycle them. However, recycling in this context does not mean that all materials have to be reused. The incineration of materials also counts as recycling. In fact, vehicle manufacturers get rather few vehicles back, as customers are not obliged to return them. [45]

4 Low-Carbon Drive Concepts

Innovative drive concepts and fuels to fight climate change are being developed worldwide and are one promising solutions for the future of the mobility sector. There is no standard for the definition of a low-carbon drive concept, so an own definition is given in this thesis. The carbon footprint of the entire life cycle of a vehicle with an internal combustion engine, powered by gasoline, is considered as the starting point. Alternative drive concepts are only considered low-carbon if they undercut the carbon footprint of the initial vehicle by at least 50%. The approach to these low-carbon drive concepts can be very different. On the one hand the type of drive can be changed (e.g. from internal combustion engine to electric motor or fuel cell), often resulting in using a different energy carrier (e.g. electricity or hydrogen instead of gasoline or diesel), on the other hand the production of the fuel can be improved (e.g. increasing efficiency or reducing upstream emissions), or new methods can be deployed (e.g. synthetic fuels instead of conventional fuels). But also other concepts do exist, that are not focused on the drive of the vehicle itself but consider mobility as a whole, as discussed later on in ***5.5***. However, this thesis mainly focuses on the potentials of the different drive concepts. This chapter is deliberately called low-carbon drive concepts and not carbon-neutral drive concepts, since, contrary to the frequent presentation of some of these concepts by the media and also by the legislators, no concept is actually completely carbon-neutral if the entire life cycle is considered. There are of course possibilities to compensate for the greenhouse gases that arise during the different stages of the life cycle. Reforestation, for example, but even if a company does reforestation to compensate for their greenhouse gases, the actual vehicle life cycle does not remain carbon free.

4.1 Battery Electric Vehicle (BEV)

The BEV will probably be the most promising solution for the coming decades. That is why many OEMs are investing billions of Euros in the development of new models with electric drives [46]. The basic concept of a battery electric vehicle is the drive by means of an electric motor, and the required power is provided by a battery, which gets recharged at a charging station. This can be done by conventional household electricity, which corresponds to a period of several hours for full charging, but also by fast charging systems, where the battery can be fully charged within about 30 minutes. In any case, there are several standardized plugs for this purpose. Due to the possibility of generating electricity from renewable energy sources, GHG emissions can be greatly reduced, as shown in the following sections [47].

4.1.1 Types of BEVs

Basically, electric drivetrains need the following components: e-machine, energy storage, inverter, AC/DC converter and engine & powertrain control unit. The key components here are the electric motor and the traction battery, of which there are many different types. With the electric motors, a distinction is made between direct current machines (DCM), asynchronous machines (ASM), synchronous machines (PSM) and switched reluctance machines (SRM), whereby ASM and PSM are the most applied types today. Commonly used battery types are Lead-Acid (Pb-Acid), Nickel Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH) and Lithium-Ion (Li-Ion), whereby the Lithium-Ion battery is the most common one for the use as a traction battery. Furthermore, a distinction can also be made based on the arrangement of the electric machine(s). A central drive machine, similar to conventional ICE, or individually driven wheels are options for the arrangement [48–50].

4.1.2 Vehicle Production (including Battery)

Vehicle production makes up for a significant part of the total emissions over the entire vehicle life cycle, especially for BEVs. The production emissions split into battery and glider & powertrain for BEVs produced in Europe and in China are shown in ***Figure 16***. The presented data shows the results of three sources, namely two European and one Chinese study. Commissioned by the European Commission, prepared by Ricardo Energy & Environment in collaboration with E4tech and ifeu, a study about the environmental impacts of different drive concepts was published in 2020 that is the most comprehensive one up to this date. The center of focus in this study lies in analyzing the individual life cycle stages of conventional and low-carbon drive concepts using LCA methodology starting from 2020 up to 2070. For this reason, this study (hereby called the EC study) is the main data source in this thesis [51]. In 2020, the Transport & Environment published a life cycle analysis of electric cars focusing on the clarity and transparency of LCA data, while utilizing some of the most up-to-date data in the field. This publication (hereby called the T&E study) is from utmost importance for LCA consideration of BEVs and ICEVs in Europe and is therefore mentioned in this thesis [52]. On the contrary, there are far fewer studies for China regarding life cycle assessments of BEVs. Although, Qiao et al., 2019 [53] reported the life cycle GHG emissions of an electric car on the Chinese market based on averaged data. As a result, only this study was consulted in this thesis for representing Chinese publications to this topic.

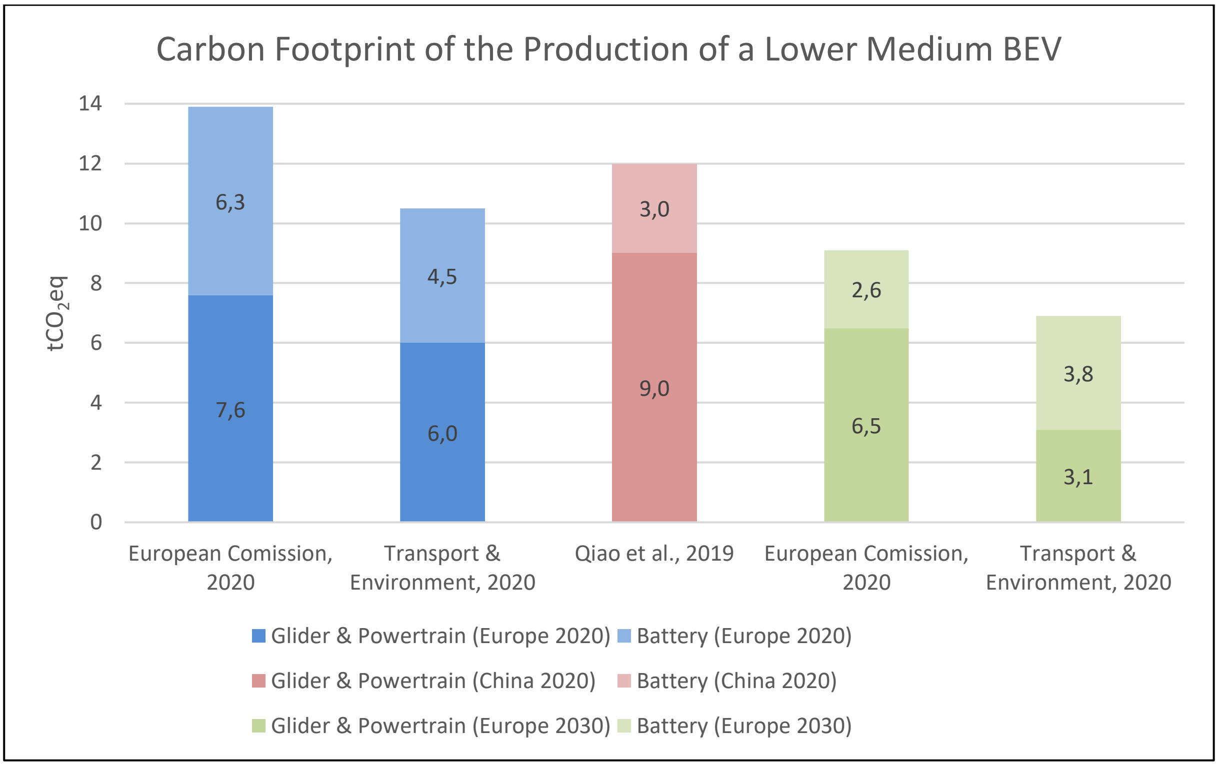

Figure 16 - Carbon Footprint of the Production of a Lower Medium BEV
Own figure - data obtained from [51–53]

Corresponding to the results for Europe, the EC study used a battery size of 58 kWh for the representation in 2020 and 64 kWh for 2030 and the T&E study used a similar battery size of 60 kWh for both 2020 and 2030. In both studies it is assumed that the battery does not have to be replaced, as it is designed for the entire life cycle of the vehicle, which corresponds to 225.000 km over 15 years. Qiao et al., 2019 relates to the production emissions of an average BEV in China and therefore calculated with a battery size of only 27 kWh. This is about half compared to the other two studies for Europe.

Furthermore, a vehicle lifetime of 150.000 km was assumed, which also means the battery does not have to be replaced. The different results of these three studies can be explained by several reasons.

First, the emissions from the production of glider & powertrain in Europe differ a little in 2020. The reason for the difference can be traced back to the boundary conditions of the studies. The EC study is based on a vehicle with an empty weight of 1350kg (without battery) while the T&E study used a vehicle mass of 1255kg (without battery). For comparison, the study concerning China calculated with a vehicle weight of 1300kg (without battery), which is in the middle of the other two studies. The energy mix used for calculation can be given as a further reason. The EC study calculated with a carbon intensity of the European grid mix of 439 gCO_2eq/kWh of produced energy and the T&E study calculated with an intensity of 319 gCO_2eq/kWh of produced energy. Qiao et al., 2019 did not mention any details about the electricity grid mix in China. However, since both the Chinese industry (mainly based on coal, oil and gas) and the Chinese electricity mix (about 1000 gCO_2eq/kWh according to the EC study) are more carbon-intensive than in Europe, there is also a higher production impact for a similar vehicle mass.

Second, the big difference in the potential to reduce production emissions by 2030 in Europe is due to the rather optimistic approach of the T&E study. There, the reduction in emissions was applied linearly with the approach to improvement in electricity generation. However, since a large amount of fossil fuel is required in the production phase incl. logistics, especially when mining raw materials, this approach must be questioned very much. Furthermore, the estimated vehicle masses for 2030 of the two studies also differ. The EC study assumed a mass of 1220kg and T&E study assumed a mass of 1085kg (both without battery). All in all, it can be concluded that the approach of the EC study to the potential of reducing GHG emissions from vehicle production sounds more reliable than the approach of the T&E study.

Third, the emissions from battery production in 2020 in Europe (which is not yet the case on large scale) differ a lot and the potential to reduce those emissions is much higher in the EC study. These differences can be explained relatively easily. As a starting point in 2020, the EC study used a mix of lithium-ion NMC batteries currently in use (NMC 111, NMC 532, NMC 622, NMC 811) while the T&E study only used the two most common NMC batteries (NMC 532, NMC 622) for the calculation. Since a lot of electricity is required in battery production, another big difference is the energy mix used for Europe in 2020, as mentioned before. Regarding China, the shown result is not directly comparable since the battery capacity is about the half of the others. Nevertheless, if the battery capacity were to be adjusted to the capacity of the European ones, the resulting emissions would still be less than in the EC study for Europe. One reason for this would be that the NMC battery used for China is not described in detail. In addition, as no data is available on the Chinese electricity mix used for calculation, no further statement can be made. However, the result for battery production in China according to Qiao et al., 2019 can be refuted with the analysis of the T&E study on the influence of the electricity mix on battery production in Europe and China, which will follow later.

Fourth, the big difference in the potential of reducing the carbon footprint of battery production in Europe up to 2030 lies in the rather conservative approach of the T&E study. This study only considered an improvement of battery cell density and not in the upstreaming processes like mining, refining and transportation. Furthermore, only the NMC 811 battery was used for calculation, which is estimated to make up 57% of the market by 2030. Since the EC study included both, an improvement in the batteries themselves (mix of NMC 622, NMC 811, NMC 910), as well as the reduced emissions due to the improvement in the energy mix to a carbon intensity of 254 gCO_2eq/kWh of produced energy, there is a greater potential for reduction.

In the final analysis, the greatest potential for short-term periods lies in improving the energy mix, as a lot of electricity is required for the vehicle and battery production processes. But there are also other significant approaches to lowering the carbon footprint. Production volume increase, more efficient production, application of new chemicals, increasing the energy density and extending the battery lifetime (Romare et al., 2017 [54]).

As already mentioned, the T&E study also made a comparison between battery production in different areas (Europe, China), which is shown in ***Table 6***. The influence of the energy mix on the carbon intensity can clearly be seen. Based on the EU average, battery production in countries with a high share of renewable energies (and also nuclear energy), such as Sweden, will cause 21,3% less CO_2eq emissions in 2020 and in countries with a poorer energy mix such as Poland, 42,6% more CO_2eq emissions. This is also the reason why China is currently not doing so well compared to the EU average. A battery produced in China causes 46,6% more CO_2eq emissions in 2020 than a battery produced in Europe. Of course, the comparison is flawed because China has a different starting point in electricity generation than Europe. And therein lies China's enormous potential to massively reduce its CO_2 footprint if electric energy production is moved to CO_2-neutral sources. This is also shown by the EU low value for 2030 where the battery is produced from almost 100% low-carbon energy sources. A further reduction only due to the electricity mix is therefore not possible, since most emissions are caused by upstream processes that use a lot of fossil fuel. The unit of the values shown in ***Table 6*** is kgCO_2eq/kWh battery size.

Table 6 - Carbon Content of Battery Production (including Upstream)
Own table - data obtained from [52]

Production Region	2020	2030
EU average	75	64
EU low	59	56
EU high	107	84
China	110	100

4.1.3 Electricity Production

A lot of electricity is required for almost every low-carbon concept, for example as an energy for BEVs and for the production of hydrogen or e-fuels. Furthermore, apart from other energy sources, a lot of electricity is required in industry for the production processes of vehicles and batteries. To sustainably supply electricity for all of these applications, the electricity has to be produced from renewable energy sources, which does not mean they are carbon neutral but at least low-carbon intensive.

The carbon footprint of different energy sources used for producing electricity in Europe is shown in ***Figure 17***. The horizontal black lines in the bars indicate the respective median. Due to the large number of parameters influencing an LCA study, no study can be compared with another. For this reason the results shown in ***Figure 17*** are from the same study (Schlömer et al., 2014 [55]) published by IPCC in order to create comparability. The upper limit for hydropower in this study is 2200 gCO_2eq/kWh due to the consideration of pumped storage power plants. This may be a typing error, since even using coal-fired electricity to pump water up into the reservoir, and accounting for efficiency losses and power plant's infrastructure, would not result in such a high carbon intensity. For this reason, another study published by IPCC (Bruckner et al., 2014 [56]) is used to present a more realistic upper limit value. The results of these two studies show that the use of renewable energies is not entirely carbon free, but the lifecycle GHG emissions are far below those of conventional power plants that are operated with fossil fuels. If the lower values of the renewable energies shown get compared, it can be seen that, except for biomass, very low carbon balances can be achieved. The same applies to nuclear energy, but due to risks for people and the environment in case of an accident and the nuclear waste produced, this technology is not considered further in this thesis. The wide range in biomass results on the one hand, from the fact that there are many different plants/crops that can be used, and on the other hand, from the considered boundary conditions in the LCA. In principle, the CO_2 released during combustion has already been captured from the atmosphere beforehand, but the CO_2 balance depends on other factors like transport or counterfactual emissions. Since the decision as to which renewable energy source is the best overall depends on other factors such as ecological and economic conditions, no ranking is made.

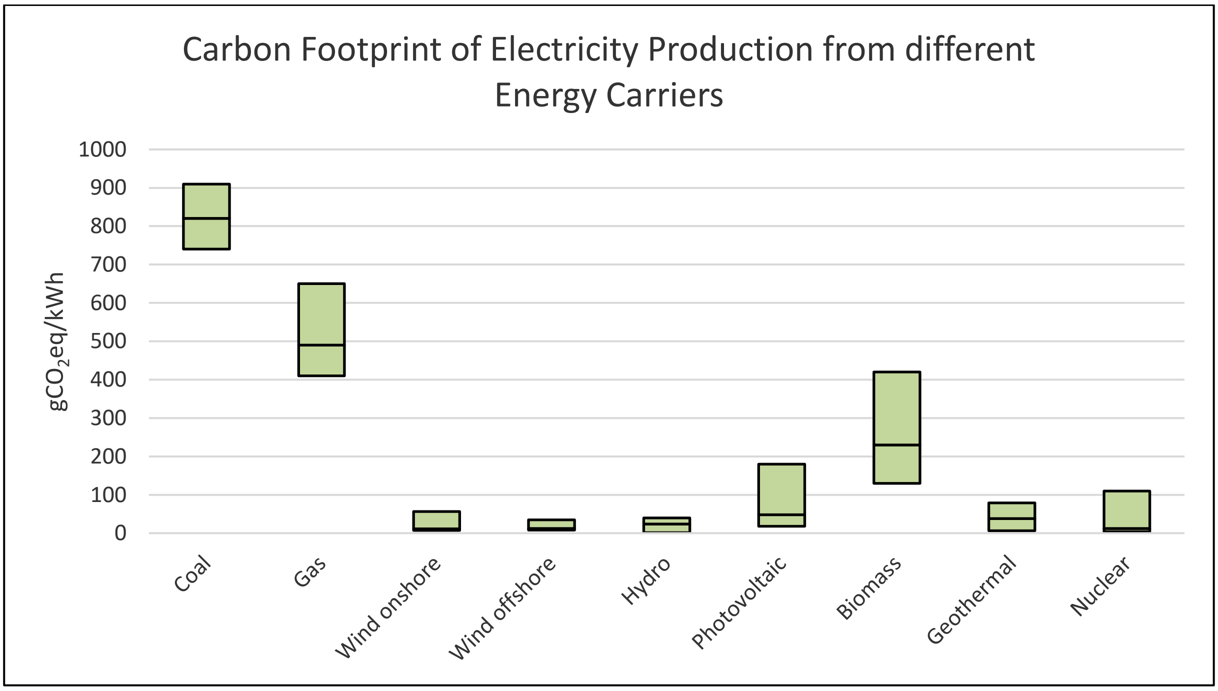

Figure 17 - Carbon Footprint of Electricity Production from different Energy Carriers
Own figure - data obtained from [55, 56]

4.1.4 Use-Phase

In contrast to the internal combustion engine, the conversion of electrical energy into kinetic energy in the electric motor does not release any emissions. Therefore, no direct CO_2 emissions (tank-to-wheel) are emitted during the use-phase. That’s why electric cars are considered as carbon-free in the legislation. However, the abrasion of brakes, tires and the road can very well cause emissions with regard to e.g. particulates. Moreover, the indirect emissions (well-to-tank) arising during the production of the fuel (energy) depending on fuel (energy) consumption should be counted for a reality-based point of view.

One problem that occurs is the calculation of the electricity mix from which the electricity is produced, as this is related to the region the car is used und can change significantly over the lifetime of the vehicle. Furthermore, upstream and operating emissions of the power plant, as well as pumping, trade and losses must be compensated (Hoekstra et al., 2020 [57]). There exist several studies showing different values for the European and the Chinese electricity mixes and their carbon intensity (EC study, T&E study, Hoekstra et al., 2020, Li et al., 2017 [58], Shen et al., 2019 [59]). Upon closer analysis, the EC study appears to have used the most reliable data. This means a carbon intensity of the European electricity mix of 439 gCO_2eq/kWh of electricity produced in 2020 and a carbon intensity of the Chinese electricity mix of 1000 gCO_2eq/kWh of electricity produced in 2020. For reasons of comparison with conventional technologies, the 2020 electricity mix will be used for calculation rather than the average over the vehicle's lifetime.

For displaying the GWP for the use-phase and subsequently the potential for improvement, the energy consumption of the BEVs must be specified. There are different approaches to this. A standardized test cycle could be used, for example NEDC or WLTC, or real consumption parameters could be used, too. In order to create comparability, the energy consumption measured by the WLTC is used and displayed in ***Table 7***. The Renault ZOE, the VW e-Golf and the Tesla Model S have been selected so that a vehicle of each vehicle class (low, middle, high) is represented.

Table 7 - Energy Consumption of BEVs in the WLTC
Own table - data obtained from [60–62]

Renault ZOE	VW e-Golf	Tesla Model S
17,20 kWh/100km	14,10 kWh/100km	18,50 kWh/100km

The final carbon footprint of BEVs in their use-phase, in comparison driven in Europe and in China, is shown in ***Figure 18***. The results are based on the 2020 electricity mix of Europe and China of the EC study, which were already mentioned before, and on the energy consumption of the different vehicles, shown in ***Table 7***. The influence of the electricity mix can clearly be seen. The horizontal blue line marks the European legislation for fleet emissions and the horizontal red line marks the Chinese one, as described in ***3.2.1***. Since BEVs do not emit tailpipe emissions, they are not subject to this legislation, but it is a respectable comparison to vehicles with combustion engines. This comparison shows that electric cars driven in Europe would be below this legal limit and electric cars driven in China would be above. Nevertheless, they are considered emission-free in the legislation, which does not correspond to reality. In defense of the ICE's, however, it must be said that well-to-tank emissions are also not taken into account (in the legislation) for them, too. Further, the result depends on the country in Europe and on the province in China where the car is operated, as the electricity mix differs a lot.

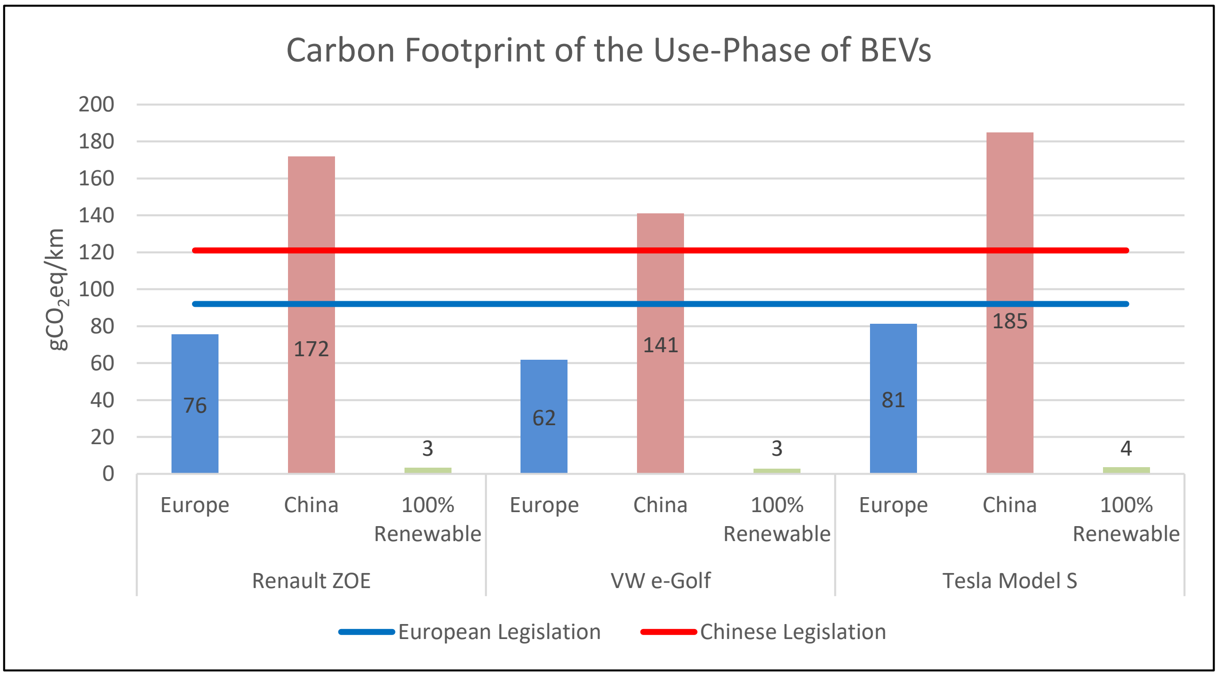

Figure 18 - Carbon Footprint of the Use-Phase of BEVs (basis: WLTC)
Own figure - calculated data based on previous results

The potential to reduce the carbon footprint is largely due to the electricity mix, but also due to the efficiency of the propulsion technology. If 100% of the electricity required can be generated from low-carbon renewable energy sources, emissions could be reduced to 2 to 4 gCO_2eq/km, depending on the vehicle.

4.1.5 End-of-Life

Every vehicle reaches the end of its life at some point and must be disposed. To protect the environment and possibly even reduce life cycle emissions, vehicles should be recycled. However, it is only advantageous in terms of climate change if the reuse of materials saves at least as much energy as is needed for the recycling process. With BEVs, recycling mainly revolves around the battery, as its raw materials are rare and precious, and the production makes up a major part of the emissions generated in the life cycle of a new vehicle, as shown later on in ***4.5***. For this reason, the legislators have already implemented some regulations about battery recycling and work on further legislations [63, 64]. But also the glider and powertrain should be recycled to keep the carbon footprint as low as possible, as defined in the European legislation [45].

Regarding the battery, there are basically two options after reaching the end of its life. The battery can be recycled, or it can be used in a "second life" cycle, e.g. in stationary powerplants. For the recycling process, there are many different methods that recycle different materials. The three main methodologies are pyrometallurgical, hydrometallurgical and direct cathode recycling. Whether a recycling process reduces the GWP of the vehicle or battery depends on whether the energy input for the recycling process is higher or lower than the energy input for raw material extraction of the materials reused. There are several studies on the recycling processes of lithium-ion batteries. Romare et al., 2017 and Buchert et al., 2016 [65, 66] came to the result that a saving of 3 kgCO_2eq/kg battery can be achieved through battery recycling. Mohr et al., 2020 [67], on the other hand, used state-of-the-art recycling processes for their LCA and reported a GWP reduction potential of about 20 kgCO_2eq/kg battery for NMC batteries. Since there are no LCAs yet that use primary industrial scaling values, it is reasonable to assume that as new giga factories including recycling are built, the potential to reduce GHG emissions will continue to increase [68].

The use of batteries in a "second life" makes sense, since they are no longer usable in a car if they only have 70% or less charging capacity, but they could be used in other applications, for example as an energy storage device to store excess energy from renewable energy sources. Even though, there are still too few studies and empirical values to give concrete figures for this method (Hoekstra et al., 2020).

To be able to quantify the potential through recycling of the entire vehicle including battery, two studies are analyzed. The EC study shows a potential for BEVs through the recycling process of 2,25 tCO_2eq per vehicle. Bothe et al., 2020 [69] analyzed 38 different studies regarding end-of-life of BEVs. The results range from a reduction of 0,87 tCO_2eq to an increase of 1,63 tCO_2eq.

In conclusion, it always depends on the boundary conditions of the performed LCA. In any case, greenhouse gas emissions can be reduced by using the latest recycling technology and a low-carbon electricity mix.

4.2 Internal Combustion Engine Vehicle (ICEV)

Internal combustion engines are based on the principle of internal combustion and conversion of the released thermal energy into mechanical energy. Usually, carbon fuels like gasoline, diesel and natural gas are used for the combustion; also bio-fuels can be used. However, it is also possible to burn hydrogen in an ICE, but this is an enormous technical challenge. The main problem by burning fossil fuels are the arising emissions such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC) and particles (PM, PN). Sulphur dioxide (SO_2) used to be a problem, but this has been solved with legislation on the constituents of fuels. As good as the exhaust aftertreatment system is today, the pollutants arising during a cold start cannot be converted by the catalytic converters completely. And for CO_2 emissions there is no technical way of offsetting it in the vehicle anyway.

Until now, the ICEV is the most common type of passenger car all over the world. But this will change significantly in the coming years, due to new legislations to fight climate change. Experts do not quite agree on whether they will be completely suppressed or whether they will still play a major role in future. However, the fact is that by 2030 almost every car with an internal combustion engine will have some kind of electrification in the European and Chinese market. Without such a development, the upcoming legislation on CO_2 emissions could not be complied with.

4.2.1 Types of ICEVs

As mentioned before, most ICEVs are based on burning fossil fuels. Conventional fossil fuels are gasoline, diesel and natural gas. Due to their chemical properties, they cannot be burned in the same engine. Therefore, a distinction between gasoline engines and diesel engines needs to be made. Due to chemical similarities of natural gas to gasoline, there are also applications in which natural gas can be burned in gasoline engines. However, this application is more likely to be found in large gas engines; in the passenger car sector it is a niche area. Since burning fossil fuels is not a low-carbon concept, alternatives to conventional fuels must be found. The answer to this is b-fuels or e-fuels. A more detailed explanation can be found in ***4.2.4***.

4.2.2 Vehicle Production

In contrast to battery electric vehicles, vehicles with internal combustion engine only have a small lead-acid battery. Since the production of a traction battery causes much more emissions than the production of an internal combustion engine, the total emissions arising due to the production of an ICEV are lower than those of a BEV. The results of five different studies regarding the production impact of ICEVs operated with gasoline in Europe and China are shown in ***Figure 19***. In addition to the three studies already cited for BEV production, one study each was added for Europe and China to make the depiction more comprehensive. Wietschel et al., 2019 [70] reported the greenhouse gas balance of vehicles with different propulsion systems and different fuel types in Germany using a life cycle analysis. This study is based on recent data and is an excellent complement to the other two studies and was therefore selected for this thesis. Qiao et al., 2017 [71] already conducted an analysis of production emissions of BEVs and ICEVs for China in 2017 and thus represents a good comparison to the more recent publication Qiao et al., 2019.

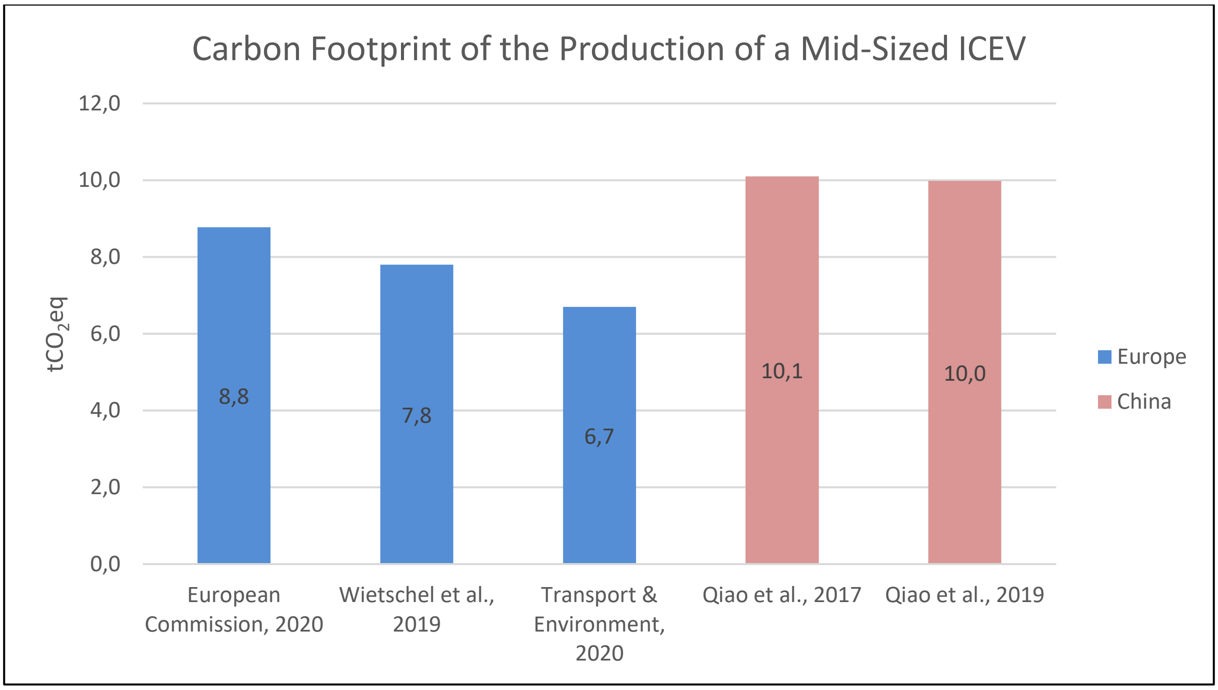

Figure 19 - Carbon Footprint of the Production of a Mid-Sized ICEV
Own figure - data obtained from [51–53, 70, 71]

Regarding the results of the European studies, they differ significantly. This is of course due to the boundary conditions that have to be set for each study, as already mentioned in ***4.1.2***. The EC study calculated with a vehicle weight of 1325kg and a carbon intensity of the European electricity mix of 439 gCO_2/kWh of produced energy. Wietschel et al., 2019, on the contrary, is based on a vehicle weight of 1300kg and a carbon intensity of the electricity mix of 421 gCO_2/kWh. Since both values are huge influencing parameters, the lower production impact can be explained. However, the T&E study used a higher vehicle mass (1395kg) and results in a lower carbon footprint than the others. On the one hand, this could be due to carbon intensity of electricity production, which was chosen to be significantly lower at 319 gCO_2/kWh. On the other hand, the production emissions were simply extrapolated from the vehicle mass and no details about production processes or raw material extraction were given. Furthermore, the results also depend on the databases used. By all these influences, the shown differences for the production emissions of a mid-sized ICEV in Europe can be explained.

The carbon footprint of the production of an ICEV in China, as shown by Qiao et al., 2017 and Qiao et al., 2019, is higher than in Europe. The results of these two studies are very similar, as both are based on the average mid-sized vehicle sold in China and were performed by the same author. It was to be expected that production in China would produce slightly more carbon emissions than in Europe, as the Chinese industry is more carbon intensive than the European industry.

The potential to reduce those emissions in the future is at a similar level to that of BEVs if battery production is disregarded. Based on the EC study's data for the production of a gasoline ICEV, a reduction of 10,5% by 2050 can be assumed for Europe.

4.2.3 Fossil Fuel Production

Burning conventional fossil fuels isn't a low-carbon concept for the future, but it forms the starting point for all other concepts. That's the reason why they are also dealt with in this thesis. It is well known that the combustion of these fuels produces CO_2 emissions and that is why ICEVs are under disrepute. A point often overlooked in the debate about ICEVs are the emissions arising during the production and transport of fossil fuels (well-to-tank). Therefore, these are treated in more detail in this section. To illustrate the upstream emissions of fossil fuels, four studies (EC study, T&E study, Hoekstra et al., 2020 and Peng et al., 2017 [72]) are compared with one another, as shown in ***Table 8***. Since the results from the T&E study and Hoekstra et al., 2020 are presented in the unit gCO_2eq/L of final fuel, they are divided by the respective calorific value of the fuel (38,3 MJ/L for diesel and 33,5 MJ/L for gasoline [57]). The results of the EC study and the T&E study are very similar, as both are based on European crude oil and refineries. Apart from that, the results from Hoekstra et al., 2020 differ a little, as global data for crude oil production and transportation to the refineries was used, but contrary to that European data for refining and fuel distribution was used. Peng et al., 2017 is based on Chinese data for fossil fuel production and the results are therefore slightly higher than the European ones. In conclusion, the values from the EC study are used in the coming analysis to represent Europe and the values of Peng et al., 2017 are used to represent China. In addition, the upstream emissions of LPG, CNG and LNG from the EC study are shown as well in ***Table 8***, as they can be used in ICEs, too. Nevertheless, using gas for ICEs in passenger cars isn't common in most markets. All values shown in the EC study are based on conventional extraction methods. If unconventional extraction (e.g. fracking) is taken into account, the carbon footprint would be higher.

Table 8 - Upstream Emissions of Fossil Fuels
Own table - data obtained from [51, 52, 57, 72]

	Gasoline [gCO_2eq / MJ]	**Diesel** [gCO_2eq / MJ]	**LPG** [gCO_2eq / MJ]	**CNG** [gCO_2eq / MJ]	**LNG** [gCO_2eq / MJ]
EC study	18,7	18,1	19,1	11,16	16,8
T&E study	18,3	19,2	-		
Hoekstra et al., 2020	21,5	16,7			
Peng et al., 2017	19,2	23,1			

4.2.4 B-Fuel & E-Fuel Production

The approach of making an internal combustion engine a low-carbon concept is based on the type of fuel used and its production. For this, there are two options: biogenic fuels (b-fuels) and synthetic fuels (e-fuels). The principle of these fuels is based on the fact that the CO_2 emissions released during combustion are previously bound from the atmosphere. In the case of b-fuels, the crops used for production bind the CO_2 during their growth and in the case of e-fuels, the CO_2 is either bound from waste of other processes or directly from the atmosphere.

The topic of biofuels is extremely complex, since a life cycle analysis according to DIN EN ISO 14040 and DIN EN ISO 14044 leaves a great deal of freedom to define the boundary conditions [73]. It is therefore important, especially in the LCA of biofuels, to pay attention to which factors are considered. Since counterfactual emissions and substitution are often taken into account, the results are sometimes not really meaningful. Biofuels from secondary fossil or secondary biogenic feedstocks are disregarded because their consideration goes far beyond the topic of this thesis. For the production of biofuels out of direct biogenic feedstocks the GWP varies to the type of the crop, best results from the EC study are shown in ***Figure 20***. The reason for the negative footprint of synthetic gasoline out of short rotation coppice wood is due to the consideration, that the soil where the crops are planted is able to store additional CO_2. However, if it would be taken into account that there are other plants or trees whose planting can store more CO_2 in the soil, the footprint of this method would no longer be negative but would result in additional CO_2 in the overall balance. Additionally, the substitution of electricity production was considered. That means, the electricity production out of SRCWood causes more GHG emissions than the production of synthetic gasoline. This is one more reason, why a negative footprint results. That's just one example of the difficulty of defining an LCA for biofuels. In conclusion, it can be said that depending on how the production of biofuels is evaluated, they may well represent a low-carbon concept, but there are definitely better solutions, even if one thinks of the fact that instead of the plants for fuels, plants for food could be cultivated and so the world hunger could be worked against.

As a result of the analysis, biofuels are not considered in the further calculations and depictions of the low-carbon drive technologies. Nevertheless, biofuels are commonly used in a mixture with conventional fossil fuels to make them more sustainable, as described more detailed in ***4.2.5***. However, this will not be considered further in this thesis.

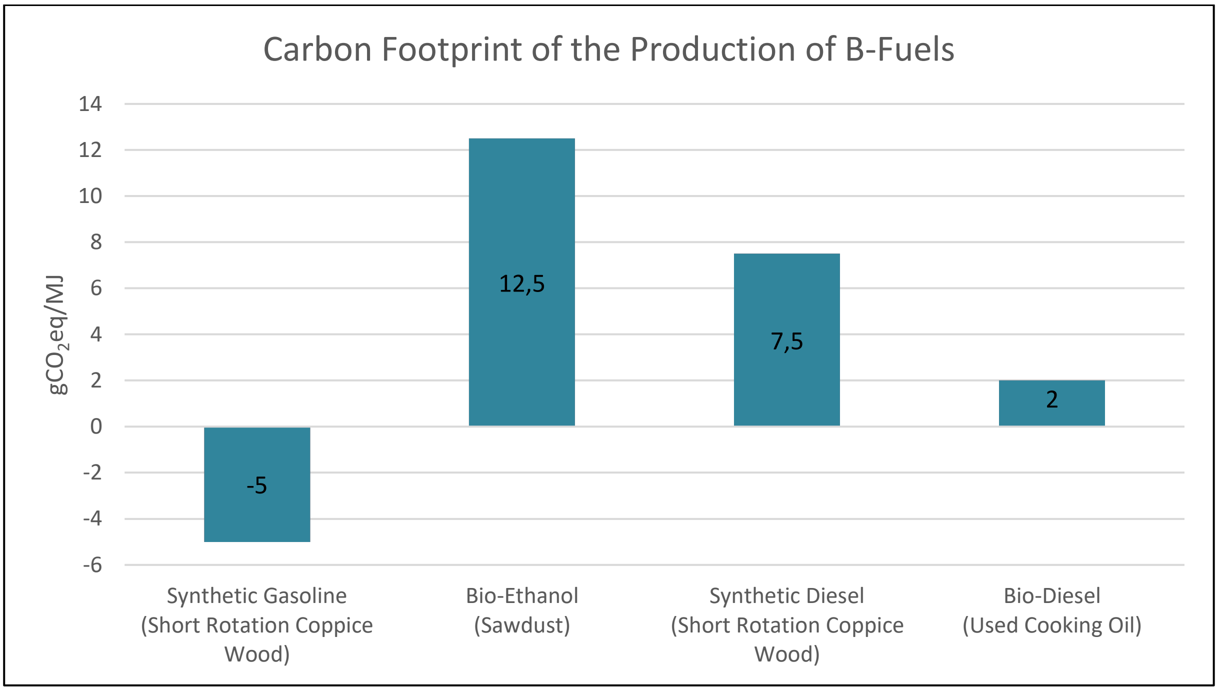

Figure 20 - Carbon Footprint of the Production of B-Fuels
Own figure - data obtained from [51]

The second option for low-carbon fuels are synthetic fuels (e-fuels). The production of e-fuels, in which a fuel is generated from hydrogen and CO_2 using electricity (Power-to-Liquid or Power-to-Gas) actually causes a lot of carbon emissions today due to the enormous amount of electricity needed, as shown in ***Figure 21***. It is important to note that the binding of CO_2 from the atmosphere or waste streaming processes in the fuel is not included in the plot. Using the current European electricity mix, the production of synthetic gasoline would result in around 1030 gCO_2eq/MJ of final fuel and in around 495 gCO_2eq/MJ of final fuel for the production of synthetic diesel. The higher impact of synthetic gasoline compared to synthetic diesel is due to a lower process efficiency, which amplifies process emissions. If these fuels were to be produced in China using the Chinese electricity mix, emissions would at least double. The potential of e-fuels lies in improving the electricity mix up to 100% renewable. This could reduce their carbon footprint to 71,5 gCO_2eq/MJ of final fuel for gasoline and to 43 gCO_2eq/MJ of final fuel for diesel. Another potential of these fuels for the future is the possibility to increase the process efficiency. With increasing the efficiency and using renewable energies, the carbon footprint could be massively reduced. The great advantage over conventional fossil fuels is that the carbon emissions generated during combustion (tank-to-wheel) do not affect their GWP [51].

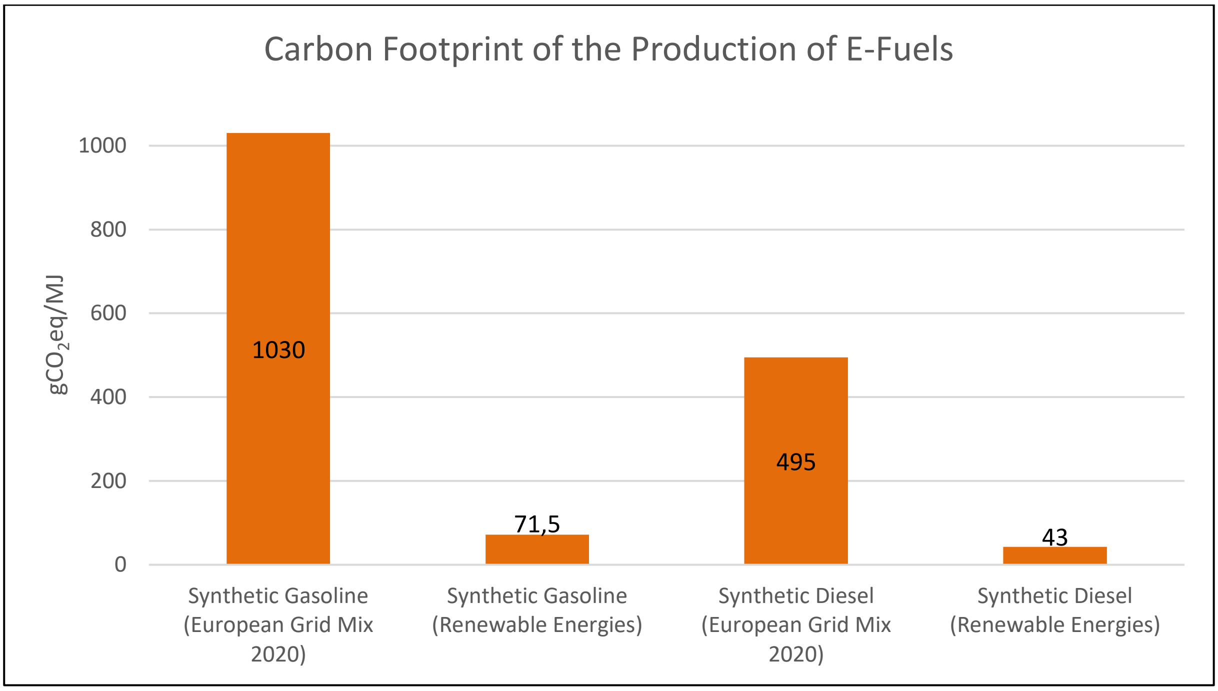

Figure 21 - Carbon Footprint of the Production of E-Fuels
Own figure - data obtained from [51]

4.2.5 Use-Phase

For the representation of the total GHG emissions arising during the use-phase of an ICEV, both the direct (TTW) and indirect emissions (WTT) must be added for carbon fuels. However, in the case of b-fuels and e-fuels the direct emissions emitted during combustion were previously bound from the atmosphere or waste streaming processes, which is considered in the indirect emissions. In reality, the conventional fuels are often mixed with b-fuels. In Europe, for example, there can be up to 10% bio-ethanol in gasoline (E10) and up to 7% bio-diesel in diesel (B7) [74]. To consider that in calculating the emissions for the use-phase would create a highly complex and evolving framework, which is out of scope in this thesis. Therefore, mixed fuels are no longer considered. As for BEVs, the fuel consumption of an existing car is needed. For this reason, the VW Golf Rabbit is selected and it's fuel consumption according to the WLTC is 6,5 L/100 km using gasoline and 5,2 L/100 km using diesel for operating [75].

Figure 22 shows the carbon footprint of the use-phase of the VW Golf Rabbit operating with different fuels. It has to be mentioned, that the depiction of using e-fuels is the best-case scenario, according to the applied LCA methodology of the EC study. The carbon footprint of using e-fuels heavily depends on the electricity mix used for producing. Basically, it can be seen that the carbon footprint for conventional fuels is slightly lower for diesel engines than for gasoline engines, because they are more efficient. The results shown for conventional gasoline and diesel are based on European data because the difference to Chinese data would only account for 1 or 2 gCO_2eq/km, which could not be seen in the diagram. The tank-to-wheel emissions can be calculated with the factor of 2,38 $kgCO_2/L$ for burning gasoline and 2,65 $kgCO_2/L$ for burning diesel [76]. Synthetic fuels from renewable energies can reduce overall emissions, but an energy mix from 100% renewable sources is unlikely for both Europe and China in the next few decades. The horizontal blue line marks the European legislation for tailpipe emissions and the horizontal red line marks the Chinese one for this type of vehicle. In these legislations only the tank-to-wheel emissions are considered. Nonetheless, using conventional gasoline or diesel would not fulfil these legislations. That's the reason, why other concepts are needed to accomplish the fleet consumption targets.

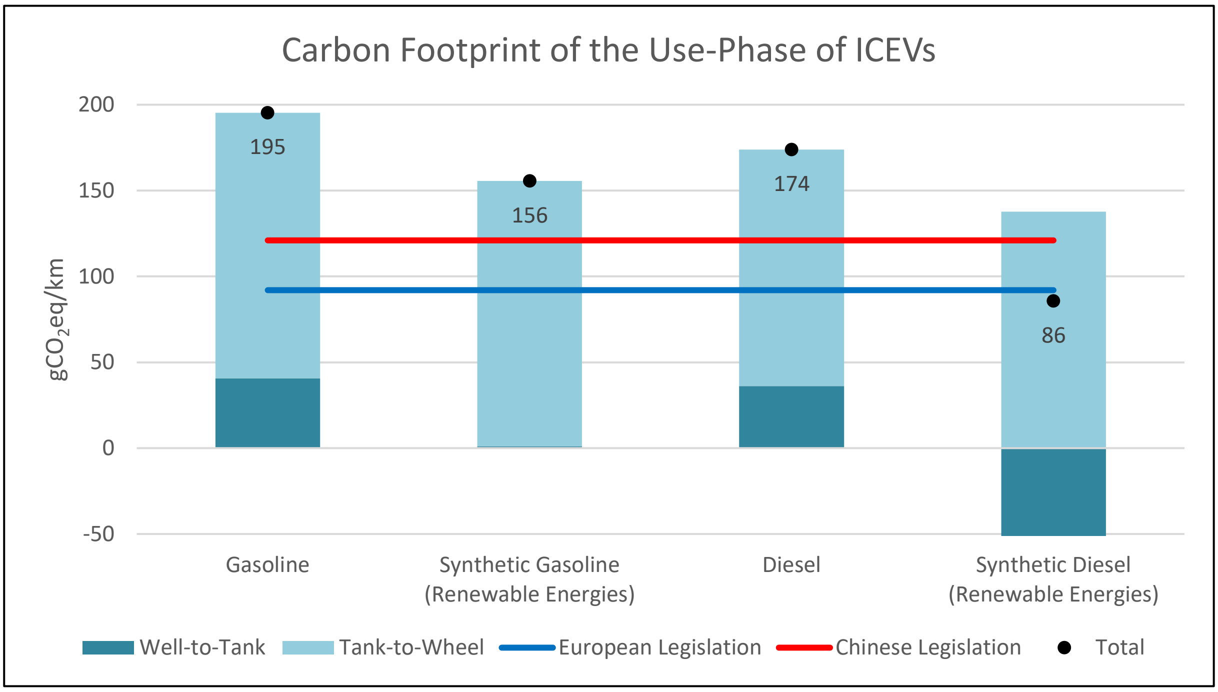

Figure 22 - Carbon Footprint of the Use-Phase of ICEVs (basis: WLTC)
Own figure - calculated data based on previous results

4.2.6 End-of-Life

When an ICEV reaches the end of its life, it should be recycled in any case. In reality, however, the vehicles are very often shipped to other countries with not so strict legislations and continue to operate there in conditions that would not allow for registration in Europe. The far better solution would be the mandatory recycling of vehicles. Even though, as the vehicles can change hands many times during their lifetime, no binding contract for recycling can be concluded between the manufacturer and the buyer of the new vehicle. Nevertheless, there already exist vehicle take-back regulations for example in Austria, but this only forces the manufacturer to take back the vehicles, not the customer to return the vehicle at the end of its life. Legislators are therefore called upon to create incentives and solutions for this.

To demonstrate the potential of recycling, Bothe et al., 2020 has analyzed 26 studies on gasoline vehicles and 22 studies on diesel vehicles. The result of this analysis shows a carbon footprint from -0,87 tCO_2eq to +0,8 tCO_2eq for gasoline engine vehicles and from -2,07 tCO_2eq to +0,67 tCO_2eq for diesel engine vehicles, depending on the vehicles investigated and the boundary conditions of the studies. In the EC study, however, the recycling of a gasoline powered ICEV has the potential to reduce the carbon footprint by 8 gCO_2eq/km. Extrapolated to the assumed lifetime of the vehicle of 225.000 km, this results in a total potential of 1,8 tCO_2eq, which is significantly better than in the studies analyzed by Bothe et al., 2020.

4.3 Hybrid Electric Vehicle (MHEV, HEV, PHEV)

Hybrid electric vehicles represent some kind of "intermediate solution" between battery electric vehicles and internal combustion engine vehicles. By installing both drive technologies in one car, the weaknesses of one technology can be replaced by the strengths of the other. However, it also means that the vehicle could be struggled with the disadvantages of both. Furthermore, the vehicle mass increases by installing both propulsion systems, which has a negative effect on fuel consumption.

4.3.1 Types of HEVs

Because a hybrid electric vehicle is a combination of two propulsion systems, there exist a hybridization factor HF for the classification of the hybridization. The value of HF is pending between 0 and 1, HF = 0 means the vehicle is an ICEV and HF = 1 means the vehicle is a BEV. The factor is made up of the ratio of electrical power to total power (electric motor + internal combustion engine). Depending on the ratio, HEVs can be classified as the following [77, 78]:

- Micro-Hybrid (HF < 0,1): A micro-hybrid vehicle uses the power of an electric motor, which is limited, for fast start/stop operations. Therefore, the electric motor works as a combination of starter and alternator and allows the ICE to propel the vehicle after starting procedure. That means, the ICE can be stopped when the vehicle is in a standstill condition and this can save up to 10% of final fuel consumption.

- Mild-Hybrid (HF < 0,25): A mild-hybrid vehicle has two additional functions. It can boost the ICE during acceleration and regenerate braking energy. However, the electric motor is not able to drive the vehicle alone. The final fuel consumption can be reduced by approximately 10 - 20%.

- Full HEV (0,25 < HF < 0,5): The propulsion of a full HEV can be provided by the ICE or the electric motor alone. Furthermore, electric propulsion can be substantially provided to support the ICE. If the EM propels the vehicle alone, this can only be used for short distances. The fuel consumption may be improved up to 50%.

- Plug-In HEV (HF > 0,5): A PHEV uses a battery as the storage device, which can be recharged from a residential power grid. The ICE charges the battery when the power is insufficient. Therefore, an on-board generator and the ICE are accommodated in the vehicle. The electric motor is able to propel the vehicle at higher velocities and longer distances.

Another possibility of classification is by the mechanical connections of ICE and EM, which can be in series, parallel or series/parallel. In a series HEV, the EM is responsible for the propulsion power, while the ICE is used to recharge the battery. In a parallel HEV the EM and the ICEV support power to the drivetrain and in a series/parallel HEV is an additional planetary gear used to drive the powertrain either in series or parallel [77].

Parallel HEVs can be divided into different categories depending on the mechanical arrangement. The designations for this range from P0 to P4 [79, 80]:

- P0: EM in front of the ICE, e.g. connected to the crankshaft of the ICE via belts
- P1: EM rotatably connected to the crankshaft of the ICE
- P2: EM sits at transmission input shaft, between ICE and EM there is a clutch.

- P2.5: EM sits in a dual clutch transmission on the input shaft of one transmission side
- P3: EM firmly connected to the gearbox output shaft, the EM is located between gearbox and differential
- P4: also called “Axle-Split”: Electric axis made of EM and differential or EMs as wheel hub motors, no mechanical connection (shaft) to the ICE

4.3.2 Vehicle Production

The total emissions from vehicle production of different hybrid electric vehicles are between those of ICEVs and BEVs. The breakdown into vehicle production (glider, powertrain, electronics etc.) and battery production is shown in ***Figure 23***. Represented in blue are the results of the EC study for a lower medium HEV and a lower medium PHEV with an electric range of 50 km using the European electricity mix of 439 gCO_2eq/kWh of produced energy. Since only the total emissions are given for the HEV in this study, the emissions from vehicle production are assumed to be the same as for vehicle production of the PHEV and the emissions from battery production are calculated from this.

As no studies with primary values (e.g. supply chain, logistics, processes) exist for China, the presentation is based on secondary data. Thus, only the carbon intensity of the Chinese power grid remains as a primary point of comparison. Samaras et al., 2008 [81] carried out the life cycle GHG emissions of HEVs and PHEVs with various ranges according to different electricity scenarios. In this regard, the carbon-intensive scenario, with an electricity production impact of 950 gCO_2eq/kWh of produced energy is used for representing China (red bars in the diagram). Compared to the results of the EC study, the influence of the electricity mixes on vehicle production can be seen. It is also possible to see the relationship between the electrical range (size of the battery) and the resulting production emissions. Further shown in green are the results based on an electricity mix of 200 gCO_2eq/kWh of produced energy. Although the data from Samaras et al., 2008 is somewhat out of date, the potential for reducing greenhouse gases by improving power generation is clearly evident.

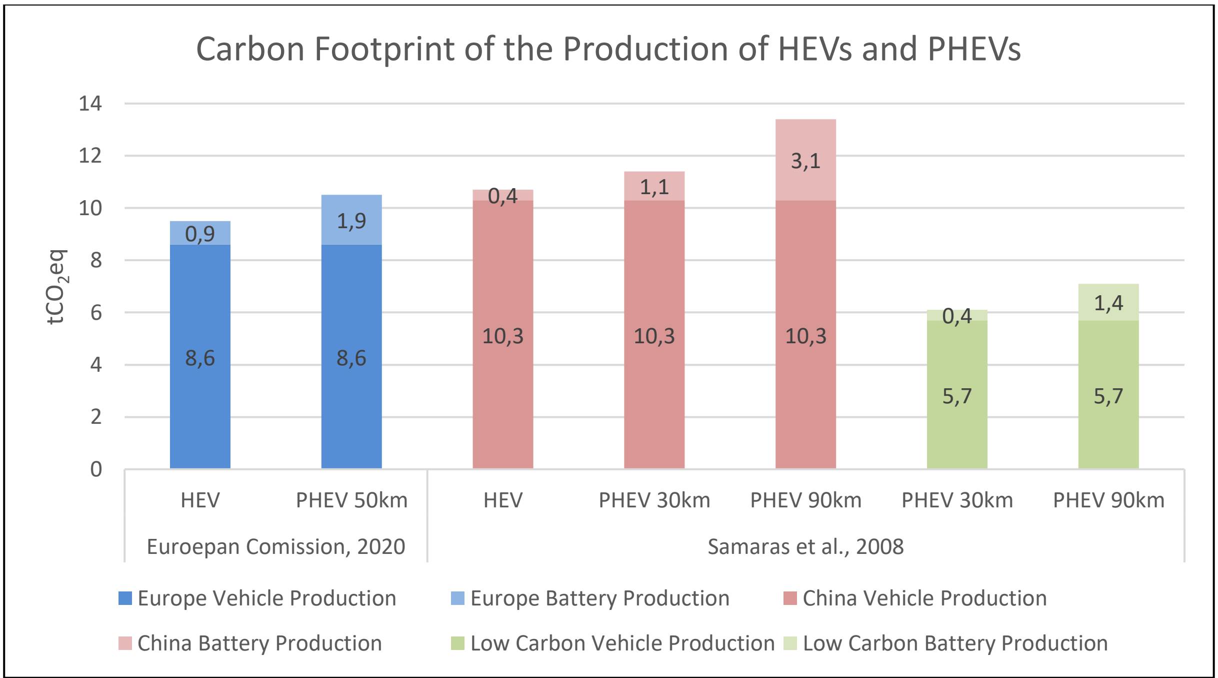

Figure 23 - Carbon Footprint of the Production of HEVs and PHEVs
Own figure - data obtained from [51, 81]

4.3.3 Use-Phase

To be able to calculate the use phase, a mid-sized vehicle model is required once as a full hybrid and once as a plug-in hybrid. The Toyota Prius is selected for this. Mild-hybrid and micro-hybrid vehicles are not shown due to the rather low savings potential compared to normal consumption of an ICEV. The standard gasoline consumption of the Toyota Prius Hybrid is 4,5 L/100km according to WLTC [82] and the standard gasoline consumption of the Toyota Prius Plug-in Hybrid is 1,3 L/100km and the standard electricity consumption is 9,9 kWh/100km also according to WLTC [83]. It has to be mentioned that the WLTC procedure is different for PHEVs. The test cycle has to be driven several times starting with full battery and ending with empty battery. Out of these results an utility factor (UF) is calculated to determine the electric range and the respective CO_2 emissions [84].

Given these points, ***Figure 24*** shows the carbon footprint of those two vehicles in their use-phase for different fossil fuels and electricity mixes. The horizontal blue line marks the European legislation for tailpipe emissions for this vehicle class and the horizontal red line marks the corresponding Chinese legislation. However, it must be mentioned that the legislation only considers the tank-to-wheel emissions and does not count the well-to-tank emissions. Looking at the results for the full hybrid vehicle, the potential for reducing the carbon footprint is rather low. Only if the production efficiency of the synthetic fuel could be greatly increased the potential would rise to a considerable level. Regarding the results for the plug-in hybrid, it must be said that the respective electricity mixes are not assumed as an average value over the entire service life of the vehicle. The values used are the same as for the use-phase of BEVs representing the 2020 standard. For the depiction of 100% renewable energy, a value of 20 gCO_2eq/kWh of produced energy is assumed. Based on these results, one can see that the plug-in hybrid is already well below the legal limit (***3.2.1***) in Europe, even if all the emissions generated during production of the fuels (well-to-tank) are taken into account. In China, however, the PHEV would slightly fail the regulated value if well-to-tank emissions were considered. Without counting those emissions, the PHEV would easily fulfil the emissions legislation regarding fuel consumption. If the vehicle is operated with 100% renewable electricity, the GHG emissions could be significantly reduced. If conventional gasoline is replaced by synthetic gasoline out of 100% renewable electricity, emissions could be further reduced. The ability to cover greater distances with the electric motor also means that the fuel consumption of fossil fuels can be reduced.

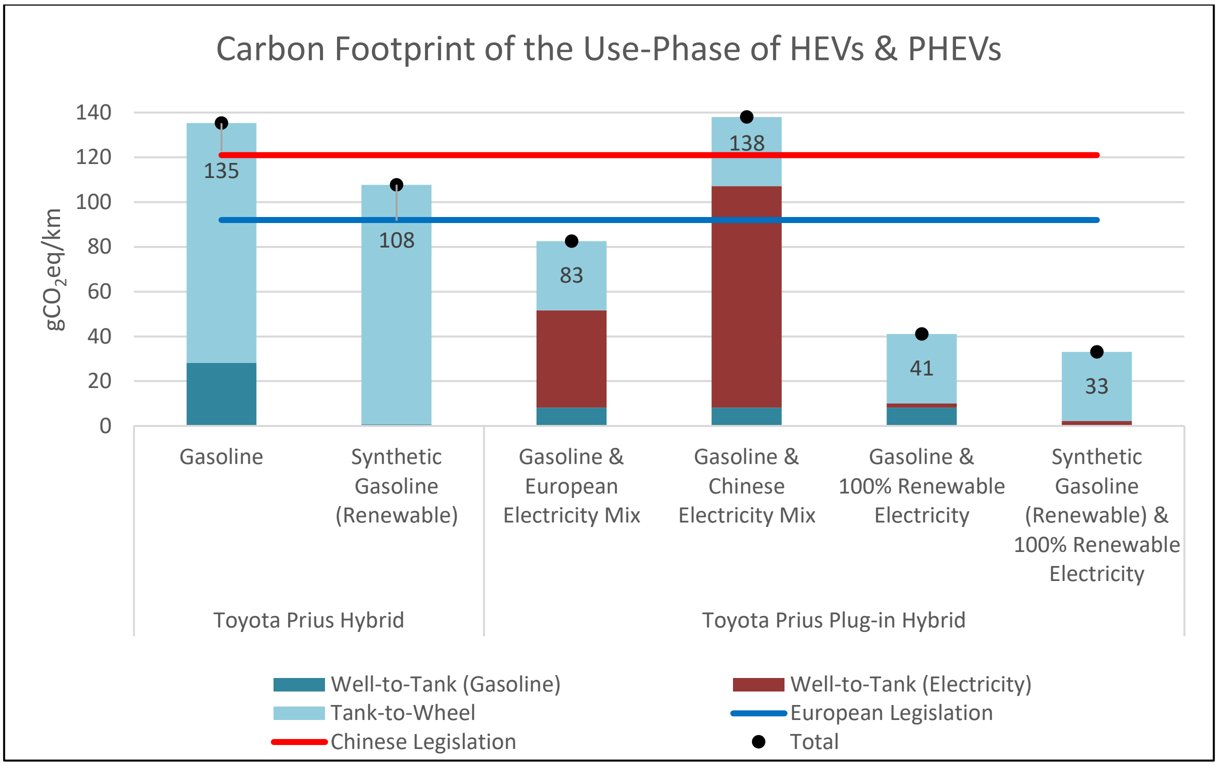

Figure 24 - Carbon Footprint of the Use-Phase of HEVs & PHEVs (basis: WLTC)
Own figure - data obtained from previous results

All things considered, the PHEV definitely represents a low-carbon alternative to the BEV in the use-phase. At present, the HEV cannot yet compete with those two concepts due to its dependence on fossil fuel. But, if the manufacturing processes for synthetic fuels get further improved, the HEV could also be able to compete with the other concepts in the future.

4.3.4 End-of-Life

Since hybrid electric vehicles have installed two drive technologies, their recycling is very similar to ICEVs and BEVs if the same battery type is applied. As technologies, nickel-metal hydride batteries and lithium-ion batteries come to use. The details of lithium-ion battery recycling are mentioned in ***4.1.5*** and the details for recycling of the rest of the vehicle including the ICE in ***4.2.6***.

For the recycling of nickel-metal hydride batteries, Silvestri et al., 2020 [85] published an LCA-based study. This publication shows an increase of GHG emissions through the recycling process. Based on the German electricity mix, the life-cycle emissions of the examined battery would be 22,4% higher if recycled materials were used instead of raw materials to produce a new battery. There are two main reasons for this result. First, the used recycling procedure was the hydrometallurgical process, which dissipates a lot of energy. Second, the study is based on the German electricity mix, which is very carbon intensive compared to a lot of other European countries. Nevertheless, the result also shows benefits deriving from the recycling of Ni-MH batteries for the preservation of natural resources and human toxicity. There does not exist any recycling study using primary large-scale values, which would significantly increase the GHG reduction potential through recycling.

All in all, the EC study concludes that the potential for GHG emission reduction for HEVs is similar to that of ICEVs and for PHEVs it is similar to that of BEVs. Of course, the specific vehicle characteristics are not identical. This results in a GWP reduction potential of 1,8 tCO_2eq for HEVs and 2,5 tCO_2eq for

PHEVs. The EC study is based on a recycling process that saves energy in total. But as already mentioned with BEVs, the recycling of vehicles and batteries is not always associated with a reduction in GHG emissions. This depends very much on the process used and the place where the recycling is carried out.

4.4 Fuel Cell Electric Vehicle (FCEV)

The baseline concept of a fuel cell electric vehicle is generating electricity out of hydrogen in a fuel cell to run the vehicle by an electric motor. A battery serves as an intermediate storage device from which the electric motor draws its electricity. At first glance, this seems like an excellent solution for a low-carbon drive concept because no harmful or climate relevant emissions are produced during operation. But appearances are deceptive, as this technology brings several difficulties with it. First, the required hydrogen must be generated with low-carbon technologies, which is further described in ***4.4.3***. Second, if the hydrogen, which has a low energy density, gets not produced at the fuel station, it must be transported there. Third, the hydrogen has to be stored in a specific high-pressure tank in the vehicle. This doesn't sound too difficult at first, but the chemical properties of hydrogen require special technologies for storage. For the transportation and the storage of hydrogen, its volumetric energy density is the most important value. For pure hydrogen in gaseous condition at 700 bar pressure the volumetric energy density is 1,3 kWh/dm^3 and in liquid condition at -253°C and ambient pressure it is 2,3 kWh/dm^3. In contrast to that, for gasoline in liquid condition it is 8,8 kWh/dm^3. So it can be stated that much less energy in the form of hydrogen than in the form of gasoline in a tank of the same size can be stored and transported. Furthermore, the storage of hydrogen in gaseous condition at 700 bar pressure dissipates 10 - 15% of the stored energy and in liquid condition at -253°C 20 - 30% of the stored energy, whereby boil off losses for liquid storage are between 0,3 and 3% each day occur. Additionally, the double conversion of the energy, on the one hand for the production of hydrogen and on the other hand for the conversion into electrical energy, reduces the overall efficiency of this technology, especially in comparison to BEVs [86].

4.4.1 Types of Fuel Cells

There exist different types of fuel cells, whereby just portable fuel cells are relevant for passenger cars. The two common portable fuel cell types are proton-exchange membrane fuel cell (PEMFC) and direct-methanol fuel cell (DMFC). Since the DMFC uses methanol as an energy supplier and this contains carbon if it has fossil origin, it is not of great importance as a low-carbon concept for passenger cars. It is often used to power small electrical appliances. Therefore, only the PEMFC is considered further. [87]

4.4.2 Vehicle Production

In addition to the glider, the energy storage systems (e.g. for electricity and hydrogen) and the fuel cell itself make up a large proportion of the GHG emissions arising during production. This is largely due to the hydrogen tank, which is mostly made of carbon-fiber reinforced plastic, as it is very energy-intensive to produce. But the battery (mostly lithium-ion) also has its share of the emissions, although these are much lower than with the BEV because it is relatively small and only serves as a buffer for the EM. Almost 10% of production emissions are due to the production of the fuel cell system, which also makes up a notable proportion [51].

Figure 25 shows the carbon footprint of the production of mid-sized FCEVs according to different studies. All studies are based on gaseous hydrogen storage at a pressure of 700 bar. The EC study and Helms et al., 2019 [88], both in cooperation with ifeu, present nearly the same carbon footprint. The only difference worth mentioning is due to the emissions deriving from the assembly, which are considered in the EC study. Without considering these emissions, the result would be the same, namely 12,2 tCO_2eq for the production of an averaged mid-sized FCEV produced in Europe. Compared to ICEVs, these are significantly higher emissions (due to the hydrogen tank, the fuel cell and the battery) and compared to BEVs, the emissions are slightly lower. Evangelisti et al., 2017 [89] analyzed the production impact of a mid-sized FCEV using different materials and specifications especially for the hydrogen tank and the fuel cell stack (80 kW power). Therefore, the results vary from 11,4 to 16 tCO_2eq. Rauecker, 2019 [90] is based on the Hyundai Nexo, but no further details about boundary conditions are given in the publication. Nevertheless, the data sheet from Hyundai [91] shows, that the Nexo model has a fuel cell stack with a power of 95,3 kW and an EM with a power of 120 kW. However, since no more precise details about the carried out LCA are known, it cannot be clearly stated why the result is significantly lower than that of the other three studies.

A distinctly higher result is shown by Chen et al., 2019 [92] for the production of an FCEV, based on the data of the Toyota Mirai, produced in China. In this study every single step for the production of the vehicle is considered in a Chinese context. Since Chinese industry and energy production are carbon-intensive, the result for the production of the vehicle is much higher. Because all the other Chinese studies regarding the other low-carbon drive concepts, mentioned in the previous section, have also shown higher results compared to Europe, but not to such an extent, it is necessary to understand this result. One reason are the used energy types for energy consumption in the different stages of vehicle production. For raw material acquisition there is an energy consumption of 1.738 kg coal, 416 kg crude oil and 509 kg natural gas assumed. For parts manufacturing and vehicle assembly the energy consumption was assumed almost just out of coal (533 kg for parts manufacturing and 998 kg for vehicle assembly). Another reason could be the usage of a very old life cycle assessment method of 2001 (CML2001). Furthermore, a different model compared to the European studies was used for the raw material acquisition stage (GaBi model). Additionally, for parts manufacturing they did not have any data for the manufacturing processes of the Toyota Mirai, so they used data of existing manufacturing processes of Chinese plants. Given all these points, the high result can be explained. However, if lower carbon-intensive data, latest methodologies, and real production processes were used, the result could be reduced drastically. For this reason, the carbon footprint of vehicle production in China will be assumed based on European values in the further calculation.

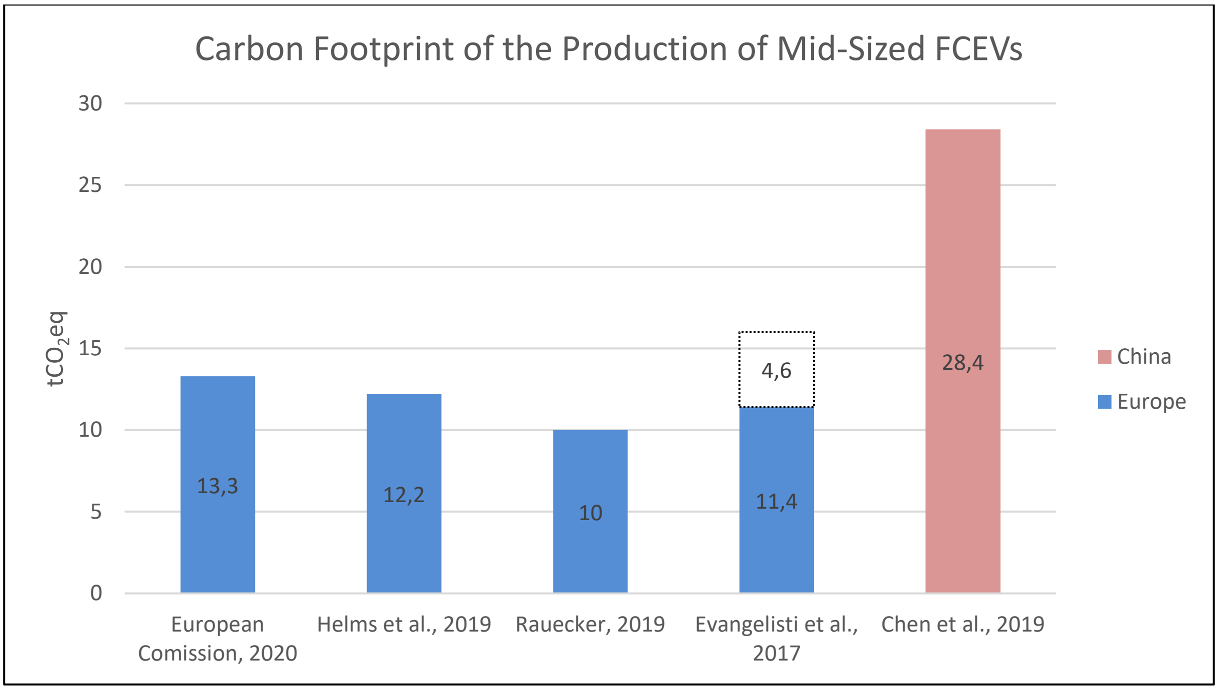

Figure 25 - Carbon Footprint of the Production of Mid-Sized FCEVs
Own figure - data obtained from [51, 88–90, 92]

4.4.3 Hydrogen Production

Since vehicle production, similar to BEVs, causes a huge proportion of GHG emissions, the production of hydrogen must be as low-carbon as possible in order to be able to compete with conventional technologies. ***Figure 26*** shows the carbon intensity of hydrogen production in Europe for different technologies carried out by three different studies. The production using electrolysis based on the European and German electricity mix clearly stands out in a negative way, as shown by the EC study and by Helms et al., 2019. This is due to the low process efficiency and therefore the amount of electricity needed. On the other hand, a very low carbon footprint can be achieved with the same technology using renewable electricity (green hydrogen), as shown in all three studies. The grey hydrogen produced by a conventional technology like steam methane reforming (SMR) and the blue hydrogen from Capture Carbon and Storage (CCS) are in the middle of the field. Using biomass gasification for hydrogen production shows the lowest GWP of all technologies, because the carbon emissions arising during production were absorbed before by the crops, as shown by Valente et al., 2020 [93]. Since many aspects play a role in biofuels and can have a negative impact, it can be concluded that the production of hydrogen by means of electrolysis using renewable electricity (green hydrogen) is the best method. To avoid unnecessary losses through transport, the fuel should be produced directly at the filling station. Approaches and first projects already exist [94].

The carbon intensity of hydrogen production in China based on Ren et al., 2020 [95] is shown in ***Figure 27***. The trend of the results is similar to that in Europe, however, the individual technologies are more carbon intensive. The biggest carbon footprint results from coal-based hydrogen, followed by natural gas-based hydrogen. In case of natural gas-based hydrogen, the emissions arising during production in China are almost double than in Europe. Same for hydrogen production through electrolysis out of low-carbon electricity. With process optimization a carbon footprint like that in Europe could be achieved.

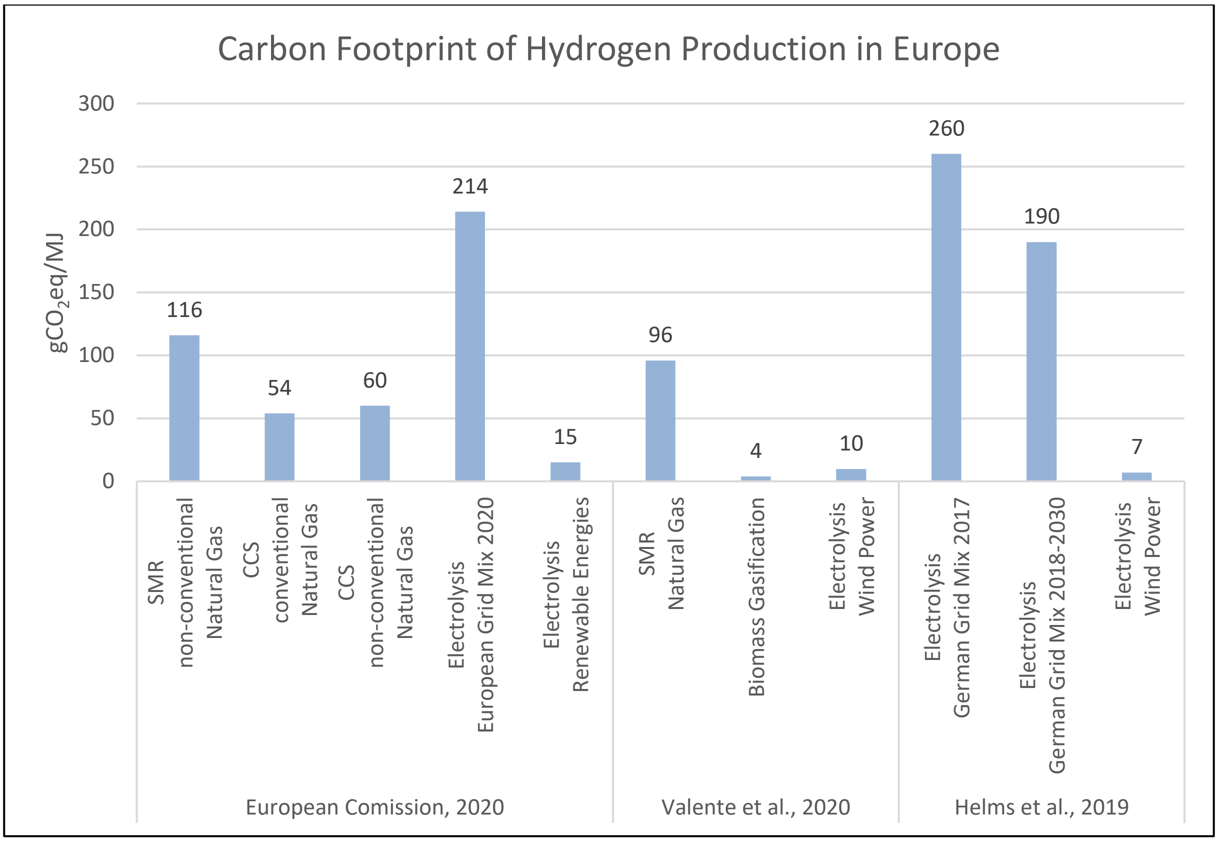

Figure 26 - Carbon Footprint of Hydrogen Production in Europe
Own figure - data obtained from [51, 88, 93]

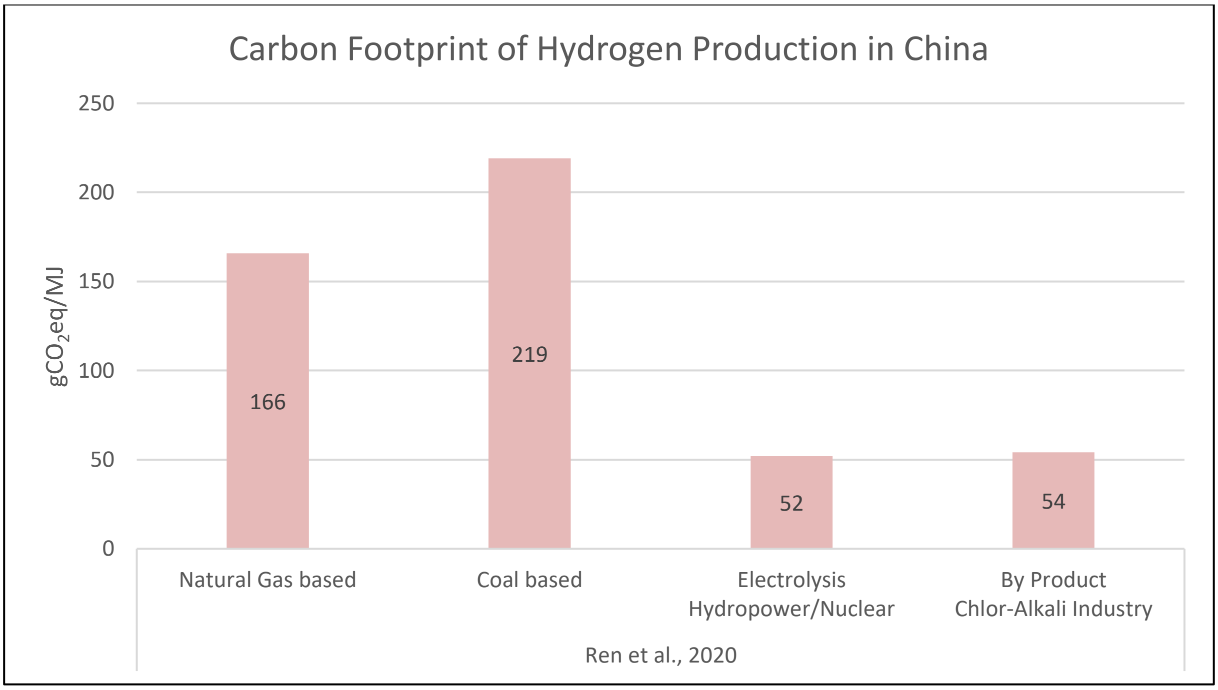

Figure 27 - Carbon Footprint of Hydrogen Production in China
Own figure – data obtained from [95]

4.4.4 Use-Phase

The Toyota Mirai with a fuel consumption of 0,94 kgH_2/100km according to WLTC is used for the analogous representation of the total emissions during the use phase [96]. The results for operating with hydrogen produced out of different energy carriers are shown in ***Figure 28***. The calorific value used for the calculation is 119,972 MJ/kg [97]. It has to be mentioned, that FCEVs are considered as carbon free in the legislations because they do not emit any tailpipe emissions. Nevertheless, if the well-to-tank emissions arising through hydrogen production get compared to the legal limit for tank-to-wheel emissions for the same vehicle mass of 1850kg (the horizontal blue line indicates the European legislation and the horizontal red line the respective Chinese legislation), the FCEV would only in some cases fulfil the limit. By operating with hydrogen produced by electrolysis using the European electricity mix, the emission would be well above the limit. The same applies in China for hydrogen based on coal or natural gas. In Europe, the limit value could still be met with hydrogen produced from natural gas using SMR. By far the best solution in both Europe and China, however, would be to produce hydrogen from renewable energies, as this would massively reduce the emitted GHG emissions of the use-phase.

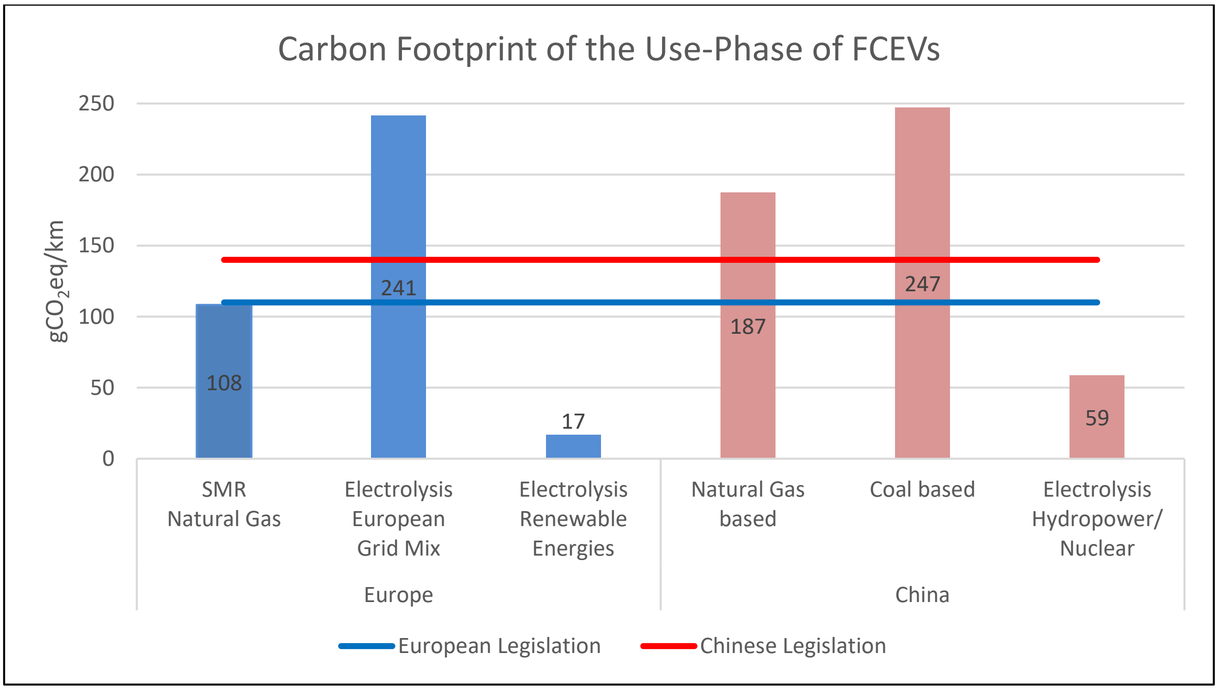

Figure 28 - Carbon Footprint of the Use-Phase of FCEVs (basis: WLTC)
Own figure - data calculated from previous results

4.4.5 End-of-Life

The recycling potentials for the glider, powertrain and battery are already shown by the previous concepts. In the FCEVs there are two more important components for recycling, the fuel cell and the hydrogen tank. Not least because both components account for a significant part of the total emissions in production. Basically, there are not a lot of studies on the recycling of fuel cells and especially of hydrogen tanks. Nevertheless, some results are shown here.

Stropnik et al., 2019 [98] examined the recycling of a 1 kW PEMFC. According to this study, the huge potential of recycling lies in platinum. Including the platinum recycling with a ratio of 76%, the manufacturing emissions can be reduced by 12,2% due to the reuse of the recycled materials. If platinum recycling is not considered, the potential shrinks to 0,4%. Since the result is based on a 1 kW fuel cell and those with an output of 80 to 130 kW are used in vehicles, this result is not representative for vehicle applications. Evangelisti et al., 2017 comes to the conclusion, that there is a potential of lowering the carbon footprint of FCEVs due to recycling by 1 tCO_2eq. According to the EC study the potential of reducing the carbon footprint due to recycling of the whole vehicle is 2,25 tCO_2eq. This potential lies in the same range as for BEVs and thus contributes a large part to reducing the overall GHG emissions. Nevertheless, an optimal recycling process is assumed there, which does not always correspond to reality. Bothe et al., 2020 analyzed five different studies regarding recycling of FCEVs. The results of the analyzed studies range from a saving potential of 3,4 tCO_2eq to an GWP increase of 1,7 tCO_2eq.

It can be concluded, as for all LCAs, the results vary according to the boundary conditions. However, there exist a significant potential for the recycling of FCEVs to reduce their carbon footprint. Especially when it is considered that this technology will be intensively developed in the coming years and can then be scaled up.

4.5 Life-Cycle Comparison of all Concepts

In the following, the life cycle of vehicles based on the different drive concepts in an LCA application are compared. The phases vehicle production, well-to-tank (WTT), tank-to-wheel (TTW), maintenance and end-of-life (EOL) are taken into account and represented in the unit gCO_2eq/km. The results shown are based on literature and own calculations; a separate LCA is not performed. For each LCA in literature, certain framework conditions must be established in order to arrive at a result. In most cases, this also includes a sensitivity analysis. In this thesis, framework conditions are also set for three different scenarios, and assumptions are made. A sensitivity analysis is not performed. Most of the used data refer to previous sources, however, some further calculations are carried out when necessary. In order to illustrate the results more clearly, the exactly used data for calculation and depiction are presented in tables, as non-variable parameters are shown in ***Table 10*** in the appendix.

Additionally, illustrated in ***Figure 29***, an overview of the carbon footprint of fuel production from different energy carriers is given. This depiction is used to compare the fuels of the different drive concepts regarding their GWP related to one MJ. Shown are conventional gasoline, diesel and hydrogen, as well as all e-fuels used in this thesis based on 100% renewable energy, whereby electricity based on the European grid mix 2020 is shown, too. From today's perspective, the production of electricity and hydrogen by conventional technologies causes much more GHG emissions than the production of conventional gasoline and diesel. However, they do not cause any additional CO_2 emissions in the TTW-phase, which allows them to almost match fossil fuels. Thus, the consumption of one MJ of electricity or hydrogen causes slightly more GHG emissions than the combustion of one MJ of gasoline or diesel if WTT & TTW are included. If the higher efficiency of drive concepts that do not run on fossil fuels is added to this, they are better overall than conventional drive technologies despite the higher carbon intensity of production. This advantage is further enhanced when all drive concepts are operated with e-fuels based on 100% renewable energies. Considering the saving of CO_2 from the atmosphere during the production of synthetic gasoline and diesel, the carbon footprint of these fuels is even negative in some cases, but the difference to electricity and hydrogen production is much smaller than with conventional technologies. If the additional emissions from combustion and the poorer efficiency of the ICE are added, the ICEV is clearly inferior to BEVs and FCEVs, as also shown below in the different scenarios.

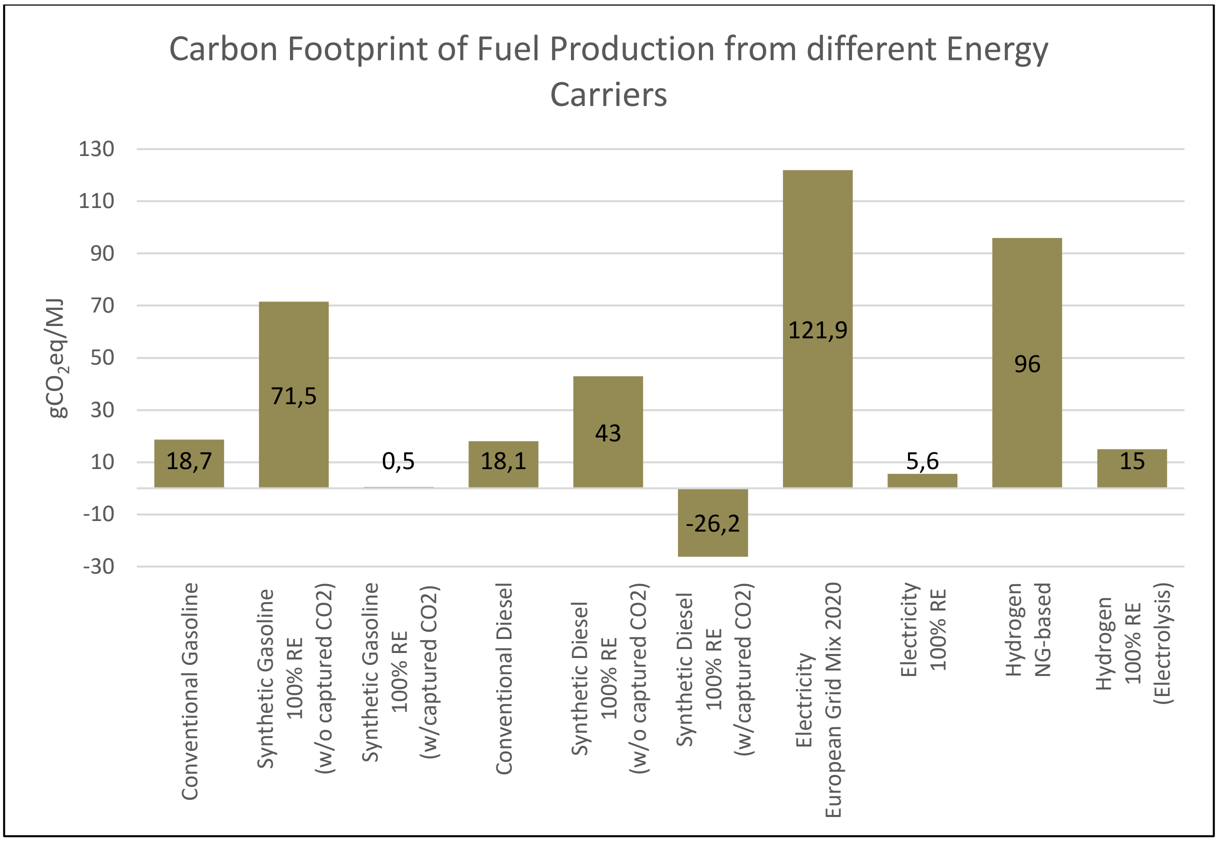

Figure 29 - Carbon Footprint of Fuel Production from different Energy Carriers
Own figure – data obtained from previous sources

4.5.1 Scenario 1 - Different Drive Concepts Operating with Most Common Fuels in 2020

The first scenario shows a comparison of the different drive concepts operating with the most common fuels / energy sources in 2020 for Europe in ***Figure 30*** and for China in ***Figure 31***. Due to the fact that practically no diesel passenger cars are sold in China, they are not included in the representation in ***Figure 31***. The general parameters for Scenario 1 are shown in ***Table 11*** and the specified vehicle parameters are shown in ***Table 12***, both attached in the appendix. One of the most important parameters for the depictions is the vehicle lifetime mileage, which is assumed to be 200.000 km for Scenario 1. The most common fossil fuels for the ICE are conventional gasoline and diesel, the electricity needed for the EM is based on the respective electricity mix of Europe and China for 2020 and the most common hydrogen is for both countries produced out of natural gas. Electricity production pathways will change enormously in the coming years as a result of legislation and the fight against climate change, but to better illustrate the situation for 2020, this improvement is not taken into account. Altogether, Scenario 1 forms the starting point for improvements of the presented concepts for future.

Looking at ***Figure 30***, the ICEV-G has the hugest carbon footprint, followed by the ICEV-D and the HEV-G in Europe. This is because the gasoline engine is less efficient than the diesel engine, but in the HEV-G, electrification can save that much gasoline that it consumes less fuel than the ICEV-D. The vehicle production impact is slightly higher for the HEV-G than for ICEVs because of the larger battery, but compared to the overall emissions, this influence is hardly evident. Theoretically, the production of a diesel car causes slightly more GHG emissions than that of a gasoline car due to the more complex exhaust aftertreatment, but in this illustration the emissions are assumed to be equal because the difference would hardly be visible in the diagram. The same applies for the recycling potential of those three concepts. A slightly lower carbon footprint than that of the HEV-G can be seen for the FCEV. But due to the high production impact of the vehicle and the commonly used SMR method for hydrogen production, the FCEV cannot be considered as a low-carbon drive concept today. When it comes to BEV and PHEV, things look different. Despite the current rather carbon-intensive electricity mix in Europe (439 gCO_2eq/kWh of produced energy [51]), the carbon footprint of these two drive concepts is almost half that of the ICEV-G. Since the significant improvement of the electricity mix over the next years has not been considered in the calculation and the result is just above the set condition for concepts to be low-carbon, BEVs and PHEVs can already be considered as a low-carbon drive concept in Europe. If the same representations were made for a country with a very good electricity mix, such as Sweden, the carbon footprint of those concepts would be even lower.

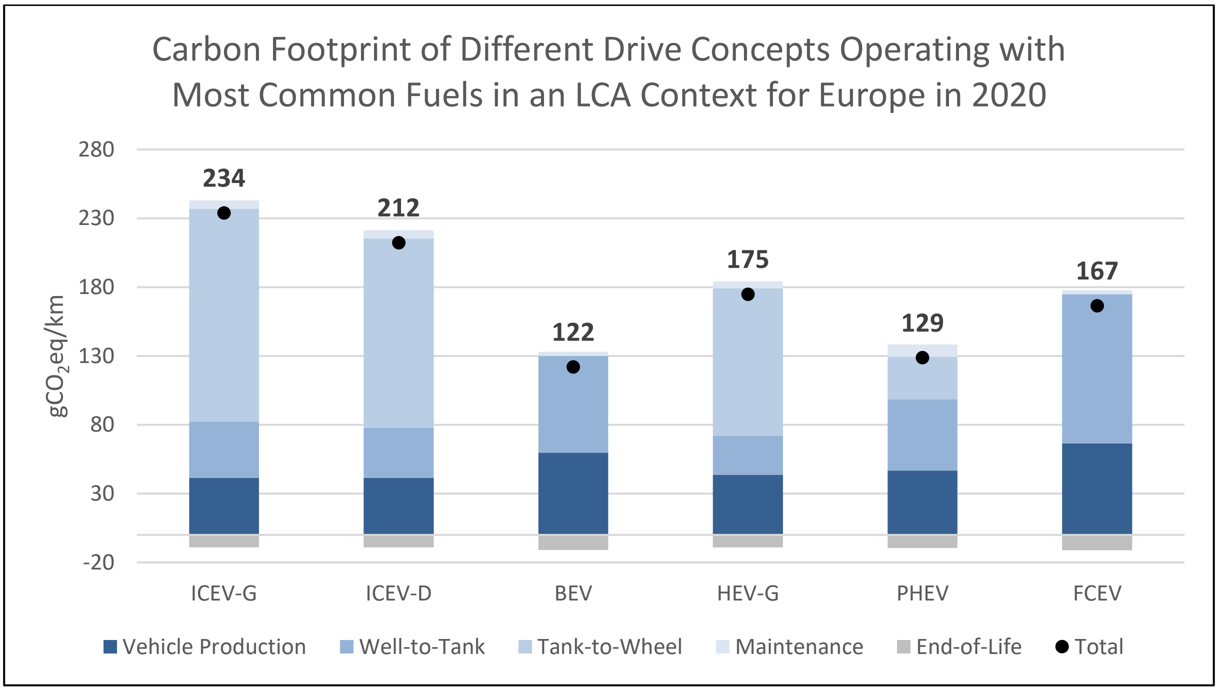

Figure 30 - Carbon Footprint of Different Drive Concepts Operating with Most Common Fuels in an LCA Context for Europe in 2020
Own figure - obtained data based on *Table 10*, *Table 11* and *Table 12*

By taking a look at ***Figure 31***, which illustrates Scenario 1 for China, the picture is different compared to Europe. While the starting point for improvements, the carbon footprint of the ICEV-G, is just slightly higher than in Europe, the FCEV represents the highest carbon footprint. On the one hand, this can be traced back to the carbon-intensive hydrogen production out of natural gas and on the other hand vehicle production has a huge impact, too. If coal-based hydrogen would be taken into account, the life cycle GHG emissions would increase decisively. In the same way, the influence of the carbon intensity of the electricity mix can clearly be seen. Thus, the carbon footprint of the BEV is only sightly lower than that of the ICEV-G. As a further reason, the vehicle production emissions of BEVs account for almost the same value as for FCEVs due to the heavy influence of battery production in China. The actual best drive concepts with the lowest climate impact are the HEV-G and the PHEV. Despite the higher emissions in vehicle production caused by battery production, the carbon footprint can be reduced. This can be seen as the reason why the sale of these vehicles has been so strongly subsidized in recent years. Finally, it can be deducted from the diagram that recycling has a comparatively small share compared to total emissions.

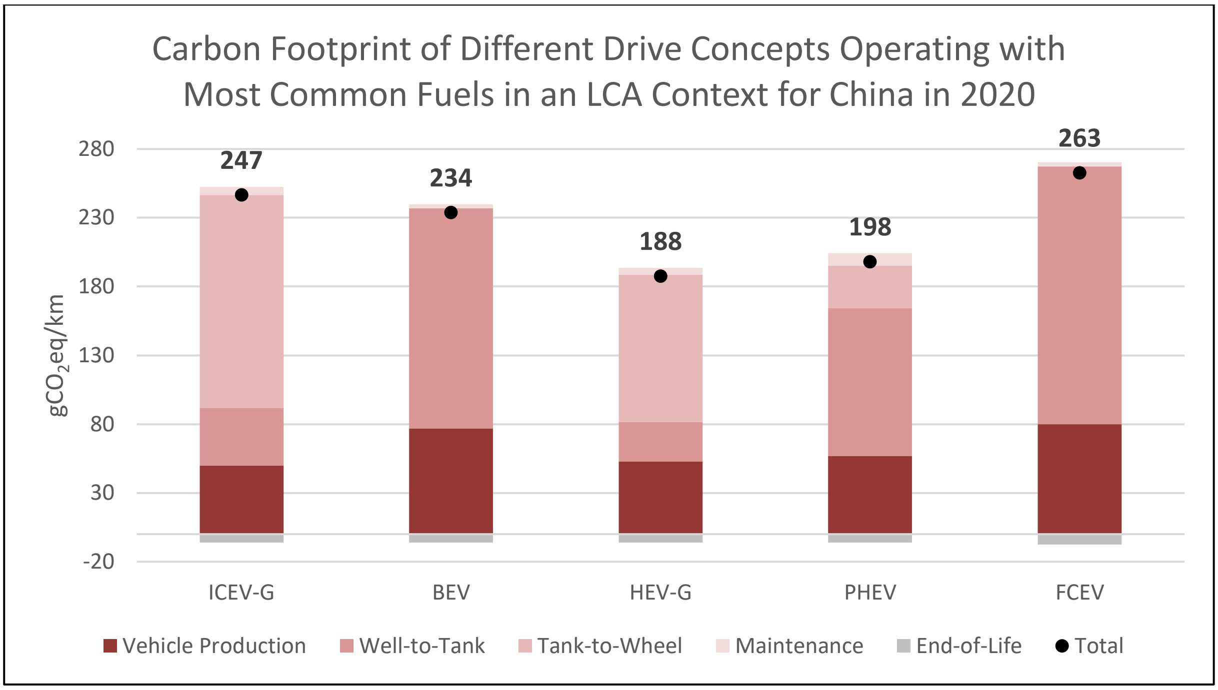

Figure 31 - Carbon Footprint of Different Drive Concepts Operating with Most Common Fuels in an LCA Context for China in 2020
Own figure - obtained data based on *Table 10*, *Table 11* and *Table 12*

In conclusion, in terms of the GWP in 2020, the BEV is already the best drive concept in Europe and the HEV is the best one in China. Even if battery recycling would increase greenhouse gases instead of reducing them, as some studies show for energy intensive recycling processes, the BEV would still perform best in Europe. In China, the potential for reducing the GWP of alternative propulsion technologies clearly lies in the energy transition.

4.5.2 Scenario 2 - Outlook to 2030

In Scenario 2, the same drive concepts as in Scenario 1 are represented including their potential for reducing their GWP. The vehicle lifetime mileage is assumed to be 225.000 km. Based on the previous results for fuel production, the fuels with the lowest carbon footprint are considered, except for bio-fuels, which has already been explained in ***4.2.4***. If the result of two types of production was conceivably close, both are shown. Same as for Scenario 1, the carbon intensity of electricity production is based on the predicted electricity mix by 2030 for Europe and China, an improvement over the vehicle lifetime is not considered. Much of the data used is again based on previous studies, while others are the author's own calculations. For conventional technologies, an efficiency improvement of 5% is assumed; for future-oriented technologies, an efficiency improvement of 10% is assumed. The exact details can be taken from the tables in the appendix. General parameters are shown in ***Table 13*** and specified vehicle parameters are shown in ***Table 14***.

Figure 32 represents an outlook of the development of the carbon footprint of different drive concepts for Europe to 2030. For vehicles with ICEs, conventional fuels are still best because the production of e-fuels requires a lot of energy, which is still too carbon intensive by 2030. However, as the European electricity mix already will reach a rather low level, the production of hydrogen by electrolysis becomes competitive and is therefore additionally shown in ***Figure 32***. In general, a reduction in carbon-intensity for each drive concept can be seen. While the improvements of concepts operating with fossil fuels are rather small, the other concepts show significant potentials for reducing their carbon footprint.

Nonetheless, the order of the concepts remains the same. As it can be seen from the illustration of the FCEV, despite the already rather low electricity mix, hydrogen production by electrolysis is still more carbon intensive than production from natural gas. The potential of BEVs in Europe is also clearly visible, where the carbon footprint is one-third lower than in 2020. In addition, the difference between the BEV and the PHEV will be greater than in 2020 due to expected developments. If the results are compared with the defined condition for a low-carbon drive concept, the FCEV can already be counted to them by 2030.

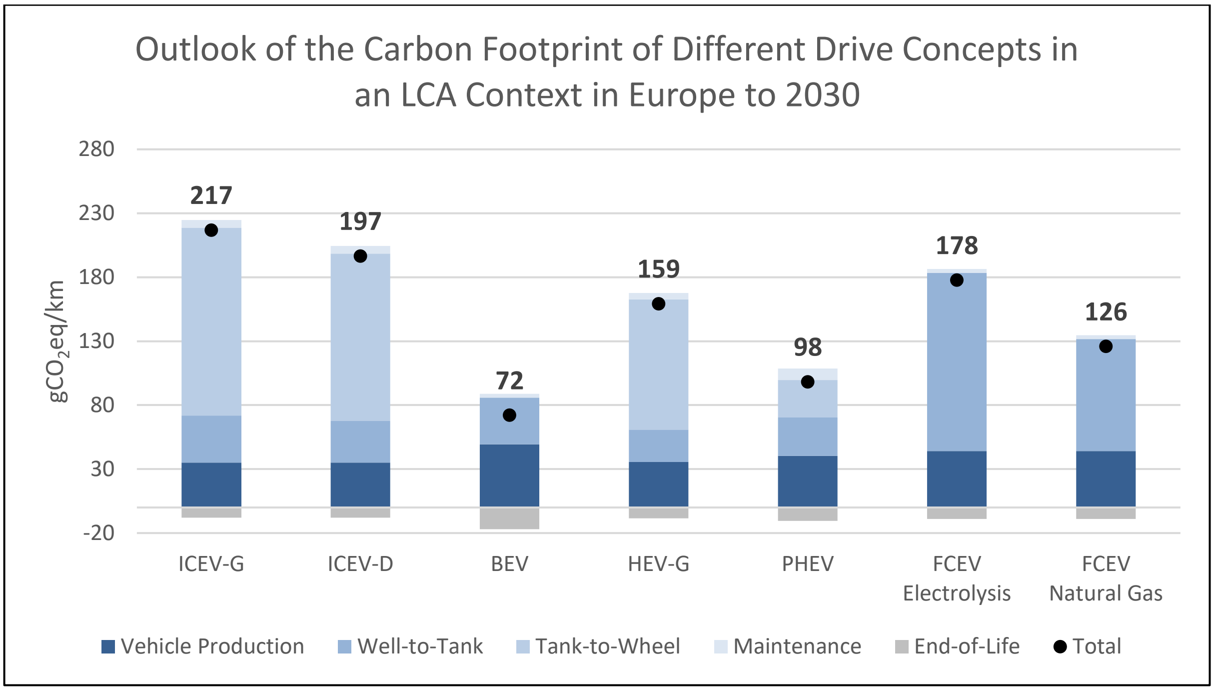

Figure 32 - Outlook of the Carbon Footprint of Different Drive Concepts in an LCA Context in Europe to 2030
Own figure - obtained data based on *Table 10*, *Table 13* and *Table 14*

The development of the carbon footprint of the different drive concepts in China is depicted in ***Figure 33***. Again, things remain different than in Europe. First, through a reduction in carbon intensity of vehicle and hydrogen production, the FCEV's carbon footprint will be lower than that of the ICEV-G, but still be higher than that of the other concepts. Unlike Europe, hydrogen production by means of electrolysis (by use of the average energy mix) would even not pay off by 2030. Second, in the race for the lowest climate impact, the BEV already comes very close to the two hybrids and shows the highest reduction potential, same as in Europe. Third, the PHEV outpaces the HEV-G and has the lowest carbon footprint in 2030. However, since the results are conceivably close, the order could be reversed again by minimally changing the initial parameters. Given these points, even considering realistic developments up to 2030, none of the drive concepts shown, can be seen as low carbon in China.

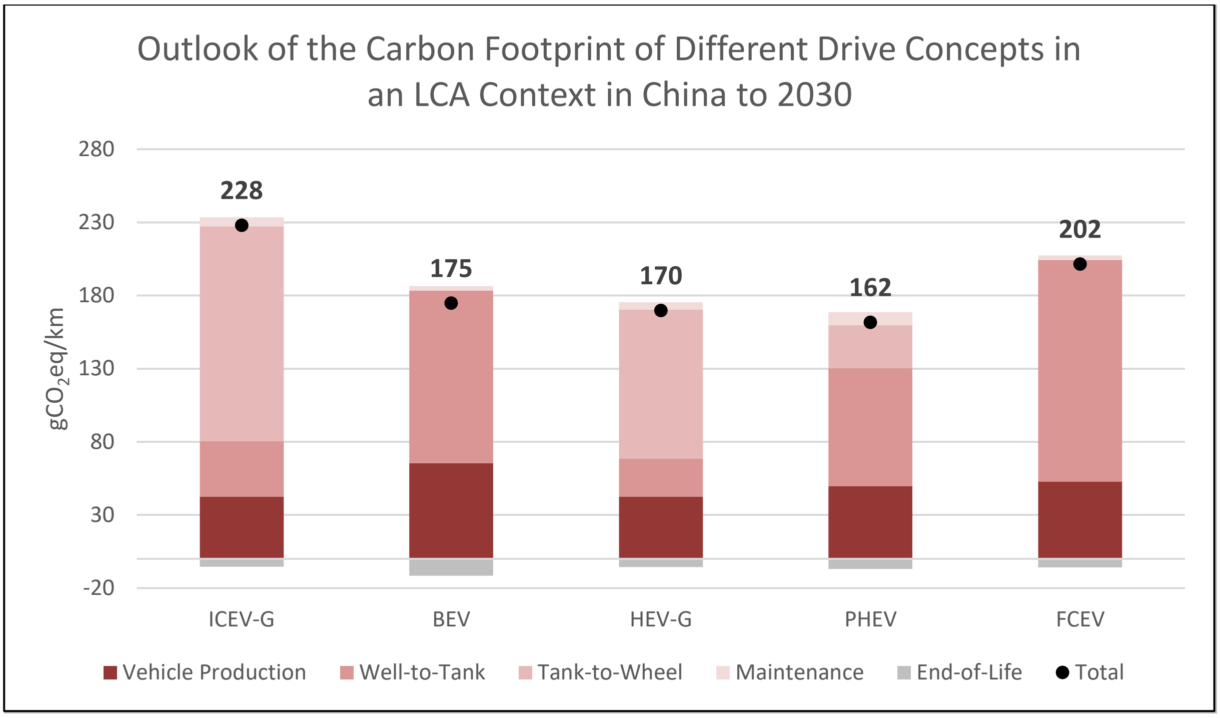

Figure 33 - Outlook of the Carbon Footprint of Different Drive Concepts in an LCA Context in China to 2030
Own figure - obtained data based on *Table 10*, *Table 13* and *Table 14*

In summary, the pioneering role of the BEV will be even more pronounced in Europe by 2030, and in China the BEV will become a strong competitor to the hybrid concepts. However, all results are purely related to the GWP and not to other influencing factors.

4.5.3 Scenario 3 - Best Case

Scenario 3 represents the best case for all drive-concepts considering reachable assumptions. The lifetime mileage is assumed to be 250.000 km. The data used for calculating the carbon footprint of vehicle production, maintenance and vehicle recycling is based on the EC study's approach for 2050. Conventional technologies are assumed to be improved by 10% and future technologies are assumed to be improved by 20% compared to 2020 level. The general parameters used for calculation are shown in ***Table 15*** and the specified vehicle parameters are shown in ***Table 16***. The fuels used for representing the use-phase are all based on production out of 100% renewable energy. It is important to note that the HEV and PHEV battery sizes are assumed to be twice as large as it is common today, and the BEV battery size is assumed to be 28% larger to 2020 level at 74 kWh. This, of course, has a direct impact on vehicle production emissions. However, an increase in battery size is quite realistic, especially if BEVs want to compete with ICEVs in terms of range in the future. Nonetheless, there are also other approaches, where the battery size will be lowered in future, because of charging infrastructure improvements and mobility behavior changes, but this is not considered in Scenario 3.

The carbon footprint of the different drive concepts based on Scenario 3 is shown in ***Figure 34***. It can clearly be seen that a switch to 100% renewables and operating with the resulting fuels have tremendous potential to reduce the carbon footprint of all drive concepts. Of course, reduced emissions through vehicle production and recycling methodologies play a big role too, but the greatest potential lies in the use-phase, especially for drive concepts operating with an ICE. The big difference between the ICEV-G and the ICEV-D lies in the process efficiency of production of the synthetic fuels. With the assumption of a 20% improvement of those processes, drive concepts using an ICE as the main propulsion technology are not able to compete with electric based drive concepts. Therefore, a lot of development in e-fuels must be done to make the ICEVs and HEVs competitive in future, regarding their GWP. In this best-case scenario, it is also evident that the FCEV represents a significant competitor to the BEV. Their carbon footprints are almost the same. Of course, it depends on several factors which of the two technologies will come out on top, but both have the potential to do so. The possibilities of implementing these technologies in the mobility sector are discussed in more detail in the next chapter.

Finally, if a comparison was made to the European legislation on fleet consumption target for vehicles operating with fossil fuels (95 gCO_2/km in 2021), it can be seen that in this best-case scenario most of the drive concepts would be clearly below the limit, even if the entire vehicle life cycle is considered. The frontrunner technologies are the BEV and the FCEV, with the PHEV also showing great potential for GWP reduction. However, should the BEV and FCEV meet all customer requirements, such as range and charging/fueling speed, hybrids such as the PHEV and HEV will become virtually redundant. The exact development of these propulsion concepts cannot be predicted, but trends indicate that future propulsion concepts will be electricity-based.

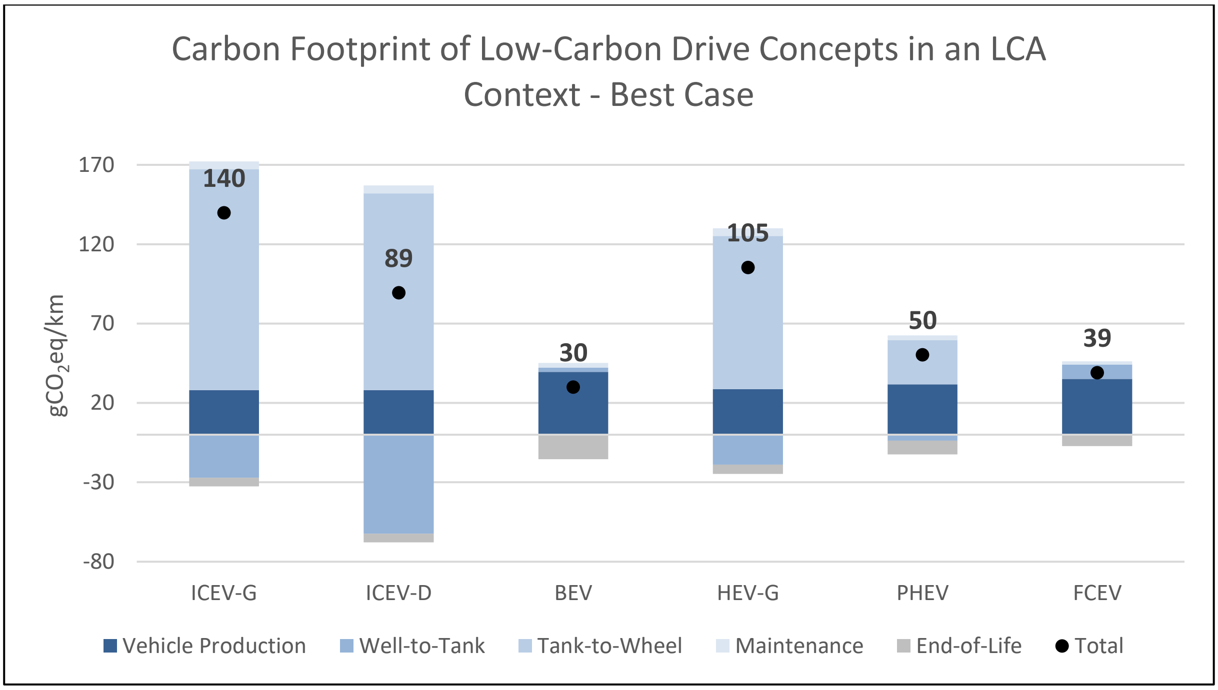

Figure 34 - Carbon Footprint of Low-Carbon Drive Concepts in an LCA Context - Best Case
Own figure - obtained data based on *Table 10*, *Table 15* and *Table 16*

4.5.4 Potentials of each Drive Concept

To better illustrate the potentials of each individual drive concept once again for Europe and China, Scenarios 1 to 3 are shown separately in a diagram for each concept. Scenario 1 represents the starting point; Scenario 2 represents the predicted development until 2030 and Scenario 3 represents the target to minimize the carbon footprint as best as possible. Basically, it can be said that none of the drive concepts will be carbon free, since too many influencing variables are involved in the life cycle for this to be feasible.

Figure 35 shows the potential for lowering the carbon footprint of BEVs in Europe and China. TTW emissions do not appear in the legend because BEVs do not emit CO_2 or any other climate gases during operation. As seen before, the BEV is already the most climate-friendly drive concept in Europe and in

China it has the potential to become so. The different starting points between Europe and China are very clear to see, as the biggest influencing factor for BEVs is the electricity mix. This is why the potential for minimizing the carbon footprint in China is many times greater than in Europe, since China's electricity mix is currently heavily influenced by coal energy. Nevertheless, the carbon footprint could also be reduced to one quarter in Europe if the electricity were produced from 100% renewable energies. A further aspect is vehicle production, as it accounts for a large proportion of total emissions and should therefore also be the focus for improvements. Especially in the best-case scenario, the production of vehicles is almost exclusively responsible for their carbon footprint. However, since the mining of raw materials is usually associated with high carbon emissions, recycling should be a clear focus, or the useful life should be extended. Therefore, the European Commission proposed a new batteries regulation in December 2020 [99]. It is also interesting to note that the reduction in GHG emissions through recycling does not increase significantly in absolute terms. Although an improvement in the recycling processes was considered, this is based on the total weight of the battery. Since an increase in energy density was also considered, the batteries will be lighter in the future for the same capacity and thus offer less potential for reducing emissions through recycling. Anyhow, mining of raw materials, refining and pre-fabrication is currently very carbon intensive, and besides has several negative aspects from an LCA perspective (e.g. toxicity, water) and economic perspective (e.g. rare earth materials).

In conclusion, the BEV is the most promising low-carbon concept for future. Nonetheless, the necessary framework conditions must be created, and above all, electricity generation must be switched to renewable energies.

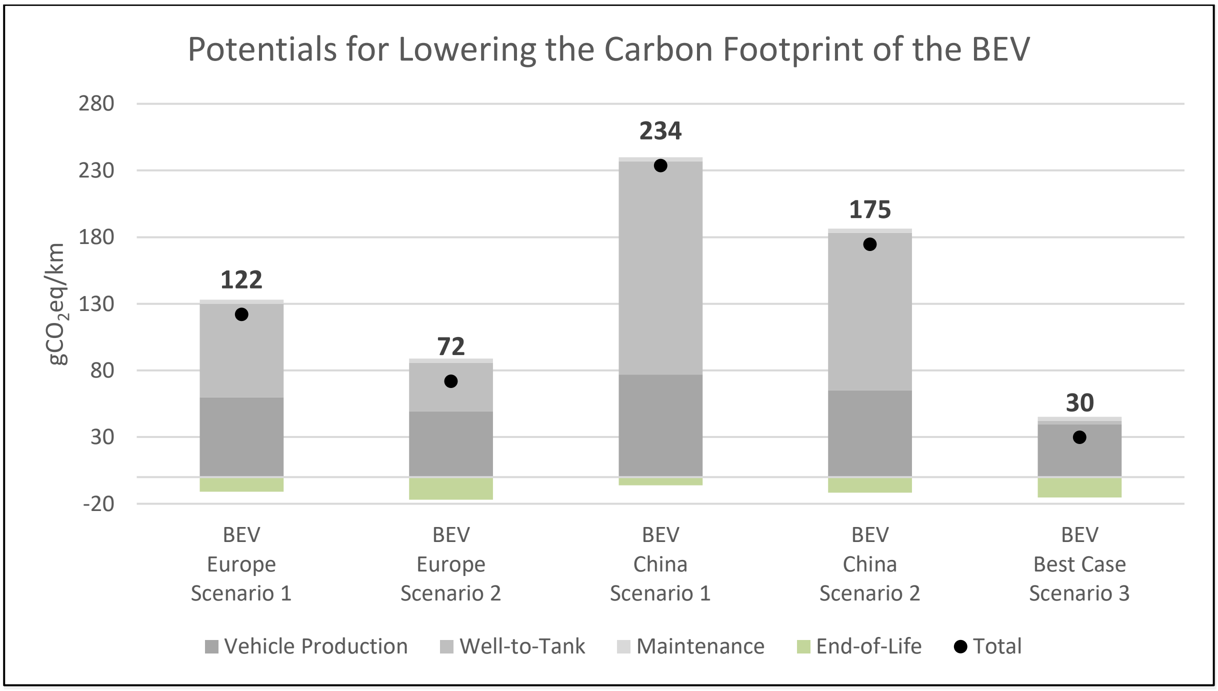

Figure 35 - Potentials for Lowering the Carbon Footprint of the BEV
Own figure - obtained data based on previous results

The ICEVs, which were proven over many decades, have been increasingly discredited for some time due to their climate footprint. The big problem are the CO_2 emissions that are produced when gasoline or diesel is burned. In the debate about how good or bad vehicles with ICEs are, however, the emissions generated during the production of the fossil fuels are often forgotten. Therefore, the carbon footprint of the whole life cycle of a mid-sized vehicle powered by a gasoline engine for Scenario 1 to 3 is shown in ***Figure 36***. The slightly higher carbon footprint for vehicles produced in China remains from vehicle production due to the carbon-intensive Chinese industry. In the use-phase (WTT & TTW), there are only minimal differences. But to mention, there is no LCA study existing, representing the real fuel pathway from exploration, extraction, production and distribution to the final destination. Nevertheless, the carbon footprint for these vehicles is rather high in both Europe and China. Most of the total emissions result from the use-phase. With little improvement in sight for conventional fuels, especially when it is considered that crude oil is becoming increasingly scarce and countries like the USA are beginning to extract oil using extremely environmentally damaging methods like fracking [100], fuel will have to be produced from other resources in future to be considered as a low-carbon drive concept. The different approaches for the production of fossil fuels from alternative energy sources have already been discussed in ***4.2.4***. Since biofuels are not discussed further for reasons already mentioned, the potential lies with synthetic fuels. The low efficiency and therefore resulting high electricity consumption for the production of e-fuels means that their use will not yet be climate-friendly by 2030. Only if the synthetic fuel was produced from 100% renewable energies, as shown in the best-case scenario, a noticeable improvement can be achieved. Vehicle production also shows potential for reducing GHG emissions, but not to the same extent as for the use phase.

However, BEVs in Europe are already more climate-friendly than a gasoline vehicle in the best-case scenario. Therefore, from today's perspective, the ICEV-G cannot be considered a candidate for a low-carbon drive concept. But there are other areas where synthetic fuels make perfect sense. For example, in applications where a battery is not sufficient to store energy for the driving distance that has to be covered, such as aircraft, ships or big trucks. But, if research succeeds in significantly increasing the process efficiency of e-fuels, they could also become interesting for passenger cars.

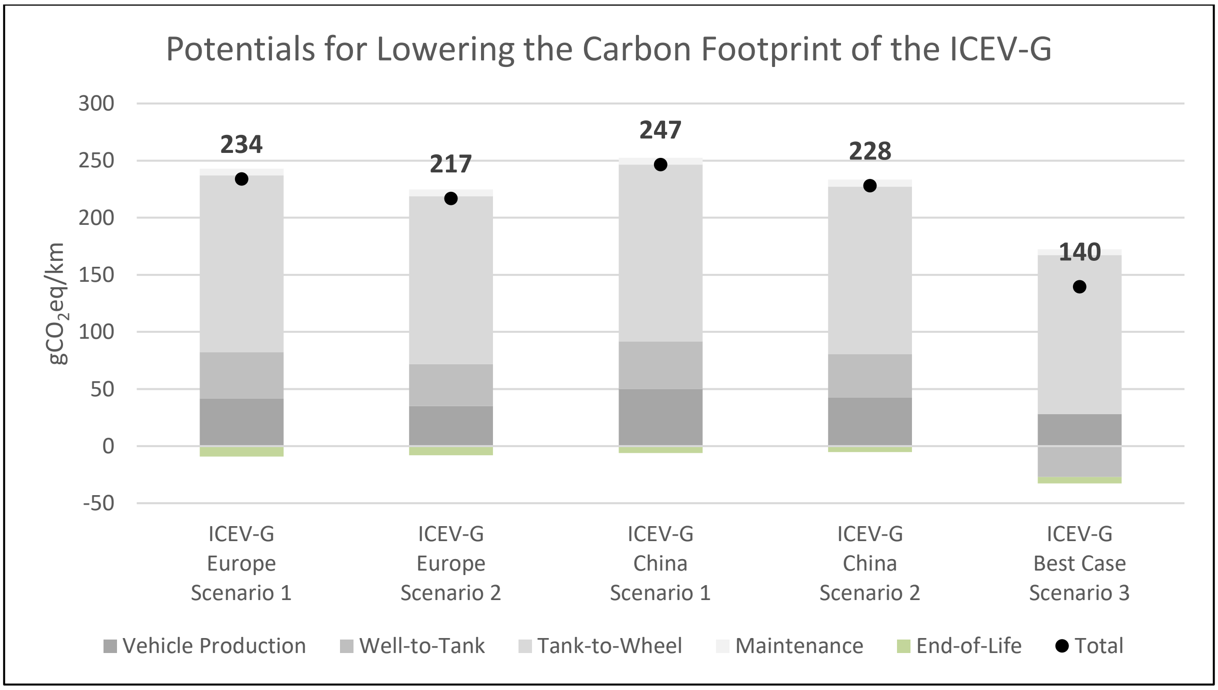

Figure 36 - Potentials for Lowering the Carbon Footprint of the ICEV-G
Own figure - obtained data based on previous results

The next depiction, ***Figure 37***, shows the carbon footprint of a mid-sized diesel vehicle for Europe from Scenario 1 to 3. China is not considered in this depiction, as there are practically no diesel passenger cars sold. The ICEV-D has a slightly lower starting point than the ICEV-G, the potential for improvement until 2030 on the other hand, is the same. However, the best-case scenario shows a significantly lower carbon footprint than for the ICEV-G. This is due to the efficiency of the production process of the e-fuel, as already mentioned. Therefore, based on the conditions set at the beginning of Chapter 4, the ICEV-D can be considered as a low-carbon drive concept in the best-case scenario, although it has a respectively higher carbon footprint than electricity-based drive concepts.

In summary, it can also be concluded for the ICEV-D, that it is inferior to other low-carbon drive concepts in terms of GWP. But the potential is there for the same applications as mentioned for the ICEV-G. With an improvement in the efficiency of the production process of synthetic diesel it could become competitive for passenger cars, too.

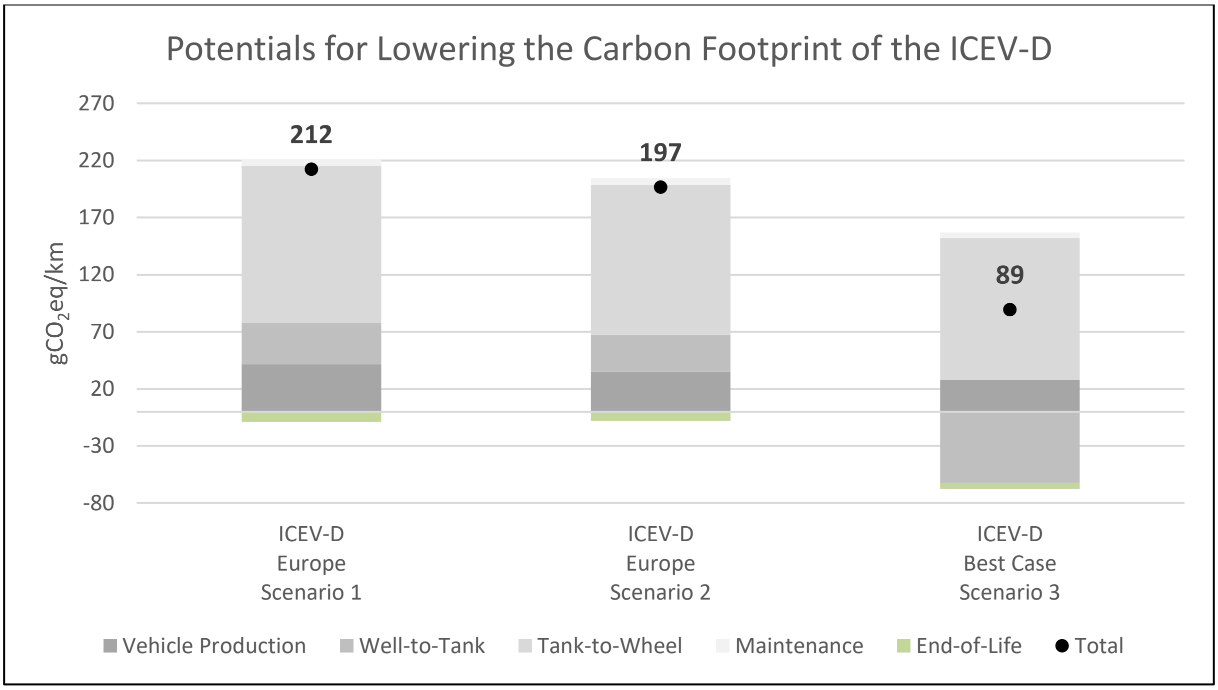

Figure 37 - Potentials for Lowering the Carbon Footprint of the ICEV-D
Own figure - obtained data based on previous results

The next drive concept shown is the HEV, whose carbon footprint for Scenario 1 to 3 is illustrated in ***Figure 38***. Because the battery of HEVs cannot be recharged at a recharging station, and therefore only their fuel consumption of gasoline or diesel is reduced by hybridization, they are very much aligned with ICEVs in terms of GWP. Thus, the picture is the same as for ICEVs, where a reduction of the carbon footprint by 2030 will be rather small but it can be optimized significantly in the best-case scenario. But even in the best-case scenario, the efficiency of e-fuel production would again have to be increased considerably to become competitive. The results shown in ***Figure 38*** are based on operating with gasoline. The same depiction for diesel engines would be less carbon intensive, especially in the best-case scenario, as already shown for ICEVs.

However, the HEV offers a good short-term solution to reduce fuel consumption. Thus, it will remain interesting as a drive concept in the coming years, but will be of little interest for future low-carbon drive concepts, especially if BEVs are developed to such an extent that they can compete with ICEVs in terms of costs, charging time and range. Then hybrids will become redundant, since they have both technologies installed.

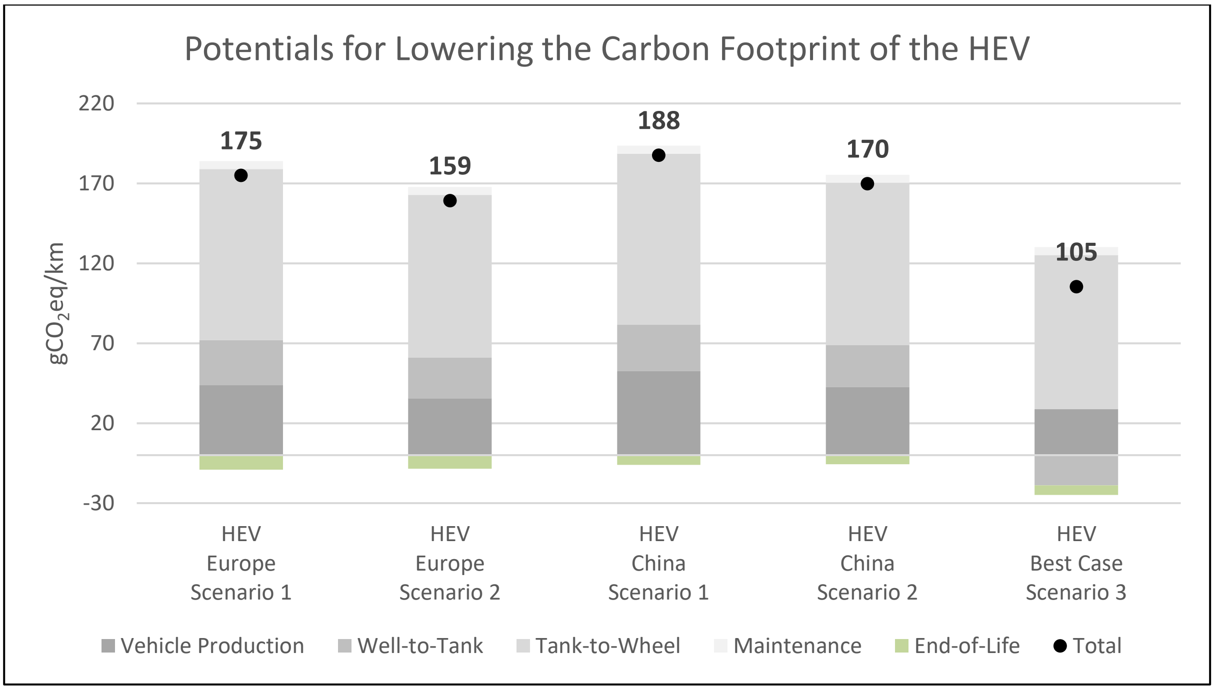

Figure 38 - Potentials for Lowering the Carbon Footprint of the HEV
Own figure - obtained data based on previous results

The PHEV represents a very interesting concept, as one can both recharge the battery from the grid and refuel the fuel tank. It is already very close to BEVs since the consumption of fossil fuel is very low. Nevertheless, the fossil fuel consumption heavily depends on the boundary conditions. The procedure to figure out fossil fuel consumption and electricity consumption through the WLTC was already mentioned in ***4.3.3***. The carbon footprint of the PHEV for Scenario 1 to 3 is shown in ***Figure 39***.

Comparing the results of Scenario 1 of the PHEV with those of the BEV for Europe and China, it can be seen that the PHEV has a higher carbon footprint than the BEV in Europe and a lower carbon footprint than the BEV in China. Thus, it depends once again on the electricity mix whether the PHEV can maintain or lose its advantage against the BEV of lower emissions through production. The reason for the lower production emissions is the smaller battery size. In China, the PHEV even represents the concept with the lowest carbon footprint for 2030. However, if the electricity mix continues to improve, it will be overtaken by the BEV in terms of climate friendliness. In Europe, the BEV is currently already better, but if a longer range is needed, the PHEV offers a very good solution. In the best-case scenario, the PHEV falls to third place, but with a carbon footprint of 50 gCO_2eq/km, it is a low-carbon drive concept in any case. The only question is whether it can survive on the market if the BEV meets all customer requirements in the future. It is not yet possible to predict today whether BEV development will achieve this or not.

Finally, the PHEV represents a perfect short-term solution for reducing the carbon footprint of vehicle fleets in both Europe and China. While in China it is even the variant with the lowest carbon footprint, it depends on the customer's requirements and usage behavior whether a PHEV or BEV is more suitable.

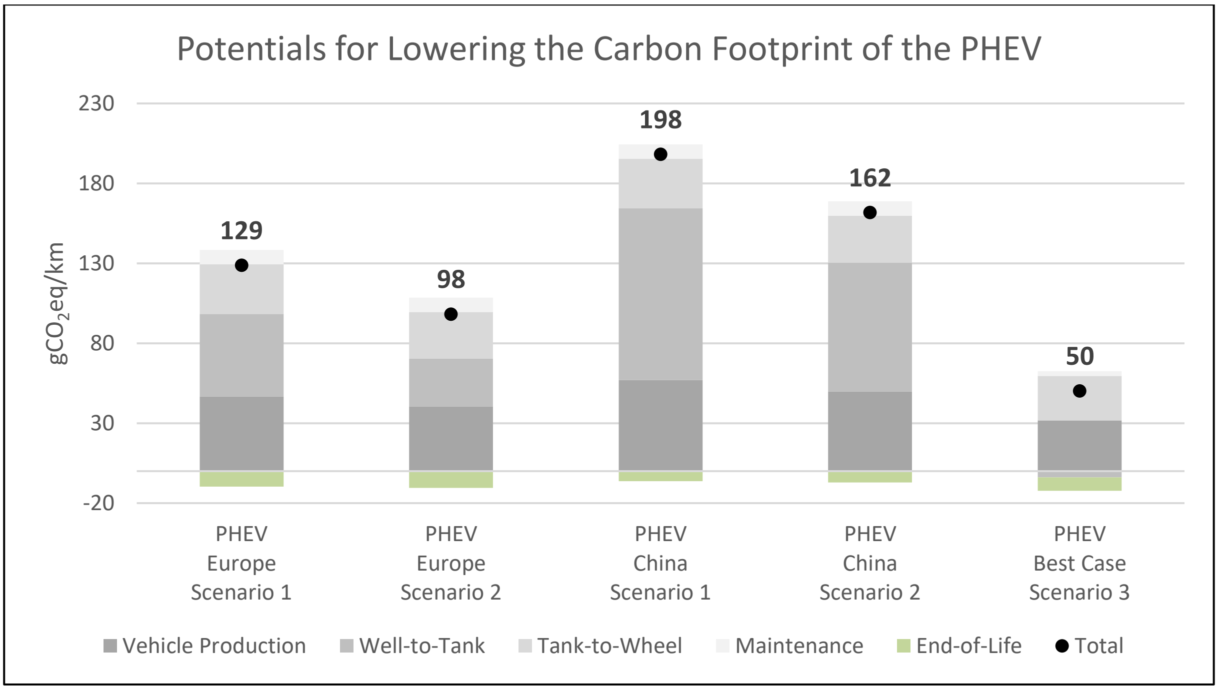

Figure 39 - Potentials for Lowering the Carbon Footprint of the PHEV
Own figure - obtained data based on previous results

The last depiction, ***Figure 40***, shows the carbon footprint of the FCEV for Scenario 1 to 3. Since no CO_2 emissions are emitted during operation, the TTW phase is non-existent. In principle, the FCEV is an excellent idea for a low-carbon drive concept. In reality, this technology still has some disadvantages, which will have to be remedied by developments in the coming years.

This starts with a very high carbon footprint due to vehicle production. The big difference to other concepts is the fuel cell system and the carbon-fiber hydrogen storage tank. To produce them, a lot of energy is required, which has a strong impact on GHG emissions, especially in China. Through improvements of these processes, the carbon footprint could be reduced in the coming years. In the best-case scenario, the production footprint is not significantly higher than with other concepts.

The second issue is hydrogen production. Today, most hydrogen is produced from natural gas, which results in high GHG emissions. It is certainly possible to produce hydrogen by means of electrolysis, but the amount of electricity required for this is that high, that with the current electricity mix it would result in a very high carbon footprint in both Europe and, above all, China. This leaves only two options: improve the efficiency of the process and/or change the electricity mix used for the electrolysis process to 100% renewable energy. This can be clearly seen in the best-case scenario, where the carbon footprint of the FCEV is reduced to 39 gCO_2eq/km, which is almost at the same level as the BEV.

The third point that does not appear directly in the graph is the low energy density of hydrogen. This makes transporting the fuel conceivably difficult, since 6.8 times as much energy can be transported in a tank of the same size in the form of liquid gasoline than in the form of gaseous hydrogen [86]. For this reason, developments in the production of sustainable hydrogen are moving toward producing the fuel directly at the filling station from renewable energy sources, thus eliminating the need for transport [94].

All in all, it can be concluded that the FCEV can be a strong competitor to the BEV in view of future developments. Until then, however, a lot of development steps are still necessary, which will be described in more detail in the next chapter.

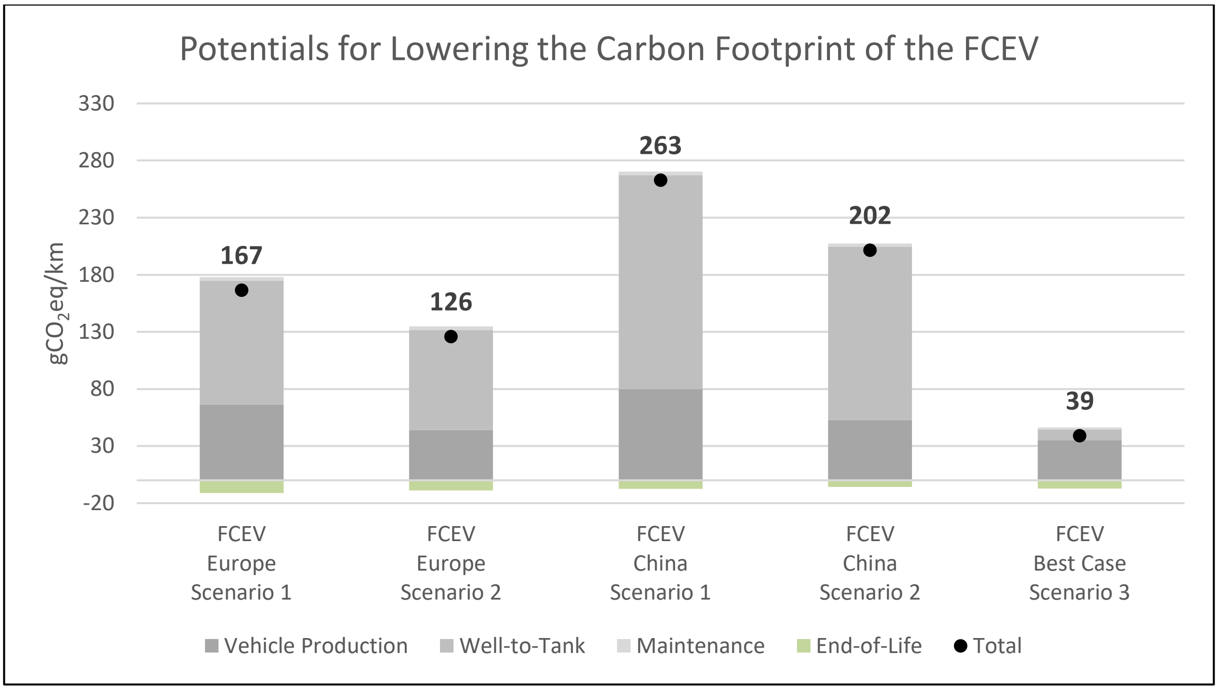

Figure 40 - Potentials for Lowering the Carbon Footprint of the FCEV
Own figure - obtained data based on previous results

5 Possibilities and Necessary Changes to Achieve a High Global Warming Potential Reduction

There are various approaches for reducing the carbon footprint of the mobility sector in the future. The potentials of different drive concepts are described in Chapter 4. In order to successfully bring these drive concepts to market, some changes are necessary. This chapter shows the most important changes and compares them with the previous scenarios and legislations. Furthermore, other possibilities for achieving a high GWP reduction are also discussed.

5.1 100% Renewable Energy

The analysis of the individual phases of a vehicle's life cycle showed that electricity is the most frequently required energy for low-carbon drive concepts. This starts with the production of the vehicles, is extremely important for sustainable fuels, has therefore a significant influence on the use-phase, where there is the greatest potential for reducing the carbon footprint, and continues through to recycling. Therefore, the most important change with the greatest potential to reduce the GWP is to produce electricity from 100% renewable energy sources.

The 100% renewable energy always sounds very good, especially in the media, but caution is advised when it comes to this topic. As already shown in ***4.1.3***, renewable energies are not carbon free either. A life cycle assessment is required to determine how much GHG emissions are emitted from the production of electricity. Since this again allows a great deal of leeway for delimiting the framework conditions, it is difficult to arrive at an exact value. This can also be seen immediately by comparing several studies with each other. It would therefore be important that all major influences are really taken into account when carrying out the LCA. An example of this would be that wind energy comes out on top in most studies in terms of GWP. But in reality, there is a huge problem, for example in Germany, where the amount of wind turbines that have reached their end of life is too high to recycle all of them in time [101]. This in turn poses risks to people and the environment. Another option for generating electricity with a low carbon footprint is nuclear energy, which is, however, disregarded due to its risks and the nuclear waste it produces.

Renewable energies are much more climate-friendly than conventional fossil energies and the changeover must be driven forward. The possibility to accelerate this lies with the legislators of the individual countries or the associations of countries. The EU's goal for 2030 for example is a renewable energy share of 32% and China wants to reach a 20% share of non-fossil fuels in primary energy consumption. However, the results from Scenario 2 in ***4.5.2*** show that this is still far from sufficient to significantly reduce the GWP. For Europe, BEVs would still have the lowest carbon footprint, but for ICEVs and FCEVs the carbon footprint would increase if e-fuels were considered. In China, the BEV would outpace the ICEV, but would still have to compete with hybrids.

Further legislations are not yet known, but it can be assumed on the part of the EU that by 2050 electricity from renewable energies must have a clear upper hand in order to achieve the goal of a climate-neutral union. China is expected to take a bit longer to get there, as they are starting from a completely different starting point. But they are well on their way to making power generation more sustainable. This is also demonstrated e.g. by recently installed giga farms with photovoltaic panels, which are driving the expansion of renewable energies [102, 103]. Nevertheless, China has a long way to go, especially to shut down the extremely harmful coal-fired power plants.

5.2 Process and Technology Developments

A further aspect for decreasing the carbon footprint of vehicles is the development of the processes involved during a vehicle lifetime. Through research and development, the existing processes can become more efficient and new ones can be investigated. This applies above all to any production processes such as vehicle, battery, and fuel production, but also to recycling, fuel consumption and charging time. In ***4.5.4***, it can be clearly seen that in addition to the use-phase, the entire vehicle production also represents a large optimization potential. In the case of the BEV, for example, the carbon footprint of production can be significantly reduced in the best-case scenario despite an increase in battery size. Such a result can only be achieved by successfully developing the battery system and increasing the efficiency of the production processes.

The main contributor to GHG emissions for all production processes is energy consumption. No matter what energy source is used, they all contribute their share to the emission of climate gases, although there are differences in the amount. Because there is not much optimization potential for fossil energy sources, future developments should be based on the use of electricity, since this can theoretically be produced from renewable sources, as shown before. Therein also lies a great optimization potential.

This development is also reflected in legislation. In its Green Deal, the EU states that by 2030 the energy efficiency must be improved by at least 32.5%. The roadmap to a circular economy by 2050 also includes key actions aimed at future developments. Some examples are "Clean, affordable and secure energy", "EU industrial strategy", "Initiatives to stimulate lead markets for climate neutral and circular products in energy intensive industrial sectors" and "Proposal to support zero carbon steel-making processes by 2030" [104]. Thus, the EU is working on comprehensive plans to achieve a maximum reduction of greenhouse gases by 2050. With the aim of increasing the share of clean energy consumption, so that non-fossil fuels and natural gas become the main energy sources, China also wants to reduce the carbon intensity of its industry. In doing so, they want to move away from coal energy in particular. But since this step cannot be made quickly and is not easy to implement, they also pursue the goal of improving fossil-fuel efficiency. In addition, China wants to use big data and Artificial Intelligence (AI) for increasing the energy efficiency. In this case it seems that China has exceeded the EU in view of digitalization.

Equally important to the production processes, the technologies must of course also evolve. According to Thielmann et al., 2015 [105], the lithium-ion battery is currently being transferred to large-format batteries with intensive further development from the material to the system and is expected to be fully developed to maturity in the next 15 to 25 years. This is likely to increase energy density and reduce costs in particular, enabling a BEV to compete with today's ICEVs in terms of range by 2030. Fuel cell technology with hydrogen as the energy storage medium must also be viewed against this time horizon and will therefore develop from today's complementary technology into a clear competitor technology. Whether hydrogen-powered electromobility with fuel cell electric vehicles is not only technically but also economically feasible will have to be examined in detail in the future, based on regional conditions and in the context of the respective mobility concepts. Additionally, the comparatively poor efficiency of converting electricity to hydrogen must also be taken into account as an obstacle.

The role of fuel production is clearly seen in ***4.5.4***, when Scenario 1 to 3 get compared. In all cases, fuel production using electricity only makes sense if the electricity is produced from renewable sources. But even under these circumstances, these fuels have a clearly visible carbon footprint. This is due to the efficiency of the production processes, which must be noticeably increased to compete with BEVs in the future. Therefore, in Scenario 2, conventional processes are assumed to have an efficiency increase of 5% and electricity-based processes are assumed to have an efficiency increase of 10% until 2030. Regarding Scenario 3, these values are doubled again. It can be concluded, that increasing the efficiency of e-fuel production is a key criterion for ensuring that technologies using these fuels can survive in the future.

Recycling, and especially battery recycling is another key factor in terms of sustainable development of low-carbon drive concepts. Whether and how recycling takes place depends largely on the legislators. For example, the EU has issued a new proposal for battery recycling that requires OEMs to collect all batteries for recycling in the future [99]. However, this does not mean that the entire battery is recycled, but only certain parts of it. Recycling must provide an energy advantage on the one hand and be economical on the other hand. With today's processes, only nickel and cobalt can be economically recovered from active materials, while lithium remains (still) in the slag. Reuse of the active materials by washing currently fails due to the lack of economic viability, but in principle certain cathode materials and spherical graphite’s can be recovered and recycled. Today, battery design for recycling is already being considered at the system level in production and adapted accordingly. An integrative approach to battery design for recycling at cell level could be addressed in the medium term [105].

5.3 Infrastructure

Another key factor for the implementation of New Energy Vehicles (NEVs), like the BEV and the FCEV is the infrastructure needed for operation. This mainly refers to charging the battery or refueling the hydrogen tank, but vehicle maintenance should not be overlooked. Only with a holistically functioning infrastructure do NEVs have a chance to prevail over conventional technologies, unless legislators possibly ban conventional technologies anyway, as some countries are already planning. Further details to this are given in the next sub-chapter “Legislations”.

BEVs require a charging station to charge the battery. There are many different designs, which are intended for slow or fast charging. A pioneer for fast charging is Tesla, which enables to charge as much electricity as is needed for a 120 km range in five minutes with its Supercharger 3.0 [106]. For now, this technology is only available for the Model 3 after a software update, but it will also be available for the Model S and Model X in the future, also after a software update. With this, Tesla sets another milestone in terms of fast charging, since 120 km range is absolutely sufficient for the majority of all car trips, provided that there is also the possibility to charge the vehicle again at the destination. For example, in Austria the average driving distance of a passenger car each day was 34 km in 2016 [107]. Nevertheless, electric vehicles can be fully charged using fast chargers in up to 30 minutes, depending on the vehicle and charging station, using direct current. With AC charging stations, the charging process takes several hours, which can be used for charging the battery over night or during work [108]. This leaves only long distances, where the electric vehicle has a significant disadvantage compared to conventional vehicles. Since most vehicles already have a range of at least 200 - 400 km and it is advisable to take a break of at least 30 minutes for such a distance anyway, this hurdle can also be overcome without further ado.

However, there remains the question of the availability of charging stations, as there are currently far too few charging stations to cover all passenger car traffic. This means, that if everyone would drive an electric vehicle today, there would be practically no free charging stations. Thus, in the course of increasing sales of electric vehicles, the infrastructure must also be adapted, and the number of charging stations markedly increased. Therein lies a major problem, since fast chargers require an enormous amount of electricity, and this is not easily manageable in one place, because it puts a heavy load on the power grid and the cables that provide the energy would have to be very thick. Now, there is also the possibility to charge the vehicle at home via a normal household socket. This is a good solution for single-family homes, but if one looks at this concept for cities, it is a big challenge. This would require to equip every public parking lot and every underground parking lot with a charging station, which is an almost unthinkable task in terms of cost and logistics [109].

Regarding the FCEV, today, there do not exist a lot of fuel stations. Germany, for example, has the most hydrogen refueling stations in Europe, with 89 [110]. So, there is still a massive need for action on the part of the EU to create the infrastructure for FCEVs. In the hydrogen roadmap by “Fuel Cells and Hydrogen” (FCH) [111] there are two scenarios for implementing FCEVs as small cars. In the ambitious scenario that could happen until 2030 and in the business as usual scenario that will happen after 2045. As it can be seen, there is a long way to go. China, on the other hand, already has concrete plans for the implementation of hydrogen vehicles [112]. Currently, this still largely concerns buses and trucks, but by 2030 commercial use of passenger cars with fuel cell drive should be possible. The plans for 2020 were to have more than 100 hydrogen fuel stations installed und by 2030 this number should rise to more than 1000.

Another obstacle are the paying methods for the charged electricity and the refueled hydrogen. While the conventional fuels can be paid with cash or ATM/credit card at any gas station, an own card or app is needed to activate a charging station for BEVs. That would not be a big problem if it is possible to charge at any charging station with one card or one app, but in reality, a separate card for almost every charging station provider is needed. A 2017 analysis of charging stations in Austria, which is a very small country by international standards, found that there are 11 different cards, keys or apps for charging stations across the country [113]. For such a small country, that's an enormous number of providers with their own payment systems, and that makes it difficult for electric vehicle users to access charging stations. The solution for Europe must be a uniform EU-wide payment system. Therefore, the German transport minister, Andreas Scheuer, said: “We want a Europe-wide standardized payment system for electricity charging and hydrogen refueling” [114]. The same also applies to China, although implementation in China will be easier than in Europe due to its more centralized approach and a better developed digitalization in this field.

5.4 Legislations

Another way to integrate new technologies into the market is through legislation. This can be used to force OEMs, so to speak, to push the development and sales of low-carbon technologies. There are various approaches for pursuing a customer to buy a vehicle. The main drivers are cost, performance, design, and quality, with cost often outweighing most other features of the vehicle. The conventional drive concepts are so well established that the majority of people do not voluntarily agree to a change in technology unless they would derive advantages from it, such as lower costs. Of course, there are also people who would switch to these technologies at their own accord or have already switched, but this is a minority. Therefore, a switch to low-carbon drive concepts is only possible through legislation, because NEVs are still rather expensive. This is precisely why legislators are called upon to interpret the laws in such a way, that OEMs must make a technology change and further develop low-carbon drive concepts that they also become lucrative for customers in terms of costs and convenience.

The sale of new vehicles is regulated worldwide by the various emissions legislations. These regulate pollutant emissions during operation on the one hand and CO_2 emissions during operation on the other. A distinction must be made between pollutant emissions, which always refer to the individual vehicle, and CO_2 emissions, which refer to the entire vehicle fleet. Thus, it is possible for a manufacturer to sell sports cars with high CO_2 emissions without penalty payments if another part of its fleet is below the legally prescribed CO_2 value. Europe and China are taking similar approaches to emissions legislation in this regard, as already shown in ***3.2***. Both have committed to WLTC as the valid test cycle and have implemented real driving emissions in their legislations. This is, because China uses the European emissions legislation as a reference for determining their emissions legislation. Finally, the lowering of limits in emissions legislation is forcing OEMs to develop and deploy new technologies [3].

There are two approaches to develop ICEs, one is to reduce pollutant emissions and the other is to reduce fuel consumption and thus CO_2 emissions. Both approaches are extremely useful in their own way in different areas. The regulation of pollutant emissions is enormously important, especially in cities, which often suffer from poor air quality, as illustrated by the major cities of China. But also small cities like Graz in Austria, have to deal with fine dust problems and bad air quality. Globally, the reduction of greenhouse gases in relation to climate change is the most important goal for the future. Therefore, there is unlikely a way around drastically reducing or even better avoiding greenhouse gases caused by mobility. OEMs are therefore facing two challenges for the continued sale of vehicles with combustion engines. Furthermore, it can be assumed that combustion engines will hardly be able to meet future legislation or will even be banned completely. Approaches to this already exist in several EU countries, although implementation will still take some time [115].

Another way to drive NEV sales is through government subsidies. In Germany, for example, BEVs are subsidized with up to 6.000€ and PHEVs with up to 5.000€ until 2025 [116]. In China, too, subsidies on NEVs have been extended until 2022 [117]. In this case, the subsidy can be up to 22.500 CNY which corresponds to approximately 2.800€. But there are also other financial incentives, such as the elimination of motor-related insurance tax for vehicles with electric motors, as is the case in Austria, for example. Another option would be to subsidize battery charging. Depending on the country, the electricity consumed for driving 100 km can even be more expensive than gasoline or diesel. To sum up, subsidies are a good option for promoting NEVs, but nevertheless, further measures must be taken to sell these vehicles to the masses.

One criticism often voiced is that BEVs and FCEVs are legislated at 0 gCO_2/km. The fact that this does not correspond to reality at all, has been clearly explained in this thesis. The reason for this regulation is that only direct emissions occurring during operation are regulated. This paints a false picture of NEVs and fuels uncertainty among the public, as there are repeated studies concluding that BEVs are more polluting than ICEVs. As already explained, the results of the studies depend very much on how the framework conditions are set. With a reasonable selection of the main parameters, however, the picture clearly emerges that BEVs already have a lower GWP than ICEVs today, but especially in the future. A good approach would be to clearly regulate the conditions for conducting an LCA and to include the results in legislation. This means that the greenhouse gases of the entire vehicle life cycle must be recorded and have to be below a certain limit value. In any case, this would inspire more confidence among the public.

To make the results of an LCA meaningful, the recycling of vehicles must also be precisely regulated by law. Otherwise, this would falsify all the results of the studies. One approach would be to legally require OEMs to collect and recycle vehicles at the end of their useful life, as already mentioned in ***4.2.6***. Unfortunately, this poses a legal problem, since the contract of sale of a new vehicle is between the manufacturer/dealer and the first buyer. However, if the first buyer decides to resell the vehicle, there is no longer a contractual relationship between the second buyer and the manufacturer/dealer. This makes the implementation of mandatory recycling even more difficult. Nonetheless, the EU recently issued a new battery recycling law that requires manufacturers to recycle all vehicle batteries from BEVs

[99]. The only criticism of this law is that while the batteries must be collected, they do not have to be 100% recycled. There are separate quotas for recycling parts of the battery to comply with the legislation. It is important to mention that recycling does not mean reusing the components. For example, if parts of the battery get incinerated, that counts as recycled as well.

In summary, legislations are the main driver for the development of NEVs today. In the future, more and more stringent legislations will be enacted to achieve climate targets and improve air quality in cities. Nevertheless, legislation would also have to be revised to provide a better comparison with reality. By implementing RDE into legislation, this has already worked successfully, now the approach to represent the life cycle emissions of vehicles is still missing.

5.5 Mobility Concepts

Another approach to reduce greenhouse gases is to revise the concept of mobility. The aim is to reduce individual car journeys and expand public transport. Especially large cities have the problem of too many individual vehicles on the road. This causes traffic jams, bad air quality and reduces space due to parking lots. The goal of sustainable mobility concepts is that people no longer own a vehicle but prefer to travel by public transport or share a vehicle with several people. In this way, both the number of vehicles and the total GHG emissions could be reduced at the same time. There are various concepts, some of which have already been implemented and some of which are under development.

First, sharing concepts are already proven in a lot of cities. A sharing concept is based on the sharing of vehicles with other people, which can be any type of vehicle. The most popular concept is bike-sharing, which has already been implemented in many major cities such as Paris, London, Shanghai, and many more and works very well. In terms of GWP, this concept is also the front-runner, as only the production and maintenance of the bicycles generate GHG emissions, while operation is completely emission-free, with the exception of some particulate matter generated by the wear of brakes and wheels. The same concept can be applied to e-bikes, e-scooters and e-mopeds, although they have a higher GWP due to the battery and the electricity needed for operation. Another important sharing concept is car sharing. Now, cars are still necessary for this concept, but the number can be significantly reduced and thus also could save greenhouse gases. In Bremen’s Sustainable Urban Mobility Plan (SUMP) for example, there was the target to reduce the parking pressure by 6.000 cars due to giving up or not purchasing cars of 20.000 car sharing users by 2020. Another option is ride sharing, where people can give rides to others who have the same route and maybe also get a small payment for it. This so called carpooling is very often used by work colleagues for trips to work [118, 119].

Second, the expansion of public transport should be strongly focused. By switching to public transportation, individual trips by car can be reduced or car purchases can even be avoided. A good example is Shanghai, which has made enormous progress in the expansion of public transportation in recent decades and now has the largest subway network in the world [120]. To be truly sustainable, however, public transportation should use alternative propulsion systems. This means, for example, that buses must run fully electrically or with fuel cells. Many developments are currently underway for this, and the first concepts are already in use. The clear leader in the use of electric buses is China, although Europe is also working very hard on the implementation of electric buses. The use of fuel cells in buses will also become an issue in the future. An important aspect is to offer the population the change to public transport voluntarily and not to force them to do so. Forcing them to do so would only cause dissatisfaction and would not be in the spirit of the matter. If the offer is developed well enough and the costs are within limits, many people will switch voluntarily [112, 121, 122].

Third, development and implementation of new means of transport. Engineers are constantly working on innovative technologies for how we will get around in the future. On the one hand, a lot of research is being done into autonomous driving, especially in the automotive sector, and on the other hand, engineers are trying to develop so-called flying cabs that can be used to travel through the air. The development of driving assistance systems is already well advanced and is used in many passenger cars. As a result, the first concepts for an autonomous cab for cities have been introduced to the markets. One example is the zoox car [123], which is already being used successfully in pilot projects in several US cities. The vehicle drives fully autonomously on a defined route and the user can book a seat in the four-seater using an app and is then picked up at a suitable location. Another concept is autonomous air cabs, which are currently being developed. Air cabs can be used to shift some of the traffic on the ground into the air and thus create more space in cities. One example of such a flight cab is Lilium [124], which is expected to be available on the market as early as 2025. The cost of such a flight is said to be similar to the cost of a regular cab ride. However, the appropriate infrastructure and airspace regulation must be created to make such a concept marketable.

Finally, all of these mobility concepts have the potential to save greenhouse gases in the future. For most concepts, however, suitability tends to be limited to densely populated cities. Therefore, the question remains how to design sustainable mobility concepts for rural areas as well. Looking at the results from ***4.5***, a switch to BEVs or FCEVs would be an effective alternative for private cars in rural areas.

5.6 Other Aspects

The successful implementation of NEVs and sustainable mobility concepts depends on many factors. One of the main influencing factors is the cost of the changeover. Currently, NEVs cost significantly more than comparable ICEVs and are also more cumbersome for the user. This should be changed in order to encourage more people to switch. Furthermore, fuel prices for NEVs are not significantly cheaper than gasoline or diesel. Thus, fuel prices might increase and / or the price of electricity would also have to fall, which is in contradiction to green energy, as it is more expensive compared to conventional power generation. A third starting point are the taxes for NEVs, which must also be more favorable than for ICEVs or be eliminated altogether, as is the case in Austria with the motor-related insurance tax and the CO_2 tax for new car sales (NoVA), for example.

Another aspect is to create trust among the population. A lot of people doubt the safety of new technologies (e.g. explosive hydrogen, burning batteries) and have kind of a range anxiety with BEVs. These fears need to be allayed by better educating people about the safety of these technologies. Additionally, many people believe that electric cars, for example, are more harmful to the environment than fuel-efficient internal combustion engines, but this has been refuted by numerous studies, as can also be seen in this thesis. It is therefore necessary to explain to people with confidence and prove with scientific facts that NEVs are significantly better for the environment and, above all, for the climate than conventional technologies. Maybe that would make a lot of people rethink.

Additionally, accident prevention concepts can also contribute to climate protection. Due to accidents a lot of vehicles get damaged or destroyed, which then have to be repaired or replaced. The production of new parts or the sale of new vehicles in turn carries a notable GWP. Thus, targeted training and accident prevention measures can also protect the climate. A positive side effect is, that such measures would also save many lives.

6 Outlook

The result of this thesis shows that, from today's point of view, there is a great potential to reduce the GWP for all drive concepts. The greatest potential for improvement clearly lies in the use-phase, which also accounts for the largest share of greenhouse gases. If the energy transition leads to a switch to renewable electricity generation, use-phase emissions can be drastically reduced, depending on the drive concept. However, emissions from vehicle production can also be significantly reduced by means of new technologies and the use of low GWP impact electrical energy. Furthermore, recycling in the form of reusing old materials is an excellent way to reduce the additional mining of raw materials and lower the carbon footprint of the vehicles. Accordingly, the Battery Electric Vehicle and the Fuel Cell Electric Vehicle are the most promising low-carbon drive concepts for the future. Internal Combustion Engine Vehicles are not capable of competing with these two drive concepts from the current state of technology, although this may of course change as a result of further developments and process improvements. For Hybrid Electric Vehicles, the future will depend heavily on BEV and FCEV developments. If these drive concepts meet all customer requirements in the future, they will not be able to compete in view of GWP.

Whether low-carbon drive concepts can be successfully integrated into the mobility sector depends on many conditions. It is absolutely clear, that in order to fight climate change, low-carbon drive concepts must prevail over conventional drive concepts. To accomplish this, on the one hand the automobile manufacturers are required to develop the vehicles accordingly and on the other hand the legislators are required to promote a smooth changeover as quickly as possible. This probably won't sound too appealing for car lovers, but this development is unfortunately inevitable to reduce global warming.

Furthermore, we must adapt to new mobility concepts to further reduce greenhouse gas emissions. Due to the rapid growth of metropolitan areas, it will no longer be possible for almost everyone in cities to have an own vehicle. A possible solution are innovative mobility concepts that enable people to move around sustainably and comfortably.

In conclusion, sustainable development in all areas of the mobility sector should be made possible and realized, and therefore the CO_2 footprint of our generation must be kept as low as possible for the following generations, so that our descendants can also live on a clean and livable planet earth.

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References

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Appendix

Table 9 - Global Warming Potential of Greenhouse Gases
Own table - data obtained from [125, 126]

Greenhouse Gas	GWP (100 years)
CO_2	1
CH_4	21
N_2O	310
HFC	140 – 11.700
PFC	6.500 – 9.200
SF_6	23.900
NF_3	17.200

Table 10 - Non-Variable Parameters for LCA Application
Own table - data obtained from the shown sources

Non-Variable Parameters	Value	Unit	Additional Information
Calorific Value Gasoline	33,5	MJ / L	Hoekstra et al., 2020 [57]
Calorific Value Diesel	38,3	MJ / L	Hoekstra et al., 2020 [57]
Calorific Value Hydrogen	119,972	MJ / kg	Wikipedia [97]
CO_2 Emissions from Gasoline Combustion	2,38	$kgCO_2$ / L	Helmholtz [76]
CO_2 Emissions from Diesel Combustion	2,65	$kgCO_2$ / L	Helmholtz [76]

Table 11 - General Parameters Scenario 1
Own table - data obtained from the shown sources

General Parameters	Value	Unit	Additional Information
Vehicle Lifetime	200.000	km	Assumption
Energy Density (Li-Ion Battery)	4	kg / kWh	SonneWind&Wärme [127]
Battery Production Europe	75	$kgCO_2eq$ / kg Bat	T&E study for 2020 [52]
Battery Production China	110	$kgCO_2eq$ / kg Bat	T&E study for 2020 [52]
Electricity Production Europe	439	gCO_2eq / kWh	EC study for 2020 [51]
Electricity Production China	1000	gCO_2eq / kWh	EC study for 2020 [51]
Gasoline Production Europe	18,7	gCO_2eq / MJ	EC study [51]
Gasoline Production China	19,2	gCO_2eq / MJ	Peng et al., 2017 [72]
Diesel Production Europe	18,1	gCO_2eq / MJ	EC study [51]
Hydrogen Production Europe (NG based)	96	gCO_2eq / MJ	Valente et al., 2020 [93]
Hydrogen Production China (NG based)	166	gCO_2eq / MJ	Ren et al., 2020 [95]
Battery Recycling Europe	-3	$kgCO_2eq$ / kg Bat	Assumption (based on various studies)
Battery Recycling China	-1	$kgCO_2eq$ / kg Bat	Assumption (based on European value)

Table 12 - Vehicle Parameters Scenario 1
Own table - data obtained from the shown sources

BEV Parameters	Value	Unit	Additional Information

Battery Size	58	kWh	EC study for 2020 [51]
Fuel Consumption	16	kWh / 100 km	Assumption (based on ***4.1.4***)
Glider & Powertrain Production Europe	7,6	tCO_2eq	EC study for 2020 [51]
Glider & Powertrain Production China	9	tCO_2eq	Qiao et al., 2019 [49]
Battery Production Europe	4,35	tCO_2eq	Calculated
Battery Production China	6,38	tCO_2eq	Calculated
Maintenance Europe and China	3	gCO_2eq / km	Assumption (based on EC study [51])
Glider & Powertrain Recycling Europe	-1,5	tCO_2eq	Assumption (based on EC study [51])
Glider & Powertrain Recycling China	-1	tCO_2eq	Assumption (based on European value)
Battery Recycling Europe	-696	$kgCO_2eq$	Calculated
Battery Recycling China	-232	$kgCO_2eq$	Calculated
ICEV Parameters	**Value**	**Unit**	**Additional Information**
Fuel Consumption Gasoline	6,5	L / 100 km	VW Golf Rabbit [75]
Fuel Consumption Diesel	5,2	L / 100 km	VW Golf Rabbit [75]
Vehicle Production Europe	8,3	tCO_2eq	Average of EC Study for 2020 [51] & Wietschel et al., 2019 [70]
Vehicle Production China	10	tCO_2eq	Qiao et al., 2019 [49]
Maintenance Europe and China	6	gCO_2eq / km	Assumption (based on EC study [51])
Vehicle Recycling Europe	-1,8	tCO_2eq	EC study for 2020 [51]
Vehicle Recycling China	-1,2	tCO_2eq	Assumption (based on European value)
HEV Parameters	**Value**	**Unit**	**Additional Information**
Battery Size	2	kWh	Assumption
Fuel Consumption Gasoline	4,5	L / 100 km	Toyota Prius Hybrid [82]
Glider & Powertrain Production Europe	8,6	tCO_2eq	EC study for 2020 [51]
Glider & Powertrain Production China	10,3	tCO_2eq	Samaras et al., 2008 [81]
Battery Production Europe	0,15	tCO_2eq	Calculated
Battery Production China	0,22	tCO_2eq	Calculated
Maintenance Europe and China	5	gCO_2eq / km	Assumption (based on EC study [51])
Glider & Powertrain Recycling Europe	-1,8	tCO_2eq	EC study for 2020 [51]
Glider & Powertrain Recycling China	-1,2	tCO_2eq	Assumption (based on European value)
Battery Recycling Europe	-24	$kgCO_2eq$	Calculated
Battery Recycling China	-8	$kgCO_2eq$	Calculated
PHEV Parameters	**Value**	**Unit**	**Additional Information**
Battery Size	10	kWh	Assumption
Fuel Consumption Gasoline	1,3	L / 100 km	Toyota Prius Plug-In Hybrid [83]
Fuel Consumption Electricity	9,9	kWh / 100 km	Toyota Prius Plug-In Hybrid [83]
Glider & Powertrain Production Europe	8,6	tCO_2eq	EC study for 2020 [51]
Glider & Powertrain Production China	10,3	tCO_2eq	Samaras et al., 2008 [81]
Battery Production Europe	0,75	tCO_2eq	Calculated
Battery Production China	1,1	tCO_2eq	Calculated
Maintenance Europe and China	9	gCO_2eq / km	Assumption (based on EC study [51])
Glider & Powertrain Recycling Europe	-1,8	tCO_2eq	Assumption (based on EC study [51])
Glider & Powertrain Recycling China	-1,2	tCO_2eq	Assumption (based on European value)
Battery Recycling Europe	-120	$kgCO_2eq$	Calculated
Battery Recycling China	-40	$kgCO_2eq$	Calculated
FCEV Parameters	**Value**	**Unit**	**Additional Information**

Fuel Consumption Gasoline	0,94	kgH_2 / 100 km	Toyota Mirai [96]
Vehicle Production Europe	13,3	tCO_2eq	EC study for 2020 [51]
Vehicle Production China	16	tCO_2eq	Assumption (based on European value)
Maintenance Europe and China	3	gCO_2eq / km	Assumption (based on EC study [51])
Vehicle Recycling Europe	-2,25	tCO_2eq	EC study for 2020 [51]
Vehicle Recycling China	-1,5	tCO_2eq	Assumption (based on European value)

Table 13 - General Parameters Scenario 2
Own table - data obtained from the shown sources

General Parameters	Value	Unit	Additional Information
Vehicle Lifetime	225.000	km	Assumption
Energy Density (Li-Ion Battery)	3,6	kg / kWh	Assumption (10% improvement)
Battery Production Europe	64	$kgCO_2eq$ / kg Bat	T&E study for 2030 [52]
Battery Production China	100	$kgCO_2eq$ / kg Bat	T&E study for 2030 [52]
Electricity Production Europe	254	gCO_2eq / kWh	EC study for 2030 [51]
Electricity Production China	820	gCO_2eq / kWh	EC study for 2030 [51]
Gasoline Production Europe	17,8	gCO_2eq / MJ	Assumption (5% less carbon intensive)
Gasoline Production China	18,2	gCO_2eq / MJ	Assumption (5% less carbon intensive)
Diesel Production Europe	17,2	gCO_2eq / MJ	Assumption (5% less carbon intensive)
Hydrogen Production Europe (NG based)	86,4	gCO_2eq / MJ	Assumption (10% more efficient)
Hydrogen Production China (NG based)	149,4	gCO_2eq / MJ	Assumption (10% more efficient)
Hydrogen Production Europe (Electrolysis)	137,5	gCO_2eq / MJ	EC study for 2030 [51]
Battery Recycling Europe	-10	$kgCO_2eq$ / kg Bat	Assumption
Battery Recycling China	-7	$kgCO_2eq$ / kg Bat	Assumption (based on European value)

Table 14 - Vehicle Parameters Scenario 2
Own table - data obtained from the shown sources

BEV Parameters	Value	Unit	Additional Information
Battery Size	64	kWh	EC study for 2030 [51]
Fuel Consumption	14,4	kWh / 100 km	Assumption (10% more efficient)
Glider & Powertrain Production Europe	7	tCO_2eq	EC study for 2030 [51]
Glider & Powertrain Production China	8,28	tCO_2eq	Assumption (based on European value)
Battery Production Europe	4,1	tCO_2eq	Calculated
Battery Production China	6,4	tCO_2eq	Calculated
Maintenance Europe and China	3	gCO_2eq / km	Assumption (based on EC study [51])
Glider & Powertrain Recycling Europe	-1,5	tCO_2eq	Assumption (based on EC study [51])
Glider & Powertrain Recycling China	-1	tCO_2eq	Assumption (based on European value)
Battery Recycling Europe	-2304	$kgCO_2eq$	Calculated
Battery Recycling China	-1613	$kgCO_2eq$	Calculated
ICEV Parameters	**Value**	**Unit**	**Additional Information**
Fuel Consumption Gasoline	6,2	L / 100 km	Assumption (5% more efficient)

Fuel Consumption Diesel	4,9	L / 100 km	Assumption (5% more efficient)
Vehicle Production Europe	7,9	tCO_2eq	EC study for 2030 [51]
Vehicle Production China	9,6	tCO_2eq	Assumption (based on European value)
Maintenance Europe and China	6	gCO_2eq / km	Assumption (based on EC study [51])
Vehicle Recycling Europe	-1,8	tCO_2eq	EC study for 2030 [51]
Vehicle Recycling China	-1,2	tCO_2eq	Assumption (based on European value)
HEV Parameters	**Value**	**Unit**	**Additional Information**
Battery Size	3	kWh	Assumption
Fuel Consumption Gasoline	4,3	L / 100 km	Assumption (5% more efficient)
Glider & Powertrain Production Europe	7,8	tCO_2eq	EC study for 2030 [51]
Glider & Powertrain Production China	9,3	tCO_2eq	Assumption (based on European value)
Battery Production Europe	0,19	tCO_2eq	Calculated
Battery Production China	0,3	tCO_2eq	Calculated
Maintenance Europe and China	5	gCO_2eq / km	Assumed (based on EC study [51])
Glider & Powertrain Recycling Europe	-1,8	tCO_2eq	EC study for 2030 [51]
Glider & Powertrain Recycling China	-1,2	tCO_2eq	Assumption (based on European value)
Battery Recycling Europe	-108	$kgCO_2eq$	Calculated
Battery Recycling China	-76	$kgCO_2eq$	Calculated
PHEV Parameters	**Value**	**Unit**	**Additional Information**
Battery Size	15	kWh	Assumption
Fuel Consumption Gasoline	1,2	L / 100 km	Assumption (5% more efficient)
Fuel Consumption Electricity	8,9	kWh / 100 km	Assumption (10% more efficient)
Glider & Powertrain Production Europe	8,1	tCO_2eq	EC study for 2030 [51]
Glider & Powertrain Production China	9,7	tCO_2eq	Assumption (based on European value)
Battery Production Europe	0,96	tCO_2eq	Calculated
Battery Production China	1,5	tCO_2eq	Calculated
Maintenance Europe and China	9	gCO_2eq / km	Assumption (based on EC study [51])
Glider & Powertrain Recycling Europe	-1,8	tCO_2eq	EC study for 2030 [51]
Glider & Powertrain Recycling China	-1,2	tCO_2eq	Assumption (based on European value)
Battery Recycling Europe	-540	$kgCO_2eq$	Calculated
Battery Recycling China	-378	$kgCO_2eq$	Calculated
FCEV Parameters	**Value**	**Unit**	**Additional Information**
Fuel Consumption Gasoline	0,85	kgH_2 / 100 km	Assumption (10% more efficient)
Vehicle Production Europe	9,9	tCO_2eq	EC study for 2030 [51]
Vehicle Production China	11,9	tCO_2eq	Assumption (based on European value)
Maintenance Europe and China	3	gCO_2eq / km	Assumption (based on EC study [51])
Vehicle Recycling Europe	-2	tCO_2eq	EC study for 2030 [51]
Vehicle Recycling China	-1,3	tCO_2eq	Assumption (based on European value)

Table 15 - General Parameters Scenario 3
Own table - data obtained from the shown sources

General Parameters	Value	Unit	Additional Information
Vehicle Lifetime	250.000	km	Assumption
Energy Density (Li-Ion Battery)	3,2	kg / kWh	Assumption (20% improvement)
Battery Production	46	$kgCO_2eq$ / kg Bat	Assumption (based on T&E study [52]) (20% improvement of upstream emissions)

Electricity Production	20	gCO_2eq / kWh	Assumption (100% Renewable)
Synthetic Gasoline Production	57,2	gCO_2eq / MJ	Assumption (based on EC study [51]) (20% more efficient)
Synthetic Diesel Production	34,4	gCO_2eq / MJ	Assumption (based on EC study [51]) (20% more efficient)
Hydrogen Production (Electrolysis)	143	gCO_2eq / MJ	Valente et al., 2020 [93] (100% Renewable)
Battery Recycling	-12	$kgCO_2eq$ / kg Bat	Assumption (20% increase of 2030 level)

Table 16 - Vehicle Parameters Scenario 3
Own table - data obtained from the shown sources

BEV Parameters	**Value**	**Unit**	**Additional Information**
Battery Size	74	kWh	EC study for 2050 [51]
Fuel Consumption	12,8	kWh / 100 km	Assumption (20% more efficient)
Glider & Powertrain Production	6,5	tCO_2eq	EC study for 2050 [51]
Battery Production	3,4	tCO_2eq	Calculated
Maintenance	3	gCO_2eq / km	Assumption (based on EC study [51])
Glider & Powertrain Recycling	-1	tCO_2eq	Assumption (based on EC study [51])
Battery Recycling	-2842	$kgCO_2eq$	Calculated
ICEV Parameters	**Value**	**Unit**	**Additional Information**
Fuel Consumption Gasoline	5,85	L / 100 km	Assumption (10% more efficient)
Fuel Consumption Diesel	4,68	L / 100 km	Assumption (10% more efficient)
Vehicle Production	7	tCO_2eq	EC study for 2050 [51]
Maintenance	5	gCO_2eq / km	Assumption (based on EC study [51])
Vehicle Recycling	-1,35	tCO_2eq	EC study for 2050 [51]
HEV Parameters	**Value**	**Unit**	**Additional Information**
Battery Size	4	kWh	Assumption
Fuel Consumption Gasoline	4,05	L / 100 km	Assumption (10% more efficient)
Glider & Powertrain Production	7	tCO_2eq	EC study for 2050 [51]
Battery Production	0,18	tCO_2eq	Calculated
Maintenance	5	gCO_2eq / km	Assumption (based on EC Study [51])
Glider & Powertrain Recycling	-1,35	tCO_2eq	EC study for 2050 [51]
Battery Recycling	-154	$kgCO_2eq$	Calculated
PHEV Parameters	**Value**	**Unit**	**Additional Information**
Battery Size	20	kWh	Assumption
Fuel Consumption Gasoline	1,17	L / 100 km	Assumption (10% more efficient)
Fuel Consumption Electricity	7,9	kWh / 100 km	Assumption (20% more efficient)
Glider & Powertrain Production	7	tCO_2eq	EC study for 2050 [51]
Battery Production	0,92	tCO_2eq	Calculated
Maintenance	3	gCO_2eq / km	Assumption (based on EC Study [51])
Glider & Powertrain Recycling	-1,35	tCO_2eq	EC study for 2050 [51]
Battery Recycling	-768	$kgCO_2eq$	Calculated
FCEV Parameters	**Value**	**Unit**	**Additional Information**
Fuel Consumption Gasoline	0,75	kgH_2 / 100 km	Assumption (20% more efficient)
Vehicle Production Europe	8,8	tCO_2eq	EC study for 2050 [51]

Maintenance Europe and China	2	gCO_2eq / km	Assumption (based on EC Study [51])
Vehicle Recycling Europe	-1,8	tCO_2eq	EC study for 2050 [51]