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Private Mobility: An Electric Future(?)

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Ass.Prof. Dipl.-Ing. Dr.techn. Michael Harasek

Klara Melbinger

01152368

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Affidavit

I, **KLARA MELBINGER**, hereby declare

1. that I am the sole author of the present Master's Thesis, "PRIVATE MOBILITY: AN ELECTRIC FUTURE(?)", 109 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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ABSTRACT

The passenger and light duty vehicle sector is currently in transition. Ever more stringent emission targets require auto manufacturers to develop more efficient and less polluting powertrain systems. The launch of sleek luxury battery electric cars and stronger battery technologies have re-ignited the interest in electric vehicles. This Thesis, using a three-pronged approach analyses the potential of electricity as a substitute for fossil fuel as powering source for passenger vehicles. Moreover, fuel cell electric vehicles are proposed as a second alternative to the internal combustion engine. The three-pronged approach includes technological developments, policy measures and socio-economic considerations. Tank-to-wheel efficiencies, environmental footprints over the lifecycle of the respective powertrains and the composition of the electricity mix form the basis of the technical evaluation. On a policy level a series of public incentives provided by European cities are compared and juxtaposed to international legislative requirements. For the investigation of socio-economic considerations, a survey on consumer preferences was conducted with 96 participants. The results of the survey showed that consumers are largely indifferent towards the choice in alternative powertrain and feel quite strongly about low tailpipe emissions and price restrictions. The overall investigation estimates that electricity could be a viable alternative in a middle-term perspective, provided that the share of renewables in the energy mix is augmented and effective infrastructure and payment systems provided, but does not believe in an all-electric future in the transport system This Thesis concludes by suggesting the co-existence of fuel cell and battery technology and consequently of direct use of electricity and of power-to-gas technology. The complementary employment of the two technologies would allow for greater diversification of energy supply and increase consumer-comfort.

Keywords: E-mobility, Fuel Cell Technology, Decarbonization, Low Emission Zones, Green Paradox

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ABBREVIATIONS

HEV	Hybrid Electric Vehicles
PHEV	Plug-in Hybrid Electric Vehicle
BEV	Battery Electric Vehicle
BHP	British Horsepower
SUV	Sports Utility Vehicle
ICE	Internal Combustion Engine
SoC	State of Charge
(Li-S)	Lithium-Sulfur Battery
(Zn-air)	Zinc-air Battery
(Li-air)	Lithium-air Battery
(Li-ion)	Lithium-ion Battery
(LiPo)	Lithium Polymer Battery
($LiFePO_4$)	Lithium Iron Phosphate Battery
SAE	Society of Automobile Engineers
IEC	International Electrotechnical Commission
EU	European Union
CCS	Combined Charging System
ReEV	Range extender Electric Vehicle
GHG	Greenhouse Gas
LEZ	Low Emission Zone
ULEZ	Ultra-Low Emission Zone
ETC	Energy Transitions Commission
FCHEV	Fuel Cell Hybrid Electric Vehicle
kW	Kilowatt
kWh	Kilowatt hour
MCFC	Molten Carbonate Fuel Cells
SOFC	Solid Oxide Fuel Cells
PAFC	Phosphoric Acid Fuel Cells
DMFC	Direct Methanol Fuel Cells
AFC	Alkaline Electrolyte
NDC	Nationally Determined Commitment
PEMFC	Proton Exchange Membrane Fuel Cells
DCFC	Direct Carbon Fuel Cells
FC	Fuel Cell
PM	Particulate Matter
NOx	Nitrous Oxide
g/mi	gram/mile
mg/mi	miligram/mile
CO	Carbon Monoxide

CO_2	Carbon Dioxide
ICEV	Internal Combustion Engine Vehicles
R&D	Research and Development
PV	Photovoltaic
V2G	Vehicle to Grid
TCO	Total Cost of Ownership
Mtoe	Million Tonnes of Oil Equivalent
ÖAMTC	Österreichische Automobil, Motorrad, und Touring Club
LCA	Life Cycle Analysis

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INTRODUCTION

IS ELECTRICITY A PERFECT SUBSTITUTE FOR FOSSIL FUELS OR RATHER A TRANSITION FUEL, CONCERNING THE AUTOMOTIVE SECTOR?

Transportation constitutes a critical component of modern-day life. Development was and still is, primarily connected to the unhindered mobility of people and goods. The United Nations Sustainable Goals (SDGs) thus considers the "access to safe, affordable, accessible and sustainable transport systems for all (…)" (SDG Target 11.2) (United Nations 2015) as vital to foster sustainable development.

Nevertheless, Transport remains a key emitter of greenhouse gases (GHGs), especially of CO_2. 18% of global human-made CO_2 emissions were a result of the transport sector. In other words, 23% of total CO_2 emissions caused by fuel burn could be traced back to transport (OECD 2015). Excessive anthropogenic CO_2 emissions are one of the primary drivers for global warming. Global Warming takes place because CO_2 – a greenhouse gas – can capture and trap heat that has been reflected by the earth and re-emit it to the earth's surface, causing the earth to warm up. Therefore, CO_2 emissions took a prominent place during the 2015 COP21 in Paris, where all 196 Parties had adopted the famous Paris Agreement to the United Nations Framework Convention on Climate Change (UNFCCC 2015). The Parties agreed to join forces to limit the increase in the global average temperature to well below 2°C above preindustrial levels and pursuing efforts to limit the temperature increase to 1,5°C above preindustrial levels (UNFCCC, 2015).

STATE OF THE ART

In 2017 the transportation sector, including passenger and freight transportation via land, air, and waterways, accounted for 23% of total energy-related greenhouse gases (IEA 2017a). Ambitious efforts to reduce anthropogenic GHG emissions had been set since the beginning of the 21st century. 62 of the world's 100 largest companies achieved to cut their emissions by 12% or more during the period 2010 to 2015. At the same time, while emissions fell, their revenues increased (IEA 2017a, 8). These companies include IKEA, ABInBev group or Givaudan. In fact, emissions caused by the transport sector have increased on a year-to-year basis ever since a brief decrease in 2008 (IEA 2017b, 13). This increase may be attributed to a drop-in oil prices on the one hand and surge in car ownership on the other hand. The rise in global population and development levels could be one factor influencing higher private car ownership and car vehicle-kilometres as they do positively correlate with GDP and economic growth (Banister and Stead 2002, 176). However, as the transport sector accounts for almost one-quarter of total energy-

related GHG emissions (IEA 2017a, 8), it will have to significantly reduce its emission to meet the objectives of the Paris Climate Agreement.
The impact of reducing oil prices and rise in economic growth rates cannot be ignored while analysing the shifting trends in the transport sector. The OECD in a recent report has stated that low oil prices pose a clear threat to the various commitments made under the Paris Climate Agreement (OECD 2017). Low oil prices give rise to more fossil fuel emissions, disincentive consumer behaviour towards the adoption of cleaner technologies, drives investments into research and development away from clean energy alternatives and increase the total amount of vehicles plying on the roads.
Low oil prices could also be a driver towards clean energy investments and adoption of cleaner technologies in the long term due to factors such as profitability and long-term competitiveness. An IEA study in 2015 had forecasted that the energy efficiency markets would continue to grow irrespective of the fluctuations in the oil market (IEA 2015, 27). This could potentially pave the way for investments into research and technology, policy support and structural changes through tightening pricing regulations and increasing subsidies for newer technologies that contribute to stemming the deterioration of air quality and the environment at large.
Air quality is affected by many factors including population growth, uptake of the personal vehicular mode of transportation, population density, and urbanization. Large cities such as New Delhi or Beijing or London and Paris, have faced significant air pollution problems in the past, which could be attributed to an increase in passenger vehicle sales and the resulting traffic. Passenger light-duty vehicles play a significant role, especially in large cities in empowering independence among their citizens, by enabling them to safely reach their workplace or enjoy leisure activities distant to their homes. Air pollution in these areas does, however, significantly affect the overall quality of life and puts a significant economic burden on private citizens and municipalities and governments at large. For OECD countries the economic costs of air pollution due to road traffic amount to up to one trillion USD per year. The health effects are enormous thus decarbonization of the transport sector must be a priority. For achieving decarbonization, a combination of a variety of policies needs to be envisaged by decision makers. The policies range from support to technology research and development up to implementing behavioural measures. Behavioural measures are vital to decarbonizing the transport industry, provided that the necessary technology is available for an affordable price (OECD 2017). Behavioural measures can be summed up into two categories: firstly “avoid traveling” and secondly “shift the mode and technology” of traveling. Since the primary focus of this thesis is on the second category, the former category will be briefly touched upon.

A shift in the mode of passenger light-duty vehicles points towards increased research and development of automotive engines. The most common alternative to the internal combustion engine (ICE) is the electric car, which includes battery-electric (BEV), plug-in hybrid electric (PHEV), and fuel cell electric (FCEV) passenger light-duty vehicles. Of these electric alternatives, BEVs seem to take the lead in the zero-emission vehicle competition. In 2016 there was some 1,2 million battery-powered electric vehicles on the road worldwide (Statista 2017). That year a new record in electric car sales had been hit, amounting to 750 thousand sales worldwide signifying a 40% increase compared to 2015 electric car sales. The largest electric car market, by far, is China, followed by the United States. On a global scale, it is noticeable that the electric car market is up until date concentrated in a somewhat limited amount of countries, namely China, the United States, Japan, Canada, Norway, the United Kingdom, France, Germany, the Netherlands and Sweden. It is in these countries where 95% of total global electric car sales are taking place (IEA 2017b; ACEA 2017a). Amongst European countries, only Norway, the Netherlands, Sweden, France and the United Kingdom have so far reached an electric vehicle market share of more than 1% of their total passenger light-duty vehicle sales in 2016. Due to a favorable policy environment, ranging from tax incentives to waivers on road tolls and ferry fees through government subsidy programs, Norway has paved the policy path for other similar countries to follow. The electric vehicle market share in Norway ranges upwards of 29% of the total Passenger light-duty vehicles (PLDVs). Large-scale electric car deployment at this stage, cannot be envisaged without proper policies and supporting incentives in place. Just like any other industry, an enabling policy environment is key to facilitating market creation and economies of scale to appeal to consumers, protecting investors, and incentivizing manufacturers.

Furthermore, along with policy support, what is equally important is the necessary infrastructure to enable the shift in consumer behaviour towards the adoption of electric cars. A vital component of the infrastructure is charging stations and related charging equipment such as cables, connectors and communication protocols between the charging station and the vehicle and the charging station and the distributor of electricity. Standardization is thus a critical need of the hour. Key standardization entities involved in the development of these standards include the International Organization for Standardization (ISO); the International Electrotechnical Commission (IEC); the Society of Automotive Engineers (SAE) of the United States; and the Standardization Administration of China (SAC), which issues Chinese national standards (GuoBiao, GB) (IEA 2017a). There are only a few Standardization protocols for EVSE-grid communication, and there is a need for concerted effort in harmonizing standards to facilitate inter-country mobility.

few standardized protocols for EVSE-grid communication, but efforts to develop them have started. Portela´s work on the Open Smart Charging Protocol is amongst the most exciting developments in this area (Portela et al. 2015, 5).

The growth of publicly available chargers accompanies the increase in the number of electric cars on the road: the growth rate in the number of publicly accessible chargers in 2016 (72%) was higher, but of similar magnitude, to that of the electric car stock growth in the same year (60%). The instalment of further public fast-charging stations in European cities is ambitious. By 2020 an additional 1,000 fast-charging stations are planned for the city of Vienna (Wien Energie, 2018). According to the European Alternative Fuels Observatory (EAFO) there at present some 131,300 fuelling stations within Europe (EAFO, 2018). While the charging infrastructure for BEVs is slowly expanding, hydrogen fuelling stations for Fuel Cell vehicles (FCV) are scarce with 82, partially publicly accessible, hydrogen fuelling stations in Europe (EAFO, 2018). A less visible but at least equally vital component of infrastructure is the electric grids. Large-Scale electrification of passenger vehicles entails an accentuation of peak load hours and additional burden on the grid, caused by accumulative fast charging periods (Göhler and Effing 2017, 8). Possibly necessary adaptations of electricity grids must form an integral part in the calculation of total public investment costs to boost a transition in the transportation sector. Private investment costs are a function of the initial purchasing price of the vehicle and operational costs, including fuel costs, maintenance, and repair, taxes and fees as well as parking. At present, total costs of ownership (TCO) are higher for BEVs than for ICEVs, due to high initial purchasing prices despite comparatively low operational costs (Redelbach, Propfe, and Friedrich 2012). The battery remains the most expensive component of a BEV. Once production costs thereof are decreasing, BEVs are likely to be more competitive (Redelbach, Propfe, and Friedrich 2012)

In the frame of an extensive survey, KPMG investigated opinions regarding the future of the automotive transition amongst executives and customers. Options regarding the potential alternative powertrain were quite divergent. While executives believe, that FCEVs have the best chances of shaping the future road transport sector, consumers are prone to favouring BEVs (KPMG 2017). Both groups are, however, in agreement that the basis for a lasting transition will be the broad scale deployment and upgrading of infrastructure (KPMG 2017).

When the leading automobile manufacturers met in Frankfurt at the annual Motor Show in September 2017, they were given the opportunity to showcase their latest achievements in areas spanning technological innovations, modern design and of course environmental progress. International ambitions to reduce emissions of greenhouse gases and to encourage a more sustainable economy have had a significant impact on the global economy including the automotive industry. Just like the long uncontested primacy of the oil industry, the car industry has also been abruptly hit by a challenge that might mark a new era for individual terrestrial mobility. Thus, at the Frankfurt Motor Show 2017, in line with the current socio-political and scientific environment, electric cars took quite a prominent place – to show how environmentally aware the manufacturers were, how they were pioneers of societal developments and how innovation would prosper from within the automotive industry. At the opening event, Volkswagen, the world's largest car manufacturer in 2016, pledged it would introduce 50 entirely electric car models by 2025, in addition to another 30 hybrid models. This constituted a significant increase compared to two years ago, where the group had only unveiled a single electric car (Financial Times 2017). Competitors such as Daimler announced that their 'Smart fleet' would also become fully electric by 2020 – this would result in the complete electrification of an entire marque that initially ran on an oil-fuelled internal combustion engine.

A recent study by McKinsey (Frankel and Wagner 2017) showed that storage prices are dropping at a fast rate and have dropped by more than 75% in the last seven years. However, questions still loom large about the long-term sustainability of lithium-ion manufacturing and the resulting environmental and social costs in addition to capacity issues. Core elements of lithium-ion batteries such as lithium and cobalt are finite, and their extraction leads to water pollution amongst other environmental consequences. Moreover, there are more significant issues like waste management of worn out batteries. A recent study by McKinsey (Frankel and Wagner 2017) showed that storage prices are dropping at a fast rate and have dropped by more than 75% in the last seven years. A 2013 study showed that only 5% or less of Li-ion batteries are recycled in the EU (FOEE 2013).

Now the question arises – where is this enthusiasm for specifically electric cars coming from? Is it environmental friendliness and price efficiency? With the ratification of the Paris Climate Agreement, the international community had agreed upon reducing CO_2 emissions, with the EU pledging to cut emissions by 80% by 2050 (EEA 2016). In 2030, average CO_2 emissions produced by new passenger cars and trailers must be 30% lower than in 2021, as decided by the EU commission (European Commission 2017a). The overarching goal is to lead the path to a zero-emissions transport system, at least within Europe. This not only concern cars, but rails and ships too. For this thesis, however, the focus will rest exclusively on cars used as individual passenger vehicles. Other forms of transport might only be marginally touched.

RESEARCH QUESTION AND STRUCTURE

The state of the art as mentioned in the previous paragraphs, raise two consequent questions that this Thesis will attempt to answer. Firstly, is electricity a perfect substitute for fossil fuels or rather a transition fuel, with respect to the automotive sector in Europe? Secondly, is the battery-electric vehicle a necessary intermediary for a paradigm shift towards an emission-free automotive industry in Europe? In answering the above research questions this thesis, in the following chapters, will lay out the theoretical groundwork by tracing the history of the development of the Internal Combustion Engine and its inherent flaws. The second and third chapters will describe and analyse two alternative powertrain systems to the ICE Vehicle i.e. Battery Electric Vehicles and Hydrogen Fuel Cell Vehicles. Both alternative powertrain systems will be analysed using three comprehensive considerations - technology, infrastructure and policy. This thesis will then further elaborate on the European policy setting by presenting and analysing the policy frameworks in different cities across Europe. The Thesis will finally analyse and discuss all the considerations and attempt to answer the above-mentioned research questions.

METHODOLOGY

The author has mainly conducted research for this thesis on secondary sources of data including the use of datasets and analyses from organizations such as the International Energy Agency, World Bank Group among others. This thesis also references works from academics and the industry alike, including research papers, reports, books and articles.

The author, to validate the trends observed from the secondary data sources, also conducted primary research through a consumer preference survey which was done using an online questionnaire.

CHAPTER 1
A BRIEF HISTORY OF THE AUTOMOBILE.

EVOLUTION OF THE CAR

Mobility as a concept has been fundamental to the progress of humankind. Since the beginning of civilization as we know it, humans have developed ways and means to reduce the time and work to get from A to B; while increasing the amount of distance one could cover over a given period. Technological developments have therefore enabled humankind to cover vast distances by land, by air or by sea while creating entire systems of transport to ensure the mass movement of people and goods.

While transport systems like the railways played a considerable role in the growth of the industrial economy of the 19th century; one of the most significant developments in transportation was the invention of the automobile. Personal mobility became one of the hallmarks of class and status in 19th-century society. Available only to a privileged few but catering to the aspirations of the masses. With time and the rapid advance of the modern technological society, the automobile became more affordable and available to the masses in the first half of the 20th century bringing with it more personal freedom of movement while providing an impetus to growing western economies to invest more in public infrastructure like roads.

The first car was invented and introduced *(as widely agreed upon)* by the French military Engineer Captain Nicholas Cugnot, who is often referred to as the father of the Automobile, in 1769. Cugnot's invention, also known as the *Fardier* was a three-wheeled artillery tractor, as he had been assigned by the army to develop a robust vehicle employable in military activities on land (Day and McNeil 2002, 320). His contraption was the first functional self-propelled mechanical vehicle intended for land use and was powered by a steam engine which would allow for his invention to reach a speed of up to 6.4km per hour while having to stop every 10 – 15 minutes to build up power! (M. Dell, T. Moseley, and Rand 2014). Our modern-day version of a car such as a Bugatti Chiron has come a long way from its three-wheeled ancestral past *(though not very unlike its ancestor when it comes to the frequency of refuelling stops)*.

The humble *Fardier* paved the way for significant developments across Europe and America in automobile technology resulting in increasing practicability, comfort and speed. Noteworthy developments were the Stanley Steamer and the White Steam Car, developed in the US in 1895 and 1902 respectively (Anderson and Anderson 2010, 14). Both vehicles showed great strength, the Stanley Steamer, a self-propelled vehicle, was even capable of reaching an incredible road speed of up to 160 km per hour (this was a specially equipped Stanley Steamer) – a major success at the time (Parissien 2014, 101). In the hour of birth of the automobile, as we now know it, several types of engines were investigated and simultaneously tested. It was a race to for discovering the ideal engine, the ideal fuel, and the most user-friendly vehicle design. It could even be compared to the beginning of the 21st century, where there seems to be anew a competition of which company and which geographic region can develop the best mobility system in line with the given requirements, such as environmental aspects, affordability, and accessibility, relevant in the post-industrialized world.

Beside the self-propelled engine, attempts had also been made to power the automobile with gas. The Frenchman Étienne Lenoir had heard about Cugnot's *Fardier* and its short-comings such as a long preheating time and bulky weight. He considered the steam engine to have exploited its full potential and could not be further improved. Therefore, Lenoir started experimenting with gas as a fuel source. Eventually, around 1860, he ended up inventing the very first internal combustion engine that would be powered by a mixture of coal gas and air. An advantage to Lenoir's motor was its silent running. However, it was highly inefficient using much gas, as the gas was not compressed, a technology that had previously been invented by Philippe LeBon in 1801 (Museum 1939). The invention of the internal combustion engine, by Etienne Lenoir, signified a massive breakthrough in the path towards an efficient and user-friendly motored vehicle.

The lack of efficiency demonstrated by Lenoir's engine was rectified in theory by the French engineer Beau-de-Rochas in 1862. He stated the now famous principle of the four-stroke internal combustion engine and patented his concept. Beau-de-Rochas pointed out that maximizing the efficiency of such an engine lay in the compression of the fuel-mixture before ignition thus leading to better utilization of the heat supplied.

The technology first introduced by Lenoir and the technical improvements of it, attested by Beau-de-Rochas, were finally combined and executed by the German Nikolaus August Otto in 1876 (Parissien 2014). Departing from Lenoir's internal combustion engine, Otto introduced the four-stroke cycle engine, known as the "Otto cycle," which was the first model of a modern-day four-stroke internal combustion engine.

With the aid of Wilhelm Maybach and Gottlieb Daimler, Otto's internal combustion engine could eventually be commercially produced. While Carl Benz was building a tricycle in 1886, propelled by a four-stroke cycle internal combustion engine, Otto continued his quest to improve further his engine. Otto´s improvements resulted in the development of the electrical ignition of the engine which allowed the use of fuels that were based on liquid petroleum, and that constituted an alternative power source to gas (Day and McNeil 2002).

Daimler had patented the light and fast engine but granted the rights to the French engineer M. Levassor, (*Automobiles of the World: An Encyclopedia of the Car* 1921, 94) who developed a vehicle that would for the first time resembled more a modern-day car than a motorized carriage. The engine was now placed in the front part of the vehicle, connected to a clutch and incorporating a sliding gear transmission and a differential as well as an accelerator and break-pedals (*Automobiles of the World: An Encyclopedia of the Car* 1921).

Around the turn of the century, gasoline automobiles were facing fierce competition from stream automobiles as well as from electric automobiles. The two latter examples benefitted from the advantage of an abundance of power, however, at the cost of low speed which on the other hand made a transmission system redundant. Electric automobiles were mainly marketed to female clients, as electric cars required little physical force during the steering process since crank-starting was not required. After all, the transmission system in the other technologies was quite rigid in the handle. On the other hand, the rise in popularity of the internal combustion engine was because steam engines with their high-pressure steam boilers suffered from significant safety concerns and electric automobiles with their batteries were coupled with inconvenient, slow recharging (Parissien 2014). The benefit of a gasoline-powered vehicle, despite the necessity of the transmission, was its ability to be quickly recharged with a comparatively small amount of fuel which would transform into much power.

In 1892, the first gasoline-powered vehicle propelled by a 4-horsepower gasoline motor, '*The Horseless Buggy*', was deployed on the street by Charles E. Duryea (Parissien 2014). By 1900, front engine vehicles were already being produced and by 1905 more than 6000 vehicles were being produced in the United States of America, and by 1908 with Henry Ford's revolutionary assembly line production technique, there were 20,000 models of Ford Model T on American roads alone (Sorensen 1978, 31)! By 1914 the share of Ford vehicles amongst American car sales would reach almost 50% (Georgano 1965).

From the turn of the century on, the automobile – functional, user-friendly and comparatively comfortable – had conquered the market. While some still considered it a threat to humankind, others embraced it. *"I do believe in the horse. The automobile is no more than a transitory phenomenon"* (Fialka 2015, 186), an excellent statement by Kaiser Wilhelm II on the ambiguous status of the car.

Soon, in the spirit of the second industrial revolution, the opportunities related to the development and the expansion of the automotive industry rose. Methods, on a technical as well as managerial level, to increase productivity would see the day of light. For instance, Henry Ford's famous "Five Dollars a day" principle (Hinshaw and Stearns 2013), which did not only attract the best workforce to his factories and boost morale but would also lead to the self-creation of a market outlet. Workers could now afford to buy the Ford product themselves and spend it elsewhere thereby enabling the creation of even more potential customers.

The next revolution in the automobile industry was the development of the spark ignition gasoline engine. It was compact, light in weight, allowed for high speed, was cooled by water, did not cause vibrations, was relatively noiseless and could be powered by a variety of petroleum-based fuels. By then, the internal combustion engine had conquered the automobile market on a global scale and completely pushed alternative engines off the market, respectively the steam engine and the electric car, due to their lack of user-friendliness (*Automobiles of the World: An Encyclopedia of the Car* 1921).

When it comes to the internal combustion engine (ICE), there are two major types – the gasoline-fuelled ICE and the diesel ICE (Stone 2012, 36). In the past, the gasoline ICE was the preferred technology for the use in cars. Due to better acceleration and top speed, the gasoline ICE has been more attractive. Compared to diesel engines, gasoline engines tend to be lighter. Over the decades, however, the weight issue was offset by introducing the turbocharger. The turbocharger was undoubtedly a critical technology that contributed to the popularity of the diesel car. By the inclusion of turbo-charger specific power output could be increased as well as the operation over broader speed ranges in addition to a reduction of noise pollution. The mass-production of diesel cars has also lead to a decrease in costs (Stone 2012). Objections to the diesel engine persisted, however, due to their high emissions production. Rigorous control of the fuelling system including the enhancement of the quality of the diesel fuel itself and the additives contributed to a creation of a more usable fuel, which was liberated from unpleasant noise and smell, and functional in cold weather conditions.

The pioneers to the broad introduction of the diesel car were the automakers Mercedes-Benz, Peugeot, and Volkswagen. Their success with the diesel car was linked to them including turbochargers in their passenger diesel cars. By 1990, commercial diesel cars could reach speeds of over 190 km per hour, and acceleration was just as good as the acceleration in gasoline engine vehicles. In contrast to gasoline engines, diesel engines emit only a third of hydrocarbons, about 1% of CO and 30% less CO_2 than the gasoline engine. A distinct disadvantage of the diesel engine is, however, that it emits significantly

more particulate matter (PM) as well as different nitrogen oxides, commonly referred to as NOx (Reşitoğlu, Altinişik, and Keskin 2015).
The real era of the Diesel heralded in the 1990s. Car manufacturers would from then on often offer gasoline as well as a diesel option in the same vehicle series, to cater to a broader customer base and enable a fast adaptation of the vehicle to the specific demands of the customer. Isuzu (Japan), Ford (UK) and Peugeot (France) were amongst those who would establish this mindset in production and contribute to the increase of diesel car sales (Miravete, Moral, and Thurk 2018).
Before the Diesel Scandal in 2015, diesel cars accounted for 41.2% of all passenger light-duty vehicles on the road in the EU (ACEA 2017a). Partly, in response to the Diesel Scandal petrol car sales surpassed diesel car sales for the first time since 2009 (ACEA 2017b).

EVOLUTION OF POLLUTION STANDARDS

With a burgeoning demand and use of personal vehicles, and increased fuel pollution due to inefficient engine technologies and resulting vehicle emissions, smog became a regular feature in American and European cities in the late 1950s - 1960s (Serra 2013, 39). California, due to the uniqueness of its location and resulting weather conditions, faced one of the worst smog during that period. The California legislation on air quality control came into effect in the form of the Motor Vehicle Pollution Control Act, 1959. California's regulations on emission standards on fuel economy remain to this date one of the most stringent in the United States. It was however only in the late 1960s, after the enactment of the Clean Air Act, 1965 and the adoption of the 1968 emissions standards (that were based on California's 1965 emission standards) that the US auto industry agreed to phase out lead from petrol and diesel fuels (Vogel et al. 2012, 4). This development gave way to the commercial adoption of catalytic converter technology – that converts harmful pollutants in the tailpipe into less harmful emissions. The first catalytic converters started appearing in American made cars in 1975. The first models of catalytic converters were mainly engineered to reduce carbon monoxide and hydrocarbon emissions, but by 1980 these converters also began to reduce nitrogen oxide emissions.
The 1970s also saw this problem of air quality compound with fluctuating petroleum prices and political instability in the middle east. The Americans, as opposed to Europe, were the first movers in the adoption of regulatory standards for vehicles in 1975 with the first Corporate Average Fuel Economy (CAFÉ) standards which came primarily as a response to the Arab oil Embargo in 1973-74. The CAFÉ standards aimed at improving vehicle fuel efficiency of cars and light trucks produced in the USA by prescribing an

average mean of fuel efficiency to be achieved in miles per gallon by passenger cars (model year starting 1978) and subsequently light trucks (model year starting 1979). In 2007, the CAFÉ standards were further tightened with new targets of 54.4 miles per gallon (approx. 4.3L per 100km) set as the desired fuel efficiency of a vehicle by 2025.

In Europe, it was only until much later that EU countries began to look at reducing emissions and set standards for fuel economy. Europe responded to the Oil Shocks of the 1970s by imposing heavy taxes on fuel to regulate consumption (Miravete, Moral, and Thurk 2018, 3). Also, it is a notable phenomenon that with the imposition of taxes on fuel, diesel was taxed lower than gasoline in most EU countries (Miravete, Moral, and Thurk 2018, 2). This led to a larger market for diesel in Europe than in the USA for example. Volkswagen's famous DTI engine along with lower diesel prices ensured that diesel vehicles went on to capture more than 50% of the European market (Miravete, Moral, and Thurk 2018, 4). While Diesel vehicles might be more fuel efficient and thus appeal to price-sensitive buyers, recent studies have shown that diesel causes more harm and contributes towards air pollution in a higher degree than a petrol version (Reşitoğlu, Altinişik, and Keskin 2015; Hooftman et al. 2016; Poliscanova, 2016). Moreover, Europe only banned leaded fuels in the late 1990s, and the first catalytic converters in European cars were deployed in the early 1990s. High lead emissions into the air had severe health effects on the pollution and the environment. Lead is a heavy metal that when having entered the body system can lead to cramps or cardiac problems (ORF Science 2010). Europe was thus a late entrant to fuel emission and vehicle fuel economy regulation as compared to the early adoption of other developed markets such as the US.

European emission standards were only adopted in 1992 (Euro I) required Nitrogen Oxide levels of 1.55g/mi compared to the US equivalent standard of 1 mg/mi. The EU was focused on reducing CO, and CO_2 emissions and EU CO_2 targets are close to 30% lower than the US standards while CO levels are nearly 70% lower than their US counterparts. However, while low CO and CO_2 targets have benefitted diesel car manufacturers in Europe who have managed to stick to these limits to the extended mileage of diesel cars; diesel engines have been seen to be one of the most significant contributors to NOx emissions in Europe.

Recent studies (Poliscanova 2016; Miravete, Moral, and Thurk 2018; Hooftman et al. 2016; Reşitoğlu, Altinişik, and Keskin 2015), has shown that EU standards for emission controls are notably less stringent than that of the US for matters such as air quality. However, as mentioned above the EU standards are more stringent in curbing greenhouse gas emissions. However, EU regulations, as the recent Volkswagen controversy demonstrated, suffer from fundamental structural weaknesses such as it allows manufacturers to choose between testing authorities and type approval authorities – this absence of a single regulator allows more leeway for manufacturers to be bound by the same stringency as their American counterparts. Regulation of vehicle emission standards in the EU has now been the subject of intense debates and the new regulations put in place especially in testing such as the adoption of the Worldwide Harmonized Light Vehicles Test Procedures (WLTP) might contribute towards a more stringent approach by the EU in controlling vehicle emissions and standardizing procedures.

In an interconnected economy, the notion of standardization can be found almost anywhere. Standardization is of particular importance in the automotive industry given its considerable geographic and sectoral scope. Ever more ambitious regulations in the field of emissions reduction and demands on high standards of living in addition to transformations in the energy sector and the change in preferences of energy sources do all execute considerable impact on the automotive industry. Perhaps the automobile industry finds itself again at a crossroad, comparable to about 100 years ago. A century ago the automotive industry opted for the ICE-vehicle which has improved ever since. The alternatives could not keep up with the existing technology. Ironically, the ICE now challenged by the practically the same alternative powering technologies, namely the electric vehicle and the fuel cell vehicle. Technologies for both alternatives have also developed since the Ford Model T. What now remains to be analysed is whether the alternative technologies are mature enough to replace the ICE and secondly which of the alternatives is most likely to introduce the new era in the automobile sector.

The essential difference to now and 100 years ago are the circumstances. Priorities for policymakers and consumers alike may have changed. The demands for light duty passenger vehicles might not only consist of being transported from A to B within a respectable amount of time.

CHAPTER 2
Electric Vehicles – Hybrid, Plug-in, and Battery Electric

The purpose of this Master Thesis is to investigate the possible extent to which battery electric vehicles (BEVs) could replace the internal combustion engine and the place they are going to take up in the field of passenger and light-duty vehicles. Furthermore, in the scope of this thesis, it will be attempted to identify seemingly unrelated trends in the fields of economics, policy-making and the industry to disclose indicators depicting the direction of where the battery electric vehicle is heading. By juxtaposing the internal combustion engine, the battery electric car and other alternative powertrains for light-duty vehicles, it might be possible that the technology – directly related to engine and powering sources – may only be secondary in the choice of future technologies in the automotive sector. The mode of energy production, be it the generation of electricity, the conversion of biological resources or the refinement of fossil fuels, is a key factor in choosing the future mobility technology. Technical considerations directly related to the car, including efficiencies may only play a secondary role in the final decision-making process. Infrastructure and energy-production modes might be the dominating factors.
As shown in the previous chapter, electric vehicles (EVs) are not an invention of the 21st century. On the contrary, EVs had seen the day of light even before the Internal Combustion Engine did. Its invention dates to the late 19th century. It was particularly popular amongst women as it did not require a lot of muscle power applied by the operator to start the vehicle. EVs were only genuinely challenged by the ICE once the electric self-ignition system had been invented. The electric self-ignition system enabled an uncomplicated and effortless way to change into the gears in the ICE. Easy operability and the increasing importance of crude oil paved the way for the ICE-vehicle (ICEV). It is indisputable that the spread of ICEVs is closely linked to the extraction of crude oil, the availability thereof and its selling price. The particular role of oil will be further discussed in this chapter.
Road-based transportation accounts for about 72% of total greenhouse gas (GHG) emissions caused by the transport sector (EEA 2017). As a result of an increased frequency of extreme weather events (EASAC 2018), to a large extent caused by human activity and anthropogenic emissions, pre-emptive measures to reduce emissions are occupying a central place for industries, civil society and policymakers alike. Therefore, EU member states have agreed to cut their emissions to 80% below 1990 levels by 2050 to stabilize atmospheric CO_2 at 450 ppm to achieve the goal of keeping global warming below 2°C

(European Commission 2016). To achieve this goal, all sectors including the transportation sector would need to reduce their share to total emissions. The total transportation sector has a potential of reducing its emissions by at least 60% by 2050 compared to the baseline of 1990 emissions (European Commission 2016).

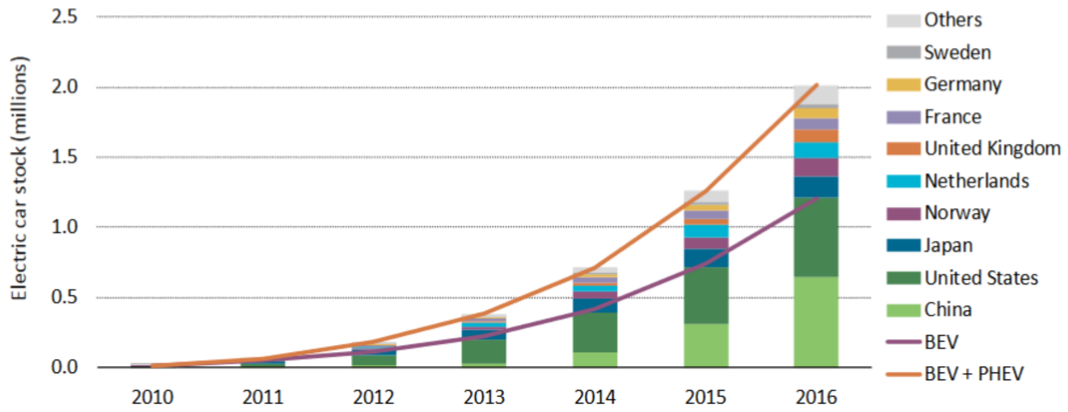
The transportation sector can be divided into several categories dependent on the transportation route, including transportation by road, air and sea. In this thesis the focus will be solely put on road transportation and more concretely on passenger light duty vehicles for private use, therefore excluding public transportation systems.

EV SALES

Currently, a renaissance of the electric vehicle is observed. This renaissance was ignited by the need to rethink the present dominance of the ICEV and possibly nudged by the launch of the Tesla electric car, which presented a glamorous option for an alternative propulsion system. At first sight, the advantages related to the EV are twofold: there are zero tailpipe emissions, and it uses alternative fuel. By resorting to another power source dependency on oil and oil exporting countries may be reduced, which is of geopolitical interest to some economies.

In 2017 a total of 252 million passenger cars were registered in the EU. The total number of passenger cars grew by 4.5% from 2016 to 2017 (ACEA 2017a, 2). Even though the amount of newly registered alternatively-powered passenger vehicles has grown over the past years, alternatively-powered vehicles do still only account for 3% of the total EU car fleet. The share of electric vehicles (including hybrid and plug-in hybrid) of total passenger cars in the EU lies at 0.5% (ACEA 2017a, 12).

Figure 2.1 showcases the evolution of the global EV stock from 2010 to 2016. There is a clear trend of increasing popularity of EVs especially in China, which has surpassed the US as the largest EV market globally in 2016. Now, China accounts for about one-third of the global stock of EVs. The orange curve indicates the accumulative sales of BEVs and Plug-in Hybrid Electric Vehicles (PHEV), while the purple line shows the sales of BEVs only. The difference between the different types of EVs will be elaborated in the section below. While the total number of EVs sold is continuously increasing, the annual growth rates of sales have been decreasing. According to the International Energy Agency’s Global EV Outlook report, electric car stock growth fell from 85% in 2014 to 77% in 2015 down to 60% in 2016 (IEA 2017a, 6).



Notes: The electric car stock shown here is primarily estimated on the basis of cumulative sales since 2005. When available, stock numbers from official national statistics have been used, provided good consistency with sales evolutions.

Sources: IEA analysis based on EVI country submissions, complemented by EAFO (2017a), IHS Polk (2016), MarkLines (2017), ACEA (2017a, 2017b) and EEA (2017).

Figure 2.1: Evolution of global EV stock, 2010 – 2016

The reasons for such a drop in annual growth may be manifold and are part of the discussion in this thesis. The lack of standardization, as mentioned in the previous chapter combined with a lack of infrastructure does partly explain this trend. The dynamic in cars sales is also primarily impacted by the fluctuations of oil prices. Baur and Todorova (2017) analysed the relationship between fluctuating oil prices and car sales and reaffirmed the negative relationship between comparatively high fuel consuming cars sales and oil prices. They also discovered the very high price sensitivity of Tesla Motors, (presently Tesla only offers BEVs in its portfolio) whose sales would spike in years of high oil prices and drop in years of low oil prices (Baur and Todorova 2017, 8). Tesla Motors exhibits a high price sensitivity, as solely BEVs are present in their portfolio.

Electric vehicles have undergone and still are undergoing a series of technological developments. Consequently, a range of alternative EVs, which differ in the configuration of their powertrain designs can be found on roads today. Such configurations entail series, parallel and series-parallel configuration. Even amongst the BEVs, there is a variety of battery technologies available, including lead-acid, nickel-based and of course the famous lithium-based batteries.

POWERTRAIN

For any given motorized vehicle, such as ICEVs or EVs, the powertrain stands for the entirety of the essential components of the vehicle that enable the locomotion of the vehicle. In other words, powertrain represents the composition of all elements in the vehicle that generate power, transfer that power to the goad surface and consequently create motion (Ehsani, Gao, and Emadi 2017, 32). The powertrain includes the engine, drive shafts, transmissions, differentials and the wheels. For hybrid powertrains, the battery and the electric motor are additional components of the powertrain. Simply put, the powertrain englobes all components of a motorized vehicle that are needed to transform and transfer the stored energy, may it be in the form of chemical, or potential energy, into kinetic energy for the propulsion of the vehicle. The most significant issue thereby is to produce the usable kinetic energy in the most energy-efficient and cost-effective way, while creating as little emissions as possible (Çağatay Bayindir, Gözüküçük, and Teke 2011, 1).

To this end, components of the powertrain have undergone constant cycles of improvement regarding efficiency. Against this backdrop, research and development (R&D) have also investigated alternative propelling systems. The EV constitutes an alternative, promising more energy efficiency and cleaner technology.

On a first level, EVs can be formally set apart by classifying them according to their vehicle hybridization ratio. There are the following three types: hybrid electric vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and Battery Electric Vehicles (BEVs).

HYBRID ELECTRIC VEHICLES

For a motorized vehicle, any powertrain must meet the following criteria: “develop sufficient power to meet the demands of vehicle performance, carry sufficient energy onboard to support vehicle driving in the given range, demonstrate high efficiency, and emit few environmental pollutants”(Ehsani, Gao, and Emadi 2017). A traditional ICEV has one energy source and energy converter (diesel or gasoline). A motorized vehicle may, however, have more than a single power source. A vehicle equipped with more than one energy sources and energy converter is referred to as a hybrid vehicle. Hybrid vehicles with an electrical powertrain as part of their propulsion system are called hybrid electric vehicles.

HEVs integrate an ICE (powered with petrol or diesel) and an electric motor (powered by electricity). An HEV is only capable of accepting regular liquid fuel (petrol or diesel) as an external powering source for its engines. This fuel powers the ICE directly and the electric motor indirectly. Consequently, an HEV cannot charge its battery with electricity from the grid. The charging process of the battery is managed by the built-in ICE or by an energy recovery mechanism, namely by regenerative breaking. By applying the breaks in any EV, the electric motor switches into generator mode. This results in the

transfer of kinetic energy from the wheels to the generator via the drivetrain. In the generator, the received kinetic energy is transformed into electrical energy and stored in the high-voltage battery (“Regenerative Braking Systems” 2018). This process can be compared to a bicycle light generator, which transforms the kinetic energy received from the wheels into electricity, used to power the light. Also, the resistance of the generator, created in the process of regenerative breaking, causes the vehicle to slow down, as the kinetic energy is converted into chemical energy or electricity.
To boost their fuel economy, augment their power and reduce costs in HEVs a variety of powertrain configurations have been developed. The most commonly represented powertrain configurations are series, parallel and series-parallel. In a series HEV, also referred to as extended range electric vehicle, the power propelling the vehicle is solely generated in the electric motor.

SERIES HEV

As mentioned above, HEVs cannot accept an external charge from the electric power grid for their battery. It must either be recharged by the ICE and a generator or by regenerative braking. The recharging process is activated whenever the state of charge (SOC) of the battery is low. The SOC is measured in point percentage. For the propulsion of the vehicle to originate from the electric motor, the electric motor is mechanically attached to the transmission and the wheels. The ICE, on the other hand, is not connected to the wheels and mechanically decoupled from the transmission (Yong et al. 2015, 4). Figure 2.2 (Ehsani, Gao, and Emadi 2017) shows a clear standard concept of a series HEV drivetrain.

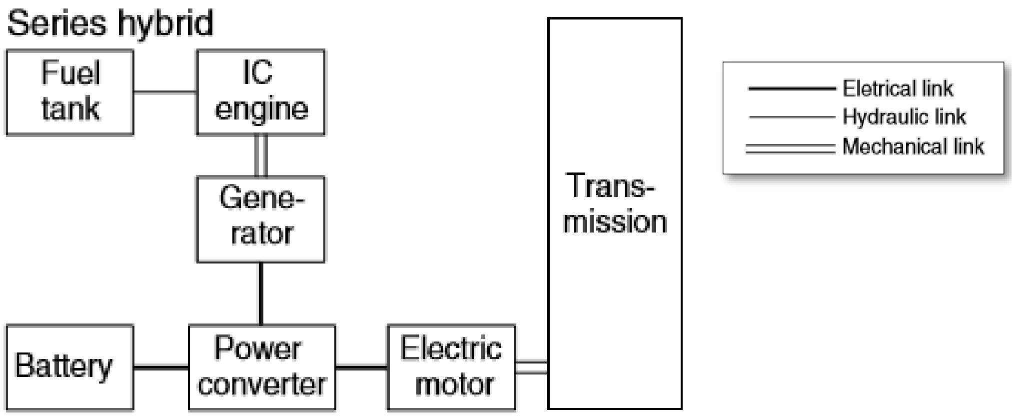


Figure 2.2: Series HEV drivetrain configuration

As seen in Figure 2.2, two power sources are feeding one powerplant – the electric motor. The electric motor is connected to the transmission and propels the vehicle. Series HEV may enter the following modes:

- Pure electric mode: the battery is the sole source of propulsion, as the engine is turned off;
- Pure engine mode: the battery does not supply not retract any power, the engine generator supplies the entire power;
- Hybrid mode: the power to propel the vehicle comes from both the engine-generator and the batteries;
- Engine traction and battery charging mode: the batteries are in a low state of charge and is recharged by the engine-generator, which simultaneously also propels the car.
- Regenerative breaking mode: the car is slowing down; the batteries are recharging, and the engine-generator is turned off;
- Battery charging mode: the electric motor is not receiving power, and the battery receives charge from the engine-generator;
- Hybrid battery charging mode: the battery is simultaneously charged by the engine-generator and by the electric motor ((Ehsani, Gao, and Emadi 2017, 122).

The series HEV is linked to several advantages. The most significant added value to series HEVs is their high suitability for urban driving. Short distances and frequent stop-and-go driving patterns can be driven with excellent fuel efficiency, given that HEVs are solely propelled by an electric engine. Compared to a simple ICEV, series HEVs are 25% more efficient (Rahman, Ehsani, and Butler 2003). Additionally, they are rather simple in design, control and theoretically easy to introduce to customers, as series HEV does not require changes in driving behaviour. Incentives for customers to choose HEVs are created by financial benefits granted by public entities. A disadvantage is the additional weight imposed on the vehicle due to the existence of two motors and the integration of a rather large battery. The battery needs to be comparatively large since the power for propulsion is mainly supplied by the battery or the electric motor. Power output in an HEV is also lower than in an ICEV simply since the ICE is smaller in the HEV. The total power output of ICE and electric motor combined is still lower than of an ICE. Given that the existence of two motors in one vehicle leads to a higher weight, car manufacturers are resorting to lighter materials for the construction of the rest of the car to prevent the burden of the weight on fuel efficiency. Poorer suspension of the body may, however, lead to more maintenance (Mi and Abul Masrur 2018). This, of course, increases the costs of ownership.

PARALLEL HEV

In a parallel HEV, both the ICE as well as the electric motor are mechanically connected to the transmission and are equally involved in turning the wheels. Due to the simultaneous supply of power by the two engines, the parallel HEV is up to 40% more efficient than a conventional ICEV (Rahman, Ehsani, and Butler 2003). Figure 2.3 shows the concept of a parallel HEV (Ehsani, Gao, and Emadi 2017).

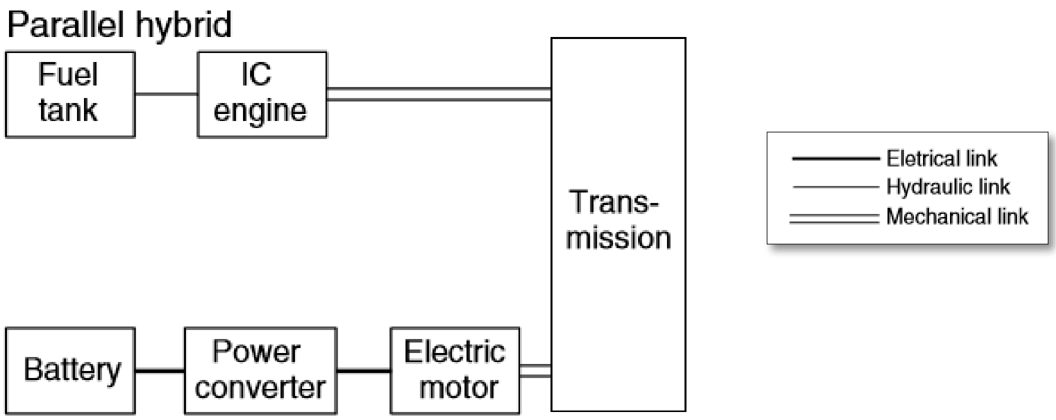


Figure 2.3: Parallel HEV power drive configuration

In a parallel HEV, the ICE is usually always in operation mode at constant power output at maximum efficiency. Once the transmission requests more power than is supplied by the ICE, the electric motor is switched on to add power to the transmission. In the reverse case, when the transmission requires less power than supplied by the ICE, the surplus energy is transferred to the battery for recharge. Regenerative braking is also practiced in parallel HEVs to charge the battery packs (Çağatay Bayindir, Gözüküçük, and Teke 2011, 4). Representative models for parallel HEVs are the Honda Insight, Ford Escape Hybrid SUV, and Lexus Hybrid SUV. This powertrain configuration is suitable to meet efficiency demands for urban mobility, stop-and-go driving pattern, as well as for highway mobility, smooth and long-distance driving pattern. The two engines complement one another and take each the lead in the respective traveling mode to maximize efficiency.

SERIES-PARALLEL HEV

Finally, the series-parallel HEV constitutes a combination of the series HEV and the parallel HEV. Figure 2.4 shows the basic design of a series-parallel HEV (Ehsani, Gao, and Emadi 2017, 121). In the case of the series-parallel HEV, both engines are mechanically connected to wheels and transmission. However, during operation of the car, it can be individually decided which mode to use. The disadvantage of the series-parallel HEV is that is it quite complex and somewhat expensive to build. A representative example for a successfully commercially deployed series-parallel HEV would be the Toyota Prius.

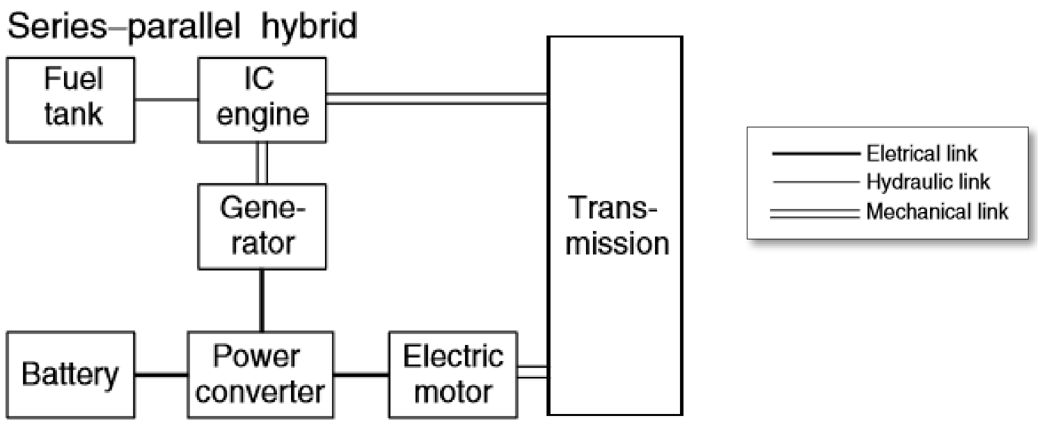


Figure 2.4: Series-parallel HEV powertrain configuration

PLUG-IN HEVS

PHEVs are comparable to HEVs in their basic construction. PHEVs are also propelled by a combination of ICE and electric motor. The most significant difference, however, is their ability to accept grid-electricity as an external energy source. Due to their ability to charge their battery with external energy and extend their driving range with the aid of onboard gasoline or diesel engine (once the battery energy has been depleted) PHEVs are also referred to as range-extended electric vehicles (ReEVs) or Range Extender. In comparison to HEVs, PHEVs do possess larger battery packs, which enables them to provide higher fuel economy during the extended driving range, as more energy generated from regenerative braking can be stored in the battery. Moreover, there is a greater scope of flexibility for engine optimization during the extended driving range (Mi and Abul Masrur 2018, 111).

Just like HEVs, plug-in hybrid electric vehicles may have series, parallel and series-parallel powertrain configurations as well. One should, however, bear in mind that PHEVs can receive external electricity from the grid. The operation of a PHEV can be just summed up by the two modes the battery can assume: charge-depletion mode and charge-sustaining mode. Most commonly, PHEVs operate in charge-depleting mode. As

long as the battery charge has not been reduced to a predefined threshold, start-up and propulsion of the car are managed by the electric motor. Upon reaching the threshold, the charge-depleting mode is switched off, and charge-sustaining mode switched on, whereby the ICE takes over to power the car until the battery has been fully recharged.
For a comprehensive overview, Figure 2.5 (Yong et al. 2015, 367) depicts all the different powertrain configurations mentioned above for HEVs and PHEVs.

POTENTIAL OF PHEV DEPLOYMENT

By the end of 2017, a total of 858,376 Plug-in electric vehicles (sum of PHEVs and BEVs) were registered in Europe. Just about more than a half of these plug-in electric vehicles were PHEVs (443,982). The front-runner in Europe is Norway, which accounts for about 18% of the total European plug-in electric fleet, though the Netherlands has the most PHEVs ("European Alternative Fuels Observatory" 2018). According to the EAFO, in 2017 alone, more than 155,000 PHEVs had been newly registered in Europe, the most substantial amount so far. The share of PHEVs is slightly higher than the one of BEVs. The advantage of the PHEVs, as already mentioned is that it allows for greater distances to be travelled due to the existence of two powering sources. PHEVs may consequently be considered as pivotal technologies facilitating a paradigm shift towards cleaner individual mobility. Knowing the average daily distance travelled by car is a relevant piece of information to estimate the advantage of PHEVs. In 2011 the European Commission commissioned the analysis of driving and parking patterns in the EU. According to the study conducted in six major EU member states, the average daily distance travelled by car ranges between 40 km (UK) and 80 km (Poland) (Pasaoglu et al. 2012, 84). This is a crucial discovery. It indicates that the most frequently covered distance can be completed by EVs (even without range extenders). The study did also hint at parking patterns and stated that almost 10% of the drivers interrogated during the survey would use private garages and parking spaces (Pasaoglu et al. 2012, 84). This implies that they would theoretically have regular and easy access to charging stations if needed.

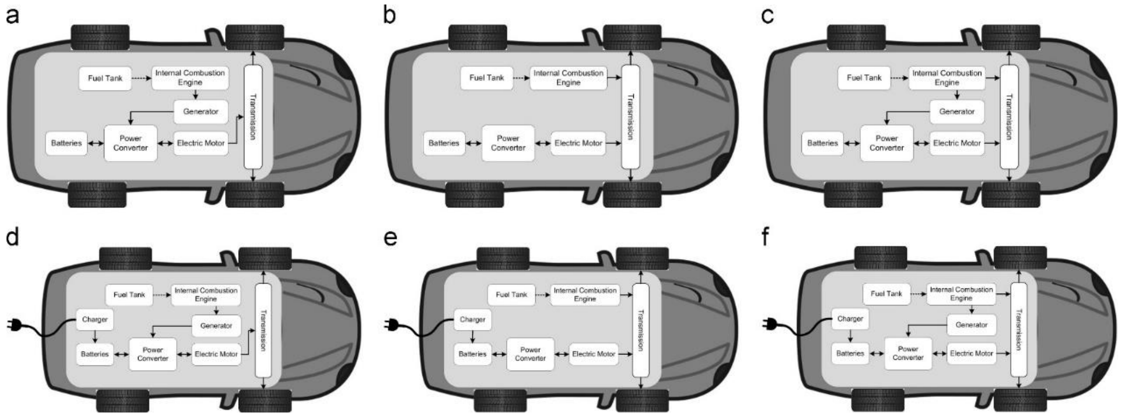


Figure 2.5: Power train configurations: a) Series HEV, b) Parallel HEV, c) Series-Parallel HEV, d) Series PHEV, e) Parallel PHEV, f) Series-Parallel PHEV

The study however only focuses on 6 out of 28 EU member states. While it might give a good indication of overall average driving distances covered daily, it might not consider regional specifications. In some regions, especially in the mountainous countryside, driving patterns are different. The construction of specific infrastructure might be tricky to implement there. However, mobility must be ensured. Thus, the role of the PHEV is by no means redundant.

Another advantage of the PHEV lies in its ability to provide a choice of fuel to the vehicle owner. The car owner can choose to fuel/charge their vehicle with electricity or with petrol/diesel. The driver is now empowered to make economies and profit from price fluctuations. Potential saving also lies in reduced maintenance costs. PHEVs, in general, require less maintenance and reparation including the replacement of brake pads of the exchange or brake fluid, as regenerative breaking is a core system of the EVs and frequently used. Additionally, fewer oil changes are necessary, given that the ICE is not operating throughout the entire drive (Mi and Abul Masrur 2018, 113).

The role of PHEVs may also become more pronounced due to transformations in the energy production industry. In an energy environment, where more and more energy is gained from renewable energy sources (mainly wind, hydro and solar power) frequency regulation and stability of the grid become increasingly critical. Against this backdrop, PHEVs might be the facilitators in a transition of the road transportation sector. In addition to allowing the use of two powering sources, PHEVs may also be regarded as mobile electricity storage units. After all, electricity is stored in the onboard battery. Even after the performance of the battery has become too weak to power the PHEV, the “retired” batteries may still find use as storage units. “Retired” batteries do often still possess a remaining energy capacity of 30% - 50% and may be given a new function in grid energy storage, facilitating voltage regulation, system stability and frequency regulation for a given power grid (Mi and Abul Masrur 2018, 114).

BATTERY ELECTRIC VEHICLE

So far, two distinct types of EV have been introduced. Both enable a gradual and non-violent transition in the road transport sector by incorporating an ICE and using fossil fuels. Consequently, their tailpipe emissions, however efficient the engines may be, cannot reach zero percent. To indeed achieve zero tailpipe emissions other alternative powertrains, need to be considered.

Among the classic EVs, it is the battery electric vehicle, that constitutes the purest form of EV and complies with the zero-tailpipe emissions target. Contrary to PHEVs and HEVs, it does not possess an ICE. BEVs are solely propelled by an electric motor. Its only source of power is the onboard electric battery, and its only source of energy is electrically charged from the grid or electricity generated by regenerative breaking (Muneer, Kolhe, and Doyle 2017).

BEVs being solely powered by an electric motor have an all-electric propulsion system and can thus only operate on charge-depleting mode (Yong et al. 2015, 4). The distance, a BEV can travel, thereby depends on the storage capacity of the battery. The immediate advantages of a BEV are its zero tailpipe emissions and their great vehicle performance. Depending on the type of battery incorporated and the construction of the vehicle, tank to wheel efficiency or instead battery to wheel efficiency in a BEV can vary between 89% and 71% (Gustafsson and Johansson 2015, 25). Compared to the tank to wheel efficiency of a common ICEV, which has been estimated at about 15% (Edwards et al. 2004, 36), the efficiency of BEVs is rather impressive. The efficiency for ICEVs varies a little according to different studies but does not exceed 22% (by much) (Muneer, Kolhe, and Doyle 2017, 3). Due to their still limited drive-range, low to zero direct emissions and insignificant noise pollution, BEVs are ideal for urban traffic use. The lack of noise, created by BEVs during operation, while of a significant advantage, can, however, also be a cause for accidents in urban areas. People would need to accommodate themselves to this. To circumvent accidents in low-speed zones, a compulsory *“Acoustic Vehicle Alert System”* will be introduced in every newly registered EV from summer 2019. The system sensors recognize their surroundings and make a reasonably loud noise to warn pedestrians (European Commission 2015)

BATTERIES

When it comes to EVs, and especially to BEVs, batteries are far from being a negligible component to the powertrain and do thus deserve quite some attention. It is the critical element that determines the efficiency, the driving range and the energy storage potential of the vehicle. In other words, it does not only define the car but sets the condition under which the future potential of EVs will be judged. Technologies behind the batteries have primarily developed ever since the invention of the electric motor in the late 19th century and are critical for the grand deployment of EVs. Figure 2.6 gives an overview of the most commonly used battery-technologies in a chronologic relation (Catenacci et al. 2013, 3).

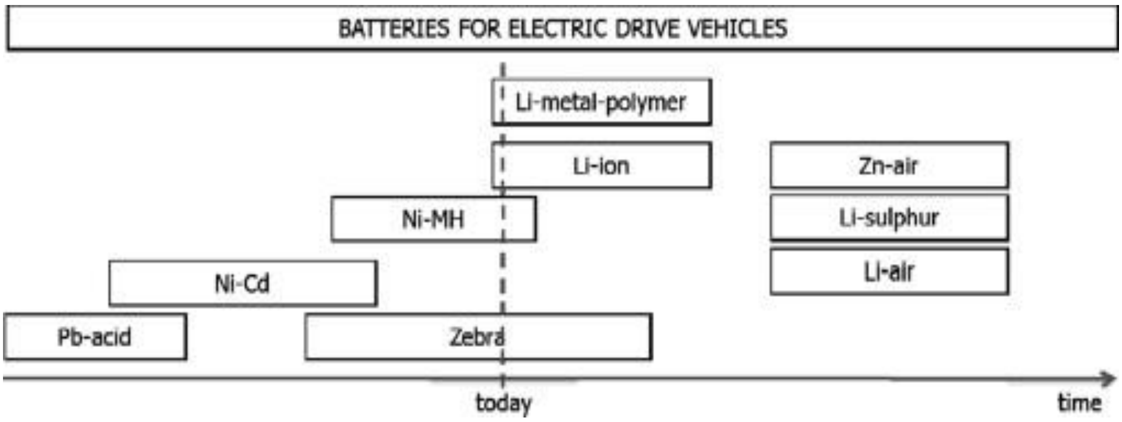


Figure 2.6: Development Timeline of Batteries for EVs

As depicted above in Figure 2.6, a variety of battery-technologies have been explored. The battery technologies currently favoured displaying a comparatively low energy density, which has a direct impact on the maximum all-electric drive range of an EV (Yong et al. 2015, 4). The ideal battery would combine high energy density, high power density, durability, preferably lighter in weight, a high degree of safety and low production costs. In this section, three battery-technologies will be briefly discussed.

Lead Acid Battery

The first battery technology employed in transportation was the lead-acid battery, where lead electrodes in acid were used to generate the electricity. While this type of battery is inexpensive in production, provides high power and is easily recyclable, it has a lower energy density than other technologies, is heavy in weight, requires regular inspection of the electrolyte level and has adverse effects on the environment (Muneer, Kolhe, and

Doyle 2017, 142–43). Therefore lead-acid batteries would be replaced by nickel-based batteries, which have a higher energy density.

Nickel-based Battery

Nickel-based batteries would mainly be employed in commercial EVs. However, they have poor charge and discharge efficiency, high self-discharge rates, a memory effect and low performance in cooler climates (Yong et al. 2015, 5). The memory effect is one of the significant drawbacks, primarily when the battery is intended to be used in an EV. In an urban driving environment with a pronounced stop-and-go driving pattern, high charge and discharge efficiency are of the essence. Additionally, nickel-based batteries suffer from high self-discharge rates (up to 10% per month), even when not in use, which makes them not ideal for EV-use. They also require long recharging times (Muneer, Kolhe, and Doyle 2017, 143).

Lithium-based Battery

A breakthrough in battery technology could be achieved by the development of the lithium-based batteries. Especially lithium-ion (Li-ion) batteries constitute a promising technology that could give BEVs the necessary nudge to conquer the automotive market. Lithium-based batteries have a high energy density, high power density, are light in weight, inexpensive to produce, are not made of toxic components and can accept fast recharge. They can be found in millions of light-weight mobile devices, including mobile phones, laptops and hearing aids (Muneer, Kolhe, and Doyle 2017, 143).

As previously stated, the ideal battery should combine high energy density, high power density, durability, a high degree of safety, low production costs and should be light in weight.

The search for the ideal battery does however not end with the Li-ion batteries. Lithium-Sulphur (Li-S), zinc-air (Zn-air) and lithium-air (Li-air) are battery technologies that are currently undergoing their experimental phase. The Li-S battery benefits from a relatively high energy density, compared to other lithium-based technologies and is relatively inexpensive in production due to the low commodity prices of sulphur, although they are showing a tendency to rise. Sulphur is a by-product of oil and gas production and used as a fertilizer (Nath et al. 2018). The increased demand for sulphur for battery production and decreased supply of it, should oil and gas production (as CO_2 emitters) be lowered then prices would soar. This would affect the price of batteries significantly and perhaps the sales of BEVs. The high discharge rate and the short life cycle of Li-S batteries make them, however, somewhat inadequate for the implementation in EVs (Kolosnitsyn and Karaseva 2008).

In contrast, Zinc-air batteries have the advantage of possessing an even higher energy density than lithium-based batteries. Nevertheless, their development is not yet mature enough due to a low power density and a short life cycle (Yong et al. 2015, 5).
Finally, the lithium-air battery, despite its initial development stage has the potential to reach an energy density of more than 1700 Wh/kg and would thus be capable of competing with an ICEV. The development of the Li-air battery is currently pushed, to enhance the all-electric drive range of an electric vehicle (Yong et al. 2015).
The issue on batteries would require a more extensive analysis that exceeds the scope of this thesis. By showcasing the case of Li-S batteries, the interconnectivity of a transition in the automotive industry was attempted to be shown. A change in resources will inevitably affect other sectors. Each battery type requires different raw materials. Cobalt, for instance, is an essential element in lithium-based batteries. Cobalt is a critical commodity: not due to its properties but due to where it can be found. About half of the worlds cobalt's resources are in conflict-stricken Democratic Republic of Congo (DRC) (Sanderson 2018). Against this backdrop, R&D may also have the responsibility to limit the creation of new dependencies. The extraction costs of the respective raw materials, geopolitical repercussions and recycling rates would all need to be analysed in an extensive study, which is not part of this thesis.
Annex II shows a selection of battery technologies and their respective voltage, energy density, life cycle and other similar parameters. (Yong et al. 2015).

INFRASTRUCTURE

This chapter has thus far concentrated on the several types of EVs available on the market and on the types of batteries along with their strengths and weaknesses. While the components directly related to the EV are of enormous importance, the related infrastructure should be considered of equal significance. The inexistence of a sufficiently secure and efficient infrastructure might constitute the barrier for the broader uptake of EVs, especially BEVs. In brief, infrastructure consists of the following components: charging infrastructure including payment systems, grid infrastructure, electricity production, public financial incentives and "smart city" facilities. The individual components will be briefly discussed in this section and in a following chapter.

Charging infrastructure

Reliable charging infrastructure is relevant for PHEVs and BEVs since both accept an external charge from the power grid for their batteries. The purpose of the charges is not only to recharge but is also acting as a facilitator, transforming the electricity from alternating current (AC) form the power grid into suitable direct current (DC) power level, for charging the battery. Therefore, EV chargers are built as AC/DC converter or rectifier. Fast charging stations have an extra DC/DC converter, that is added for even better conversion of energy (Yong et al. 2015, 370).

The broad deployment of charging infrastructure also requires harmonization of standards. Charging standards for EVs have, however, up until now not been harmonized on a global level. In general, electricity consumption is not harmonized – when traveling overseas, an adapter is often needed to charge electric devices. Attempts to introduce equal standard have been made on a regional level ("SAE International" 2018; "International Electrotechnical Commission" 2018; "Chademo Association" 2018). Plugs do also vary in their construction. The most established plug-types are the type 2-pin, the CCS-Standard, and the Chademo-Standard. Figure 2.7 (ÖAMTC 2018a) shows the differences in appearance. Type 2-pins are commonly found with private "Wall-boxes," used for charging in the private garage at home. Through a type 2-pin, it is possible to dispense up to 43kW via a public type 2 charging station.

Figure 2.7: Plug systems for EVs: 1) Type 2-pin, 2) CCS-Standard, 3) Chademo-Standard

Some EVs cannot be efficiently charged via a type 2-pin (instead of up to 43kW, only 7,2kW can be used). Therefore, a special fast-charge connector is installed for this type of car. In Europe, the CCS-Standard (Combined Charging System) could establish itself, enabling a charging power of up to 170kW. Among the Japanese E-cars, it is the Chademo-Standard that prevails, allowing for a charging power of up to 62,5 kW ("Chademo Association" 2018).

Energy source	GASOLINE/DIESEL	HYDROGEN	BATTERY		
	Fueling gasoline or diesel at a petrol station	Fueling hydrogen at a hydrogen refueling station	"Wired" charging using a plug	Battery swapping	Induction charging
Description	Conventional gasoline or diesel refueling	Hydrogen refueling (similar to natural gas refueling)	Plugging in to a charging station using a cable and plug	Replacing a battery for a fully charged one at a special swapping station	Battery in the car is charged by wireless induction charging
Time needed[1]	5 min	5 min	4-8 hrs (slow) 20-30 min (fast)	5 min	~2-8 hrs[2]
Suitable for which power-trains	▪ ICE ▪ HEV ▪ PHEV ▪ REEV (gasoline)	▪ FCEV ▪ REEV (hydrogen)	▪ PHEV ▪ BEV suitable for plug-in charging	▪ Special BEVs suitable for battery swapping	▪ Special BEVs suitable for induction charging
Example car	▪ All ICEs	▪ Hyundai ix35 (FCEV)	▪ Renault Zoe (BEV)	▪ Special model of Renault Fluence	▪ N/A (few pilot cars)
Current availability in Europe	Widely available: ~131,000 stations	Very limited: ~80 stations	Limited availability: >20,000 (slow) >1,000 (fast)	Very limited ~50 stations	Not available (few pilots in progress)

1 Time need for full refueling or recharge. For fast-charging of battery, time to reach 80% of battery capacity is commonly used
2 Since induction charging is still in pilot stage, common duration and power level are not yet established; power levels of 22 kW have been achieved
SOURCE: Europia, Fuel Cell Today, Public sources, McKinsey

Figure 2.8: Charging Infrastructure Archetypes

Figure 2.8 (McKinsey 2014, 29) gives a comprehensive overview of charging/fuelling models, which are plenty-fold and vary from conventional fuelling to innovative induction charging. Another method not mentioned are photovoltaic (PV) panels installed on the roof of an EV. Toyota is currently testing this technique with its Prius PHEV model ("Toyota Global Site | Solar Panel Charging System[PHV]" 2017). The solar roof charges the batteries when the car is parked and can increase efficiency by almost 10% (Muneer, Kolhe, and Doyle 2017, 142). There is, however, much more to the charging infrastructure than new or innovative "fuelling" stations. Adaptations to the grid infrastructure are of even more significant interest.

Grid infrastructure

EVs represent additional loads to the power grid. It is true that even under a 20% EV scenario current power grids in Europe could theoretically cope with the additional demand. Numerous studies have been conducted on that issue. One study (Hartmann and Özdemir 2011) investigated the effect of EVs on the future German load profile in 2030 and discovered that "uncontrolled charging of one million of EVs has a slight impact on the daily peak load, where the peak load increases only by 1.5%. However, if all the conventional ICEVs in Germany (around 42 million units) are replaced by EVs, then the

EV charging will increase the peak load by approximately two times. The study also shows that a maximum peak load reduction of 16% can be achieved with the use of one million EVs as grid stabilizing storages" (Yong et al. 2015, 373). The challenge to overcome is less the net increased demand for electricity, but rather the likely rise in peak demand (McKinsey 2014, 41). Peak demand is not only dependent on the time span but also on location. Measured in household electricity demand, the possession of an EV would double the household electricity demand per year. This may sound exorbitantly high on a household level, though on a broader scale including total electricity demand this does not have enormous repercussions. According to the McKinsey Report, the volume is not the issue. Disproportional peaks, however, may impact the stability of the grid. Fast charging, therefore has a destabilizing effect on the grid if done excessively.

On the other hand, EVs, especially PEVs are also presenting a solution model to a transforming electricity environment. The share of renewables in the total energy mix is to rise significantly. In the EU the target has been set of overall 20% renewables by 2020 in the European energy mix (European Parliament and European Council 2009). By the end of 2016, this share was at 17% (Eurostat 2018). More renewables in the energy mix mean more volatility in the energy supply. The overall amount of energy generated from renewables may be sufficient, but irregular input waves exert stress on the grid. Moreover, apparently decentralized energy production (i.e., PV cells on household roofs) when not entirely consumed requires the grid to ingest the surplus, which it might not be able to do. In Germany or Belgium, to name a few, wind turbines had to occasionally be switched off as the supply exceeded the demand by large (McKinsey 2014, 42). It is detrimental that load requirements for grids are anticipated. Failure to do so could require upgrades to the grid which is extremely cost intensive.

EVs, especially PEVs, could offer relief to some extent. They are to some extent mobile storage units.

With the aid of smart metering technologies, PEVs could accommodate the (surplus) electricity and if needed transfer back into the grid. 'Vehicle to Grid' (V2G) (Mahmoudzadeh Andwari et al. 2017, 422) technology entails the absorption of peak supply energy and the sending back of power into the grid at peak demand periods. V2G constitutes a still underdeveloped technology which requires top smart metering technology and attractive payment systems. These payment systems must be safe, easy to use, reliable and provide an incentive to customers. The combination of blockchain technology and the introduction of an "electricity currency" could be a strategy that deserves some investigation. The basic idea would be that this "electricity currency" becomes a currency that electricity consumers wish to possess and exchange. This could be achieved by creating a financial system in which the currency remains stable vis-à-vis its electricity exchange rate but underlies the regular rules of derivatives when exchanged into fiat money. The assurance that the value of the "electricity currency" would always be stable vis-à-vis the purchase of electricity makes it an attractive currency. When exchanged for conventional fiat money it could be a source of investment. This concept assumes that the level of electricity consumption is an indicator for economic development and means of economic growth. The further exploration of this concept does, however, exceed the scope of the thesis.

In summation, a variety of EVs are presently available on the market. HEVs, while more efficient than ICEVs urban driving can never comply with zero-tailpipe emission targets. PHEVs on the other hand could be a transition technology, englobing the best of both, traditional and innovative technologies. Long distances can easily be covered. Even retired batteries from PHEVs could be used as electricity storage modules for electrical grids. Yet, PHEVs are not totally revolutionary technologies. They have been available on the market for quite some time without ever truly challenging the ICEV. Modern HEVs have been available on the market since the release of the Toyota Prius in 1997 (Lake 2001). Yet, ICEVs are still very popular. The re-ignition of the public debate on the electrification of passenger vehicles is to a considerable extent attributable to the launch of attractive premium BEVs. BEVs introduce a completely alternative powertrain concept to the ICE. The advantages are obvious: zero tailpipe emissions, low noise emissions and high tank-to-wheel efficiency. The lack in infrastructure and high purchasing costs of BEVs do, however, constitute important barriers, in addition to a lack in standardization. Table 2.1 gives a comprehensive overview of popular EVs, including HEVs, PHEVs and BEVs. It compares the maximum driving ranges, as indicated by the manufacturer and their prices while also showcasing the prices of comparable ICE-models. Uncertainties in battery technology could also be a reason for hesitant EV production, despite the gradual release of more EV-models by leading car manufacturers.

EVs could support the transformation that the energy sector is currently undergoing and provide a means of storage. On the other hand, in the absence of a higher level of renewables in the energy mix, EVs may impose an even greater burden on the environment than ICEVs (Yong et al. 2015, 373).

Table 2.1 Comparative Overview of EV models (sourced from manufacturer web-sites)

Model	Type of EV	Fuel Type	Battery	Weight (Kgs)	Driving Range	Price Euro	Price of ICE Model
BMW i3 Range Extender	PHEV	Gasoline	Lithium-ion	1466	225-235 Km/s	47,000	37,800 (BMW 1 Series)
Toyota Prius	HEV	Gasoline	Nickel-metal Hydride	1790	3.0l/100 Km/s	29,990	26,990 (Toyota Avensis)
Hyundai Ioniq	PHEV	Gasoline	Lithium-ion	1505	4.5l/100 Km/s	23,990	24,490 (Hyundai i40)
Volvo XC60 Twin Engine	PHEV	Gasoline	Lithium-ion	2139	2.1l/100 Km/s	64,000	57,540 (Diesel)
Volkswagen e-Golf	BEV		Lithium-ion	2020	250-300km per charge	39,390	36,900 (Golf GTE)
Tesla Model 3	BEV		Lithium-ion	1610	354km per charge	35,000	27,740 (Audi A3)
Nissan Leaf	BEV		Lithium-ion	1035	389 per charge	35,600	26,900 (Nissan Pulsar)
Mercedes GLC F-Cell	FCEV	Hydrogen	Fuel-Cell	N. A	100kmper Kg	55,000	45,960 (Diesel)
Hyundai Tucson ix35	FCEV	Hydrogen	Fuel-Cell	1464	105km per Kg	40,000	40,290 (Diesel)

CHAPTER 3
Fuel Cell Electric Vehicles

" …water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable. …Water will be the coal of our future…" (Jules Verne 1870)

As elaborated in the previous section, automobile manufacturers have developed a host of electric powertrains with the general aim to find a competitive alternative to ICE vehicles and consequently to fossil fuels. While the alternative powertrain market is currently indeed dominated by HEVs, PHEVs, and BEVs due to their high level in development, it is essential to remain aware of other alternatives and their potential to encourage a transition towards a zero-emissions transportation system. The most prominent examples of alternative fuels, besides electricity, are hydrogen and biofuels. Their role might be underestimated in some cases, given specific areas in the transportation sector are very difficult to electrify, such as aviation, heavy duty fright, and shipping. The Energy Transition Commission Report suggests that there lies true potential in hydrogen and biofuel to push for decarbonization in defined transportation sectors (Energy Transitions Commission 2017, 16).

HYDROGEN FUEL CELL TECHNOLOGY

In this thesis, a clear distinction has been made of what is considered an Electric Vehicle (EV). In this thesis, EVs consist of HEVs, PHEVs, and BEVs. In some literature, fuel cell vehicles are also referred to as part of EVs. This thesis, however, takes fuel cell vehicles (FCVs) as a separate technology to avoid confusion. The reason for doing so lies in the fact that FCVs in general do not accept electricity as external fuel but use hydrogen as the external powering source. However, given their internal propulsion system fuel cell technology incorporating vehicles are hereof referred to as Fuel-cell Electric Vehicle (FCEV).

A fuel cell is characterized by its ability to directly produce electricity from a given fuel via an electrochemical process (Winter and Brodd 2004, 4259). The process is in theory like the one happening in a chemical battery, except that the reactants are not included in the fuel cell, unlike in a battery. Therefore, the power output of a fuel cell does hardly depend on its own design but rather on the availability of fuel and oxidant supply. Consequently, the performance of fuel cells is measured in power output (kW) and not by their capacity (kWh).

The first fuel cells have been the subject of research already in 1838 when William Grove took Faraday's law of Electrolysis; he created the 'gas battery' by combining electrodes in a series circuit (Ortiz-Rivera, Reyes-Hernandez, and Febo 2007).

Fuel cells have been occupying research activities as they could provide a viable and perhaps more efficient alternative source of electricity generation that meets the requirement of not depending on oil and not creating atmospheric pollutants. Therefore, fuel cells are amongst the clean energy producers. A fuel cell is an electrochemical cell, consisting of an anode and a cathode which are linked through the electrolyte – the basic construction of an electrochemical cell. Fuel cells require the continuous entering of reactants into the cell to generate the energy. In other words, an electrical current is only produced as long as fuel is available, hydrogen for example. Just as it has been seen for the case of batteries, there are also a variety of fuel cell types. Fuel cells may be primarily classified by the type of electrolyte used. Amongst the fuel cell types in operation, there are molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), phosphoric acid fuel cells (PAFC), direct methanol fuel cells (DMFC) and low and high temperature polymer electrolyte membrane (PEM) fuel cells (Curtin and Gangi 2016, 2).

In the automotive industry, a type of hydrogen-oxygen fuel cell has been experimented with. The hydrogen cell functions as follows: as gas is entering the fuel cell, it interacts with a platinum catalyst that is placed in a plastic membrane (Timberlake and Timberlake 2013). The purpose of the catalyst is to facilitate the oxidation of hydrogen atoms into hydrogen ions and electrons. Via the connecting wire, the electrons flow from the anode to the cathode, thereby creating an electronic current. The hydrogen ions travel to the cathode through the plastic membrane. There, at the cathode, the oxygen molecules undergo a reduction process. They are reduced to O^{2-} that mix with the hydrogen ions forming regular water.

The reaction process in a fuel cell can be described by the following reactions (Timberlake and Timberlake 2013):

$$2H_2 \rightarrow 4H^+ + 4e^- \quad (3.1)$$

3.1 expresses the process at which hydrogen is oxidized at the anode (positive pole) of an acid fuel cell and thereby "releasing" electrons as well as creating H^+ ions. During this process, there is also heat that is released. While (3.1) is describing the process at the anode, (3.2) describes the process at the cathode (negative pole).

$$O_2 + 4e^- \rightarrow 2O^{2-}$$
$$2O^{2-} + 4H^+ \rightarrow 2H_2O \qquad (3.2)$$

At the cathode, water is formed. Oxygen is reduced to form $2O^{2-}$-ions, which subsequently react with the H^+-ions generated at the anode, to form water. (Dicks and Rand 2018, 7). Consequently, the overall reaction equation of a hydrogen-oxygen fuel cell looks as followed (3.3):

$$2H_2\,(g) + O_2\,(g) \longrightarrow 2H_2O\,(l) + \text{heat} \qquad (3.3)$$

The overall reaction is the same for any fuel cell system, irrespective of the electrolyte used. The individual reactions at the cathode and anode do, however, differ. The reaction processes described in (3.1) and (3.2) apply to the so-called proton-exchange membrane fuel cells (PEMFC). This system had been used in the Gemini space missions.
Fuel cells with an alkaline electrolyte (AFC), used in the Apollo Space Project, undergo the below indicated reactions at each electrode.

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \qquad (3.4)$$

At the anode, hydroxyl (OH^-) ions, that are available and mobile in alkaline solutions, react with hydrogen. This reaction leads to the release of electrons and energy in the form of heat as well as the formation of water (3.4).
At the cathode, new (OH^-) ions are formed together with water as a result of oxygen reacting with the electrons taken from the anode (3.5) (Dicks and Rand 2018, 8).

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^- \qquad (3.5)$$

The products of reactions within the fuel cells are electricity, heat, and water. In contrast to internal combustion engine technologies, fuel cells are up to three times more efficient in translating the chemical energy of the fuel into mechanical energy for propulsion (Curtin and Gangi 2016, 2). Just like battery electric technology, fuel cell technology has the potential of being a 100% clean technology, provided that the production of hydrogen is done by non-polluting sources.

Fuel cells are an efficient and durable technology that has proven beneficial for the power generation on a space shuttle. Already for the Gemini missions (1965 – 1966) and the Apollo Project (1961 – 1972) fuel cells, using hydrogen and oxygen as powering fuels, were incorporated. The fuel cell modules used in the Gemini missions could each reach a maximum power of approximately 1kW. The fuel cell systems (AFCs) designed for the Apollo Program were capable of continuously supplying up to 1,5 kW of power. Later fuel cell technologies developed for the Space Shuttle orbiter could even provide 12 kW of power while also weighing less. While the Space Shuttle was still in-flight mode, the fuel cell system did supply the entire electricity demand and parallelly created the entire drinking water required (Dicks and Rand 2018, 6–7). The successful application of fuel cell technology in the space sector encouraged further research of fuel cell systems for terrestrial usage as a more efficient and emission-free energy production alternative. The oil crisis of 1974 was additional stimulus for research and development to further investigate the deployment of fuel cell technology for large-scale commercial use.

Individual fuel cells do usually function on a low voltage (typically below 1V). To increase the voltage required for a specific application, it is therefore customary to electrically connect individual fuel cells to one another in series. The connected fuel cells form a ‘stack’ (Dicks and Rand 2018, 11). A variety of designs of fuel cells have been developed. However, they do all share at least five common traits:

Electrolyte

Firstly, all fuel cells contain an electrolyte medium, that is needed to conduct the ions. The electrolyte medium may come in the form of a porous solid containing a liquid electrolyte (acid, alkali, fused salt) or in the form of a solid membrane, which could be a ceramic or a polymer. The properties of the membrane must meet the requirement of being an excellent ionic conductor in addition to being an electronic insulator and must remain chemically stable under strong reducing and robust oxidizing conditions.

Anode

Secondly, all fuel cells possess an anode (a positive fuel electrode), that contains an electro catalyst, ‘which is dispersed on an electronically conducting material. The electrode is fabricated so that the electro catalyst, the electrolyte, and the fuel come into simultaneous contact at a three-phase boundary (Dicks and Rand 2018, 11).

Cathode

Thirdly, all fuel cells do also possess a negative fuel electrode (cathode), which has a triple-point electro catalyst as well. There, the incoming oxygen is taking up electrons from the external circuit and is consequently being reduced.

Electrical Connector

Fourthly, all fuel cells in a stack are linked with one another via an electrical connector.

Seals

Finally, for all fuel cells, the different gases (hydrogen and oxygen) are carefully kept apart from one another. The seals that prevent the gases from mixing do also disable 'cell-to-cell seepage of liquid electrolyte' (Dicks and Rand 2018, 11). In the absence of such seals, short-circuits would occur.

Application in Automotive Sector

Now that the basic functioning of a fuel cell has been explained, it is of the essence to identify the variables that are fundamental in evaluating the potential of fuel cell technology deployment in the transportation sector, in the automotive industry specifically. Material and manufacturing costs are critical. Moreover, the speed of the reaction rates, especially the oxygen reduction rate, is an important technical aspect to consider, as they determine the level of power and current. Slow reaction rates lead to a low level of power and current. Furthermore, the development status of efficient hydrogen production as an indispensable complementary technology is a primary issue. In this respect, it is deemed fit to mention that while hydrogen is the most popular type of fuel for fuel cell powered, there do also exist alternatives to hydrogen. These alternatives include methanol and carbon, which are used as fuel in the fuel cell technologies such as the direct methanol fuel cell (DMFC) or the direct carbon fuel cell (DCFC) respectively.

With the intent to solve the technical issues concerning the speed of the reaction rates and the production of hydrogen, different types of fuel cells have been tested. The main differences between the various fuel cell technologies are the type of electrolyte incorporated as well as the operating temperature.

Just as the batteries, used in BEVs, fuel cells may also be categorized according to specific criteria such as temperature ranges; fuel type, etc. as shown in Table 3.1. The Proton Exchange Membrane FC (PEMFC) has so far proven to be the commercially most successful fuel cell technology for vehicles and general transport application:

Table 3.1: Categories of fuel cell technologies *(Dicks and Rand 2018, 17)*

	Fuel cell type	Mobile ion	Operating temperature (°C)	Fuel	Applications & comments
Low temperature (50 - 150°C)	Alkaline electrolyte (AFC)	OH^-	50 - 200	Pure H_2	Space vehicles (e.g. Apollo, Shuttle)
	Proton-exchange membrane (PEMFC)	H^+	30 - 100	Pure H_2	Vehicles and mobile applications and for lower power CHP* systems
	Direct methanol (DMFC)	H^+	20 - 90	Methanol	Portable electronic systems of low power, running for long times
	other liquid fuel cells				
Medium temperature (~ 200 °C)	Phosphoric acid (PAFC)	H^+	~ 220	H_2, (low S, low CO, tolerant to CO_2)	Large numbers of 200-kW CHP systems in use
High temperature (600 - 1000 °C)	Molten carbonate (MCFC)	CO_3^{2-}	~ 650	H_2, various hydrocarbon fuels (no S)	Medium- to large-scale CHP systems, up to MW capacity
	Solid oxide (SOFC)	O^{2-}	500 - 1000	Impure H_2, variety of hydrocarbon fuels	All sizes of CHP systems, 2kW to multi MW

*CHP = Combined heat and power

The different technologies listed above (Table 3.1) shows the broad range of applicability of fuel cell technology. The motorized interior of the car may generally be depicted the following way:

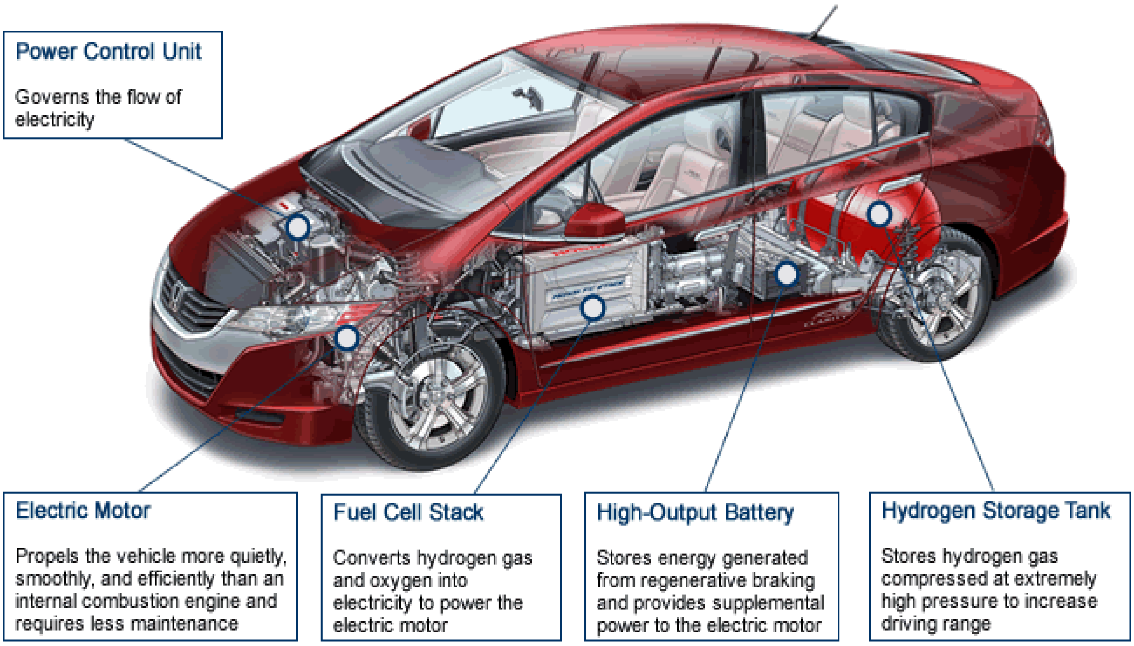


Figure 3.1: Basic model of a fuel cell vehicle

In the automotive industry, the proton exchange membrane fuel cell (PEMFC) is the FC-technology usually used. As indicated in Table 3.1 it is a low-temperature, hydrogen-fuelled cell with a platinum catalyst. The advantage of a PEMFC is its capacity to vary the electrical output, which is an important ability for the vehicle use. Other FC-technologies only allow for constant electrical output. Figure 3.1 (U.S. Department of Energy 2018) shows the different relevant components of an FC-vehicle. The FC-stacks are the most critical part and convert the onboard fuel into electricity. The most commonly used fuel is hydrogen gas, which is compressed and stored in an onboard tank. Hydrogen gas and oxygen, coming from the air, react in the FC-stack and generate electricity that propels the electric motor of the car. Due to the existence of an electric motor, FC-vehicles are sometimes also categorized as an electric vehicle. FC-vehicles do also possess a battery. This traction-battery is charged by the onboard generation of electricity as well as through regenerative breaking. In a way, it could be said that an FC-vehicle is a hybrid electric vehicle that uses fuel cell technology as a range extender (Dicks and Rand 2018).

Hydrogen Production

The unique selling point of hydrogen is its exceptionally high energy density by mass. Its energy density by mass is significantly higher than that of conventional fuels or of batteries. The volumetric energy density of hydrogen, on the other hand, is much lower compared to conventional fuels or batteries. For this reason, hydrogen must be compressed to either 350 bar or even 700 bar, which is mostly the case, to be used in cars (Hua et al. 2011).

Electrolysis

Hydrogen does not occur naturally by itself. It must, therefore, be actively extracted from compounds and molecules containing hydrogen to receive it in its pure form. The electrolysis of water constitutes a long-established technique to produce pure hydrogen. This technique involves the splitting of water into its components by using electricity. Electrolysis is considered to be especially suitable for the small-scale production of hydrogen, often directly employed at refuelling stations.

Steam Reforming

On an industrial level, hydrogen production is predominantly conducted by the steam reforming of methane. Here the conversion efficiency may reach up to 80%. While hydrolysis may be conducted without producing any CO_2 provided that renewable energy sources had been used for the electricity production, steam reforming may be decarbonized by resorting biogas as a feed (Bailera et al. 2017). Moreover, the gasification of biomass and waste constitutes another technology that is more and more frequently practiced at industrial scale.

INFRASTRUCTURE

FC-vehicles, along with BEVs constitute disruptive innovations. The term *disruptive innovation* was initially coined by the US economist Clayton Christensen. He defines disruptive innovation as “a product or service that displaces an incumbent product or service” (Christensen, Raynor, and McDonald 2015). Another definition could be that proposed by Erwin Danneels, who described it as “A Technology that changes the bases of competition, changing the performance metrics along which firms compete”(Danneels 2004, 294). The successful commercial deployment of such a disruptive innovation requires the existence of a so-called ‘relative advantage’(Rogers 2003). This means that the adoption of modern technology must be perceived to be of a more significant advantage than the continuous use of the older technology.

The ‘relative advantage’ of FC-vehicles is undoubtedly the fact that they have zero tailpipe emissions, are operating much more quietly than ICEVs, can cover long distances and do not require, in theory, a change in driving and re-fuelling behaviour. However, while the process of refuelling FCEVs remains similar to ICEVs; there remain significant barriers to mass deployment of FCEVs such as the lack of fuelling infrastructure for

FCEVs; inadequate hydrogen fuel production levels and competition with other alternative powertrain systems.

Charging Infrastructure

According to the European Alternative Fuels Observatory there currently only 82 operational hydrogen fuelling stations in Europe (EAFO 2018).

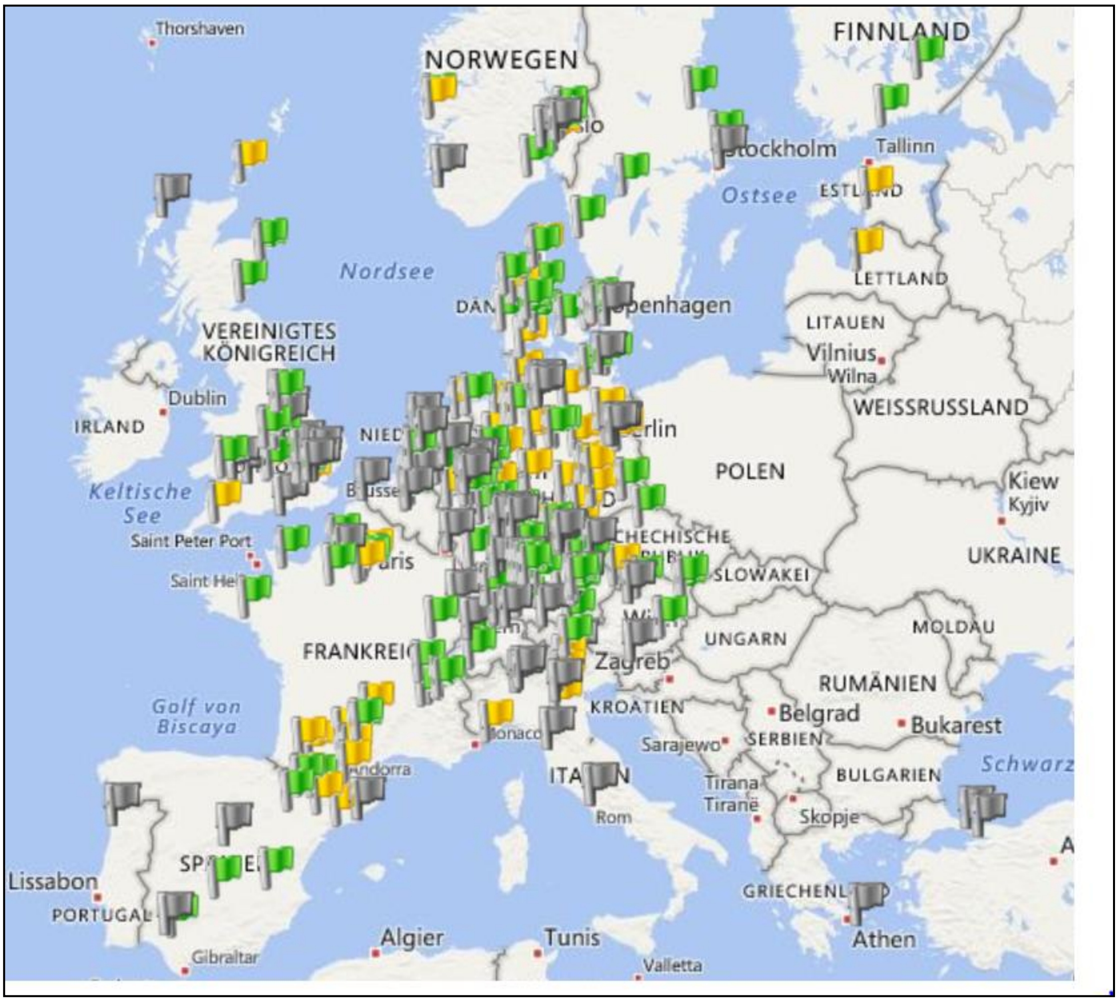


Figure 3.2: Hydrogen Fuel Stations in Europe
Green: in operation, yellow: planned, grey: old projects
Source: H2-Staions.org

This amount of fuelling stations is far from being sufficient to promote FCEVs deployment. In this respect, it is a “Chicken or Egg” problem. Too little infrastructure hampers a mass deployment of FCEVs and a conservative release of FCEVs leads to the slow growth of hydrogen fuelling stations respectively.

To overcome this conundrum and to spread the risk, in 2009 seven of the world’s leading automobile produces joined forces and signed a joint letter of understanding, addressing the oil and energy industries as well as public entities (Fuel Cell Today 2013a, 6). By this letter, the seven automakers, including Daimler, Ford, General Motors, Honda, Hyundai-

Kia, Renault-Nissan and Toyota, sent a signal that there was a serious intent to develop FCEV for mass commercial deployment. This signal was also to urge hydrogen produces to increase the supply of hydrogen fuelling stations. The scope of this infrastructure and vehicle deployment was primarily concerning Europe, with a particular focus on Germany (Fuel Cell Today 2013b).

Data indicate that FC-technology, especially in the transportation sector might be increasingly gaining in popularity on a global scale. There is an increase in MWs traded globally for transportation purposes. Figure 3.3 (Curtin and Gangi 2016) shows the growing trend from 2014 to 2016. This increase, is, however, primarily caused by the popularity of FC-mobility on the Asian market (Curtin and Gangi 2016, 3). In Japan, the Ministry of Environment launched a project in 2016 with the intent to deploy about 100 renewable hydrogen fuelling stations by 2019. 75% of the cost of this project would be borne by the Japanese Government provided that the FCEVs were to be 'used as official vehicles' (Curtin and Gangi 2016, 22). This may also be linked to the fact that Asian countries, especially South-Korea and Japan are the most prominent manufacturers of FCs. Figure 3.4 (Curtin and Gangi 2016) also depicts the weak growth of FC production within Europe. It is, therefore, little surprising that leading European automakers are partnering up with Asian car manufacturers to exchange know-how in the field of FC technology. An example of such a collaboration exists between BMW and Toyota, which are sharing a range of technologies and are planning on jointly developing an FC-vehicle platform by 2020 (Fuel Cell Today 2013a, 23). Another such collaboration was established between Daimler, Ford, and Renault-Nissan in 2013 (Fuel Cell Today 2013a, 23–24)

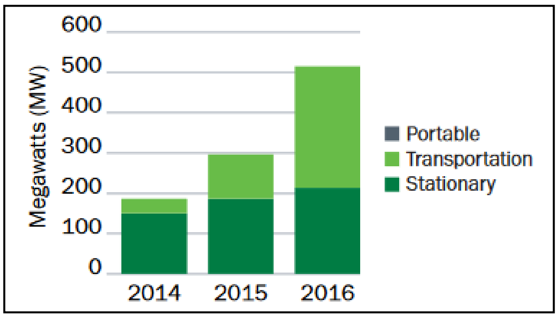


Figure 3.3: Megawatts Cells Worldwide by Application
Source: U.S. Department of Energy, Fuel Cell Technologies Office, E4 Tech

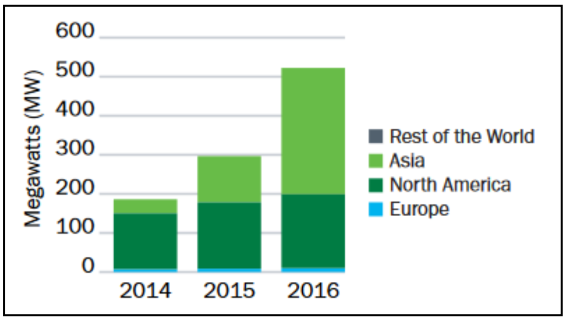


Figure 3.4: Megawatts of Fuel Cells Shipped Worldwide by Region of Manufacture
Source: U.S. Department of Energy, Fuel Cell Technologies Office, E4 Tech

Fuel Cell Electric vehicles are still rare to find on the streets of Europe. The most frequently sold models are listed in Table2.1 including their price, which is still quite high in comparison to other alternative powertrains.

The relative advantages of FCEVs are their zero tailpipe emissions, fast refuelling and low noise emissions. FCEVs are also more than twice as efficient than ICEVs. Their tank-to-wheel efficiency is estimated at 30% to 45%, compared to a tank-to-wheel efficiency of beyond 80% in BEVs (Edwards et al. 2004).

THE ROLE OF CRUDE OIL AND RENEWABLE ENERGY SOURCES

In the section above the technique of electrolysis to produce hydrogen was mentioned. It might appear odd, that fuel cell technology is still considered as a potential alternative powertrain for vehicles, given that electricity must first be generated in the first place to create the fuel to power an FCEVs, which in a second step re-converts the energy stored in the hydrogen into electricity to propel the vehicle. It is viable to address this issue. In addition, energy is lost in every of the conversion processes. First, during the process of hydrogen production, then, in the process of converting the chemical energy of the hydrogen into mechanical energy. Why are FCEVs still considered, given that BEVs are parallelly being developed and continuously improved, especially since BEVs use the electricity from the grid right away, without the need to go through an intermediary step of energy conversion? The overall efficiency would in the end only amount to 40% (Dicks and Rand 2018, 307–8).

It cannot be stressed enough that the entire automotive industry must be looked at with a holistic approach. The automobile has never been an individual product or service provider. The entire concept of it is based on numerous complementary products and services. For instance, without an extensive road-network, the car could not be as efficient as it is. Moreover, the availability of fuel and the selling price thereof have significant repercussions on the entire industry. Furthermore, the automobile industry has also become a birthplace of a host of inventions and innovations applied in other industries too, such as the sensor used in Smartphones that enables the simultaneous rotation of the screen as the phone itself is tilted.

This holistic perspective to the automotive industry becomes even more relevant as the supply of energy is changing as well as the nature of the energy sources. In an energy system that strives for increased independence from fossil-based energy sources and opts to produce energy out of renewable sources, namely solar, hydro and wind, alternative powertrains in the sphere of mobility must be evaluated parallelly to the mode-shift in energy production.

The production of hydrogen, so far, is very energy intensive. However, ambitious projects are launched to improve the efficiency. A prominent example would be the “Green Hydrogen” project launched by the project consortia H2Future, which is made of voestalpine, Siemens, VERBUND and Austrian Power Grid (APG) as well as of the scientific partners K1-MET and ECN. The undertaking entails the building of one of the largest electrolysis facility worldwide. Excess electricity generated by wind and solar power shall be transferred to the electrolysis facility, which works with an innovative proton-exchange membrane technology that can quickly adapt to the fluctuating level of energy it receives (“Voestalpine, Siemens und VERBUND Bauen Pilotanlage für grünen Wasserstoff am Standort Linz” 2017). During that process, water is split into its component, hydrogen, and oxygen. The produced hydrogen thus becomes a storage medium for future energy use. In the case of the VOEST project, the energy stored in the hydrogen would be used to power the industrial site or fed back into the grid. The concept of storing excess energy produced by renewables in the form of hydrogen is in the literature often referred to as power-to-gas (P2G) (Bailera et al. 2017).

Indeed, the project at hand constitutes a pilot project. Should it, however, prove to be efficient enough, it might be implemented on a larger scale and scope, consequently contributing to more abundant production of hydrogen. This potential increase in relatively cheap hydrogen production could nudge the development of further hydrogen fuelling stations for FCEVs. The transportation of the hydrogen from the electrolysis facility to the respective fuelling station could even be managed by existing infrastructure. Low concentrations of hydrogen can technically be mixed with natural gas and travel in the already existing natural gas pipelines (Dicks and Rand 2018, 308).

The mass deployment of FCEVs would thus encourage permanent storage of energy. This idea will be the subject of greater analysis in the concluding chapter. Finally, the statement on the success and failure of FCs made by the German Chemist and Nobel Prize laureate, Wilhelm Ostwald might become true:

“*The path which will help to solve this biggest technical problem of all, this path must be found by the electrochemistry. If we have a galvanic element which directly delivers electrical power from coal and oxygen, [...] we are facing a technical revolution that must push back one of the inventions of the steam engine. Imagine how [...] the appearance of our industrial places will change! No more smoke, no more soot, no more steam engine, even no more fire, [...] since fire will now only be needed for the few processes that cannot be accomplished electrically, and those will daily diminish. [...] Until this task shall be tackled, some time will pass by*.”(Dicks and Rand 2018, 5).

It is still quite difficult to estimate the role of fuel cell technology in the future mobility system. There are clear advantages of FCEVs over ICEVs. They showcase a larger tank-to-wheel efficiency, produce zero tailpipe emissions and operate silently. Dependence on fossil fuels is also significantly reduced, especially if the production of hydrogen is based on renewable energy sources. Fuel cells may also operate for a longer period of time than batteries. The output is to a considerable extent dependent on the amount of fuel provided rather than on the capacity of the unit itself. A very important advantage of fuel cells for the application in vehicles is the absence of a memory effect, which still constitutes a problem in battery technology. Moreover, BEVs and FCEVs both technologies have few moving parts which reduces maintenance requirements and can prolong the life of a vehicle. The FCEV can be considered a zero tailpipe-emission Range extender as it does incorporate a battery. What is interesting to note at this point is that Daimler has presented a brand-new FCEV, which is also a plug-in hybrid vehicle. The GLC F-Cell incorporates two powertrain systems. Thereby it omits the issue of long charging times and of tailpipe emissions. Hydrogen is charged when fuel is immediately needed and the Li-ion battery can be charged with electricity from the grid when prices are low and the vehicle has a long parking duration. From afar it looks like this premium car is to test both technologies and abide the institutionalization of one of the two.
Furthermore, the cause for the cautious production of FCEVs might also be related to the still high production cost of fuel cells and the agglomerated know how of it in the Asian market. Despite the significant level of uncertainties, fuel cells are likely to play a growing role in the mobility sector: if not in passenger and light duty vehicles then in hard to electrify heavy duty transportation including shipping, aviation and road freight.

CHAPTER 4
Policy Incentives & Public Trends

The scope and speed at which electric vehicles or suitable alternatives to the ICE will be adopted in Europe is a function of the following parameters: consumer demand and behaviour, technological developments and modern adaptation, and governmental incentives.

CONSUMER DEMAND & BEHAVIOUR

According to a 2013 McKinsey Report, published in collaboration with the Amsterdam Round Table, the deployment of EVs seems to be restricted with respect to geographic location as well as to income class ((McKinsey 2014). The factors that appear to be the most significant barrier to large-scale uptake of EVs are the high purchasing costs, lack of confidence in the technology that it will provide the required service and low awareness. In this study conducted by McKinsey, the profile of an early adopter firstly entails high income and secondly a high educational level which implies a tendency to seek for opportunities, where money can be saved and/or where environmental concerns can be put into practice (McKinsey 2014). According to McKinsey, the potential customers may be divided into two segments: "trendy greens" ("trendy, environmentally conscious, and willing to try new technology" and "TCO sensitives" ("care about the total cost of ownership, willing to change travel habits") (McKinsey 2014, 11). One may, therefore, conclude that purchase considerations of consumers include the possibility to reduce their carbon footprint. Environmentally conscious consumers have declared their willingness to pay a premium for zero- or low-emission alternatives to the ICE. In Norway, a prime example for EV deployment, 29% of Norwegian EV buyers have indicated environmental concerns as their core reason for their buying decision (McKinsey 2014, 11). Secondly, monetary or other benefits attributed to EV drivers by public entities such as governments or cities, with the goal to stimulate EV deployment. Incentives given by public bodies include for example 'preferential parking permits in dense urban areas' (McKinsey 2014, 11) as has been introduced in the City of Amsterdam. Depending on the current status of oil prices and consequently of fuel prices, BEVs and PHEVs might be cheaper in operation than their ICE counterparts. Coupled with government subsidies for the purchase of an EV, some consumers might be more willing to invest into EVs with a long-term saving attitude. Additionally, government benefits such as purchase tax and VAT exemptions, or reduced toll road charges and annual circulation tax may even lead to a net more favourable cost competitiveness of operation of the EV over the ICE vehicle.

This example would be true for Norway. It comes as little surprise to discover, that a study conducted in Norway, identified that among the early movers to buy an EV 41% did so to economize (McKinsey 2014, 12). There is a reliable reason to believe that this share would come out even higher if the general population was interrogated.

According to McKinsey (McKinsey 2014, 12), almost half of all passenger cars in Europe are not in possession of individuals for their own private use but are part of a larger corporate fleet, such as in car rental agencies or in government possession.

Given the benefits of EVs in urban traffic use, as discussed in previous chapters, many transportation service providers, especially taxi companies (including Uber) are increasingly opting for EVs in their fleets (Uber 2018). There is enormous potential to economize on fuel by deferring to electric powertrains, especially in a massive stop-and-go traffic environment and where driving patterns are easy to predict, as is the case in urban areas. Furthermore, a business that travels vast distances on a regular basis and operates under predictable driving patterns is the postal service. The International Post Corporation (IPC) releases statistics on the state of play in the postal sector every year. According to their 2016 Annual Sustainability report (International Postal Corporation 2016), which analysed 20 major European services including New Zealand and the USA, there are 26900 electric vehicles in a total worldwide fleet of 473111 vehicles. Thus, 5.69% of the European postal industry fleet is serviced by an electric fleet. Compared to 2014 where there the total electric fleet was 24700, there was an 8% increase in the number of electric vehicles added to the postal fleet of the 20 major postal services (International Postal Corporation 2016, 54). This shows that for customers who are prone to economies of scale, like the postal industry, large-scale deployment of EVs make the most business sense.

GOVERNMENT STIMULUS

In the following section an attempt will be made to showcase the various incentives introduced by governments to stimulate the uptake of EVs. The reason for a high public engagement are manifold: obligation to realize the goals that have been put forth in international agreements, to maintain a high standard of living by reducing sources of air pollution and to adapt to the changing requirements of future urban infrastructure and plan accordingly.

The EU has committed to rather ambitious GHG reduction targets. The total reduction to be achieved by 2050 is at 80% to 95% of 1990 levels (European Commission 2016). The European Commission estimates that for it to reach the overall 2050 emission reduction target, the transport sector would have to reduce emissions by 60% (plus) below 1990 levels.

Figure 4.1 (Amsterdam Roundtables Foundation and McKinsey & Co. 2014) illustrates the development of CO_2 reduction goals set by the European Union and compares them to other major world economies. While this thesis is primarily focusing on Europe, it is still relevant to consider other regions of the world. There are not only spill-over effects in terms of less global overall pollution, but spill-over effects in behaviour. Following the theorem of sociologist Mark Granovetter and Nobel prize laureate for economics Thomas Shelling, the behaviour of one individual is largely dependent on the number of other individuals already practicing this specific behavioural pattern (Granovetter and Soong 1986). This critical mass of other individuals engaging in the behaviour is referred to as "threshold" or "behavioural threshold". In the case of setting goals related to the reduction of any type of emissions, harming the environment at large, a critical number of economies may be necessary to actively participate, for other economies to follow suit. The negotiations at the historic Paris Climate Conference gave rise to the belief that the theory of threshold is applicable to this case.

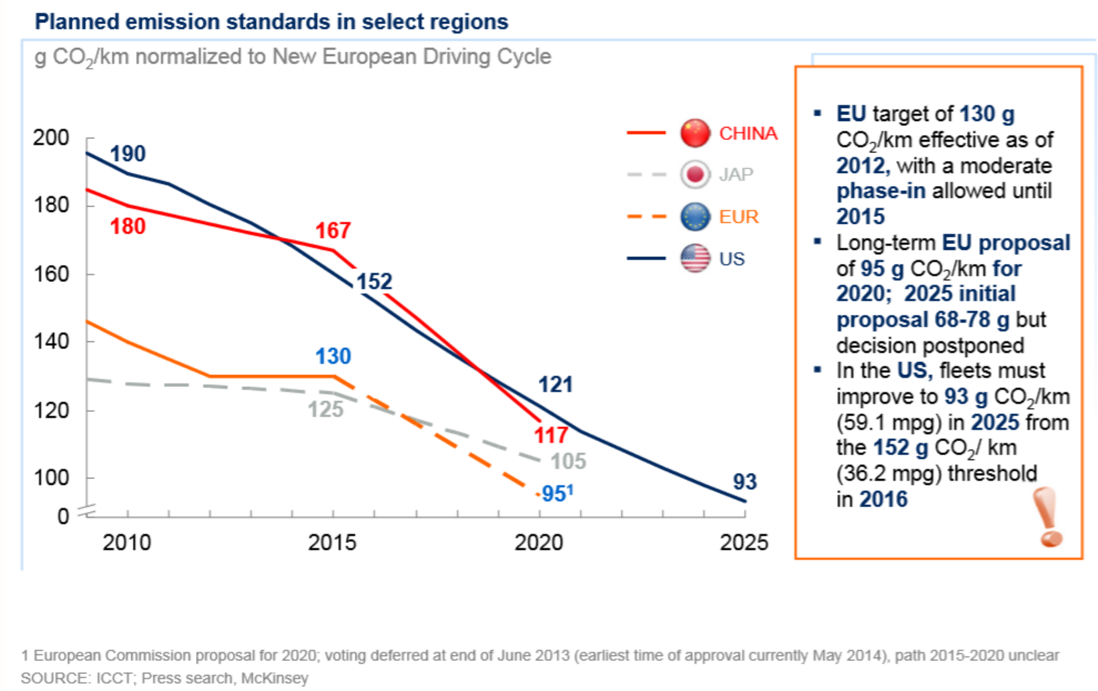


Figure 4.1 CO_2 Projected Emissions EU vs. Other Major Economies

To reach the critical threshold level, government incentives, strategies and best practices seem indispensable. The following section will show case some examples practiced in European cities. It is mainly in urban areas where the path to a paradigm change in the mobility sector can be most influenced by policy makers. In 2014, the urban population accounted for 54% of the total global population, and by the end of 2017, even in low- and middle-income countries, the majority of their population was living in urban agglomerations, growing by 1,84% every year (WHO 2017). This growth in urbanization comes with a variety of challenges for these cities. Efforts related to the provision of basic services must be increased, which included the supply and provision of energy services. Urban areas account for more than 70% of global carbon emissions (UN Habitat 2011). Transport constitutes a major aspect of urbanization and accounts itself for 23% of greenhouse gas (GHG) emissions (Ribeiro et al., 2013, 325). Consequently, transportation designates a sector with high carbon reduction potential in urban areas and a sector that may be influenced by governments and cities with a high return on investment.

Low Emission Zones

To this end, some cities have opted for a concept called "Low Emission Zone" (LEZ). A LEZ is a geographically defined area that restricts or deters access by certain polluting vehicles to improve air quality, reduce noise, and improve health. For implementing a LEZ, the city must identify the most appropriate system to be implemented, define the vehicle types that are affected, come up with awareness campaigns for the public to comprehend the reason for the transition, develop incentives for the population to resort to alternative power trains – especially for first movers and their followers – and define boundaries and phases of the program (Ellison, Greaves, and Hensher 2013). European cities have been the champions of implementing low emission zones. Most of the established LEZs are guided by the European emissions standards for air pollutants from road transport, set in the European Union framework (adopted in 2007) per type of transport (European Parliament and the Council 2007). For light-duty vehicles (i.e. cars and vans), categories range from Euro 0 to Euro 6, whereby Euro 6 constitutes the least polluting category. For heavy-duty vehicles (i.e. trucks, lorries and similar) the categorization ranges from Euro I to Euro IV, whereby Euro IV designates the least polluting category. Table 4.1 below, gives a comprehensive overview of established LEZs and the entailed policy measures. A selection of European cities has been taken in addition with Tokyo as a frame of reference. With the Japanese car manufacturer Toyota and its Prius model, the first commercially successful hybrid electric vehicle had been deployed. One might with confidence that the Japanese automobile industry had always been opting for alternative power trains. These days, however, Japan is amongst the most vocal proponents of fuel cell technology for powering light-duty vehicles (Schmitt 2017).

Table 4.1. Policy Measures in Europe for Low Emission Zones (European Commission 2018)

Stuttgart, Germany	Area concerned:	Entire city
	Year of implementation	2008
	Policy measures	• Mandatory **green sticker** (representing Euro 4 emission standard or better) since January 2013 • In 2010, a transit ban for heavy-duty vehicles above 3.5 tons was introduced and then limited to a smaller part of the city and has been removed for cleanest vehicle categories. • There's a plan to ban Euro 3 diesel cars, also if retrofitted with open particulate filters, for which an amendment of the national sticker regulation is needed: The city of Stuttgart and the federal state of Baden-Württemberg demand new stickers (blue stickers) for Euro 5 and Euro 6 cars from national government and the Real Driving Emissions of cars to comply with the Euro 6 limit values. • A public warning system will be established, where inhabitants and commuters are then asked to leave the car at home and switch to public transport or use bikes
Berlin, Germany	Area concerned:	Inner city: 88 km^2 applied to one-third of inhabitants
	Year of implementation	January 2008, getting stricter in January 2010
	Policy measures	• Establishment of a LEZ in Berlin, with proven positive effects by intensive measuring and data evaluation programs. Berlin demands

		measures on national level to incentivize Euro 6 cars • Significant reductions in GHG emissions. • Decrease in soot emissions from exhaust pipes by more than 50% and NOx by about 20%. • Shift in the composition of vehicles • About 90% of the cars driving in Berlin inside and outside the LEZ had a minimum of Euro 4 standard
Dusseldorf, Germany	Area concerned:	Almost the entire city
	Year of implementation:	February 2009
	Policy measures	• The zone was enlarged considerably beginning from 2013 onwards including also a district beyond the river Rhine • Since 2014 Euro 4 standard or better is required • Only vehicles with green stickers may enter the area • Good control system and a significantly large zone contribute to the reduction effect of the zone
Lisbon, Portugal	Area concerned:	33% of the whole city
	Year of implementation:	2011 and the area was extended in 2012
	Policy measures	• It requires Euro 2 since 2014 in the larger part of the zone and Euro 3 in the smaller city centre area • When it was first introduced, the LEZ was unenforced so they are currently evaluating a

		license plate recognition system to facilitate enforcement • The LEZ may start excluding Euro 3 cars in the smaller inner-city zone • The municipality also conducts on a regular basis public awareness campaigns
Paris, France	Area con-cerned:	The whole city inside the orbital road
	Year of imple-mentation:	February 2015
	Policy measures	• From July 2015, the first LEZ phase started to be in operation, forcing lorries and buses to meet at least Euro I emissions standards • From January 2016, all vehicles must be Euro I and it is planned that between 2017 and 2020, Euro 2, 3 and 4 and will not be accepted • However, enforcement is weak • The anti-pollution plan seeks to ban old diesel vehicles from 2015 and a complete ban on diesel cars by 2020. • There is also a traffic ban concerning heavy goods vehicles (HGVs) over 7.5 tons, restricting access to Paris during certain times of the day on certain days of the week
London, United Kingdom	Area con-cerned:	The whole city
	Year of imple-mentation:	2008
	Policy measures	• London introduced a LEZ requiring Euro III standards for particulate matter for heavy goods vehicles greater than or equal to 3.5 tons in most of Greater London

		• The regulations tightened to Euro IV emission standards for particulate matter for heavy goods vehicles and buses, and Euro III for heavier vans and mini buses from 2012
Rome, Italy	Area concerned:	City center (5.5km²)
	Policy measures	• The established LEZ (Zona Traffico Limitato) was enlarged in 2013. • Cars with Euro 0 emissions standards are not allowed in the city center at all. • Euro 1-6 cars are not allowed on workdays during the day and on Saturdays in the afternoon, unless they have, for instance, a resident's or a delivery permit. Some areas in the city centre are also closed at night-time. • Lorries without permits have different, very restrictive access times depending on their emission class. • Although electronic gates (more precisely electronic signs) and cameras control access to the city centre LEZ, enforcement does not seem not be efficient
Copenhagen/ Frederiksberg, Denmark	Area concerned:	Almost the entire city
	Year of implementation:	2008
	Policy measures	• LEZ for heavy goods vehicles since 2008 and since 2010, all vehicles heavier than 3.5t (buses and lorries) have been required to comply with at least the Euro 4 standards or to be equipped with a certified particulate filter. • Unless the national government changes the law, the city cannot impose stricter measures.

Prague, Czech Republic	Area concerned:	The whole city
	Year of implementation:	2016
	Policy measures	• Two different schemes in place: The LEZ for cars in its first stage requires Euro 1 for petrol vehicles and Euro 3 for diesel vehicles. • In 2018, diesel vehicles will need to comply with Euro 4 standards to enter the city. • The LEZs are implemented at a very low level, but regulations will be tightened in 2018. • There is also a permit scheme for lorries where buses and trucks heavier than 3.5 tons are restricted in the city centre and trucks heavier than 6t are restricted within the wider ring road. • Euro 4 compliance is obligatory to be granted a permit. • There is also the ARS (Access Control Scheme) for coaches and tour buses
Helsinki, Finland	Area concerned:	Whole city
	Year of implementation:	2010
	Policy measures	• LEZ that requires a minimum standard of Euro III for buses and Euro V for waste trucks. • Passenger cars or other vehicles are not affected and have full access.
Stockholm, Sweden	Area concerned:	Entire city centre
	Year of implementation:	1996

	Policy measures	• Diesel trucks and buses over 6 years old are required to meet at least Euro II standards. • Diesel trucks less than 8 years old need to meet either Euro II or III. • Euro IV vehicles will be phased out before the end of 2017 and Euro V trucks before 2021. • Since the LEZ addresses only part of the total vehicle fleet, it has a limited scope. However, the timetable for phasing out Euro IV & V seems promising.
Amsterdam, Netherlands	Area con-cerned:	City centre
	Year of imple-mentation:	2008
	Policy measures	• The LEZ is targeted only for commercial and heavy goods vehicles. • Only Heavy Goods Vehicles (HGVs) that meet the Euro IV or Euro V standards and retrofitted Euro III less than 8 years old are allowed in the zone. • Enforcement is close to 100% because vehicles are automatically scanned but there are some exemptions and short-term permits with daily fees.
Milan, Italy	Area con-cerned:	Area C (8 km² in the historic city centre)
	Year of imple-mentation:	2013
	Policy measures	• Area C restricts the most pollutant vehicles (petrol Euro 0 and diesel Euro 3) as well as lorries longer than 7.5 meters. • By the end of 2017, Euro 4 diesel vehicles without particulate filters are planned to also be forbidden to enter Area C.

		• Restrictions are only in operation on workdays during the day and the increase to Euro 4 in 2017 will not apply to residents' and utility vehicles or buses. • Area C is controlled through surveillance cameras at its 43 access points. • During the first year, the implementation of Area C resulted in a 30% reduction of traffic accesses, which translated to 40,000 fewer vehicles entering the area every day. • A public referendum held in 2011 showed that the Milanese population supported an enlargement of the zone. The municipality has projected to expand the area by 2022, however, no further planning has been made for that to happen.
Tokyo Japan	Policy measures	• In 2010, developed an ETS cap and trade program at the city level that aims at enhancing local air quality by targeting local pollutants, creating in the city a LEZ, with the target of reducing emissions by 25% (city-wide) below 2000 levels by the year 2020

Other cities have not established LEZs but have taken different steps to guarantee low emissions of GHG in the transport sector in their respective areas. The table below gives a comprehensive overview of their strategies.

Graz, Austria	Policy measures	• In 2012, the establishment of a LEZ was subject to referendum, where 70% voted against • However, a regional LEZ for lorries has been operating since 2014, obliging vehicles to comply with Euro III emission standards.
Vienna, Austria	Policy measures	• Vienna has banned in 2008 lorries manufactured before 1992 from its city,

		extended in 2014 to lorries with Euro I exhaust emissions class. • The ban covers the whole city including motorways (414 km²) with some exceptions for Euro II (Euro III from 2016) commercial vehicles with loading purposes.
Lyon, France	Policy measures	• There is no LEZ but it's one of eight French cities taking part in an experimental approach for a LEZ called **ZAPA**: **Zone d'Action Prioritaire pour l'Air** (Priority Action Zone for Air) • Introduction in 2008 of the **PPA** - Plan de protection de l'atmosphère – and includes small measures, like restrictions against most polluting large goods and heavy goods vehicles in the PPA area. • There is an existing ban on heavy duty vehicles with emissions standards below Euro 5 but will only be activated when there is a persistent breach in air pollution levels. • To declare a ban both on passenger cars and heavy goods vehicles, there must be a breach of at least a 6 consecutive days of air pollution limits.
	Results	• A feasibility study on ZAPAs showed the reduction of PM10 by 10% and NO2 by 17% on average. • This voluntary initiative was abandoned in December 2012. • In 2014, the revision of the PPA stated that NO2 emissions should be reduced by 40% and PM10 by 30% by 2016.
Dublin, Ireland	Policy measures	• Dublin restricts access for Heavy Goods Vehicles (HGV), which with five or more axles are banned daily from 7.00am to

		7.00pm from a designated area in the city centre. • A limited permit scheme allows delivery vehicles to enter the city centre on specific routes and only with a valid, paid permit.
Madrid, Spain	Policy measures	• Small parts of the inner city have restricted access to reduce traffic intensity, in which priority is given to residents. • There were discussions on a possible LEZ for the whole inner city of Madrid but besides the traffic calming measures, no further decisions were implemented.
Barcelona, Spain	Policy measures	• In the Ciutat Vella, the old city, there is a local traffic ban for non-residential vehicles at certain hours of the day • Also, for vehicles entering the area there is a speed limit of 10 km/h and a weight limit of 5.5 tons
Brussels, Bel-gium	Policy measures	• The possibility of establishing a LEZ was studied but based on environmental performance criteria, it was not implemented. • However, in May 2013 Brussels adopted a “Zone d’Action Prioritaire pour l’Air” (Priority Air Action Zone) which allows the municipality to introduce temporary or permanent restrictions on mobility and transport and to use subsidies to promote air quality. • No restrictive measures have been launched

ULTRA-LOW EMISSION ZONES

In the previous section low emission zones have been investigated. Some municipalities have, however, considered even more ambitious projects. In the city of London, an Ultra-

Low Emission Zone (ULEZ) had been established. A ULEZ is defined as an area where all motorized vehicles, including cars, motorcycles, vans, minibuses, buses, coaches and heavy goods vehicles (HGV) are required to meet exhaust emission standards – so called ULEZ standards – or are charged with a daily fee to travel (Ellison, Greaves, and Hensher 2013). The ULEZ developed for the city of London will come into effect in 8 April 2019, affecting an area of about 22 km^2 in central London. Fig 4.2 below depicts the site plan of the London ULEZ (Transport for London 2018).

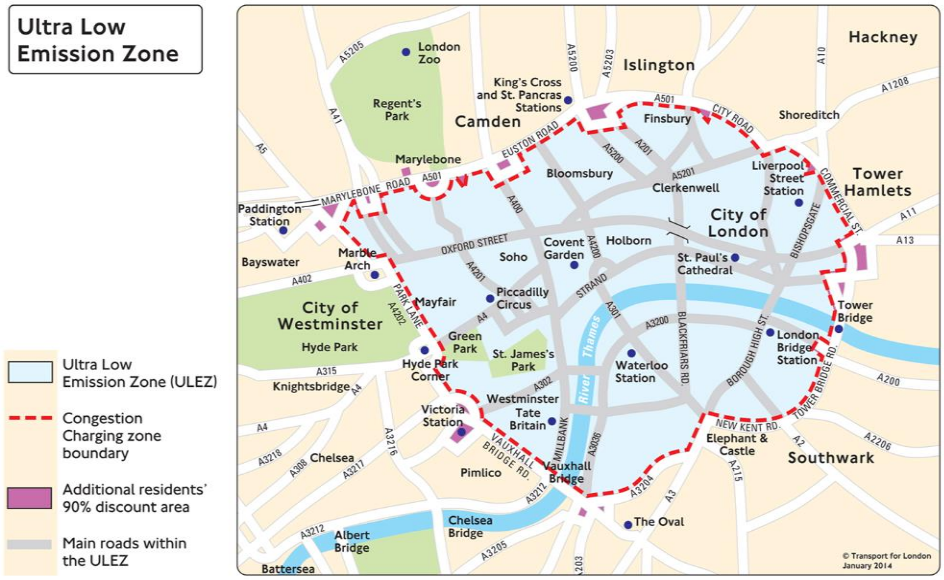


Figure 4.2: Ultra Low Emission Zone in London

Implementing an ULEZ was the result of positive feedback in terms of improved air quality, after the setting up of the LEZ in London. In 2013 CO_2 emissions in London were at 40 million tons per year. This level is expected to be reduced to less than 20 million tons per year by 2020 and even reach a level of less than 10 million tons per year by 2050 (The Committee on Climate Change 2017).

In the Spanish capital Madrid a strategy, called Plan A – a plan for air quality and climate change shall slowly be enforced from the beginning of June 2018 (Djahangard 2018b). Parts of the strategy are already in place, such as parking fees of 1,50 Euro per hour in the city centre of Madrid. This fee is only applicable to ICE vehicles. EVs, including hybrid vehicles, may still park free of charge. According to the municipality of Madrid, air pollution and traffic are the most critical problems of the city after waste management. A future goal is also the introduction of special time slots throughout the day, during which only HEVs, PHEVs, gas powered vehicles or BEVs can enter the city centre, or what is soon to be the Zero-Emissions Zone. Vehicles without a pollution badge and ICE vehicles are to be banned from parking in this zone from 2020. During the first quarter of 2018, twice as many BEVs had been purchased in the province of Madrid and 40% more hybrid vehicles had been registered, compared to the same time in 2017. Additionally, speed limits have been introduced as well as fast lanes for cars that transport at least to people (in order to incentivize car sharing) (Djahangard 2018).

While some are welcoming this new initiative and hope that car owners will resort to less polluting power train systems, others fear that their flexibility in mobility will be negatively affected. Especially low-income groups, who cannot afford EVs at their current price range might be discriminated. Speed limits and the modification of car lanes into bicycle lanes might reduce the number of cars on the street. On the other hand, though, if implemented in the wrong areas this strategy would only cause additional traffic, chaos and pollution. Businesses in the city centre, including restaurants and stores fear that restrictions to reach the centre by car will hamper their business.

Barriers to transition to Ultra-Low Emission Zones

As seen on the basis on the fears of businesses in the centre of Madrid or of the low-income population, it is vital that the implementation of LEZ or ULEZ is conducted with care, especially with regards to the provision of alternative infrastructure. The preconditions of an orderly and successful implementation of such zones does, however, come with financial requirements. The lack of access to finance to build efficient transport systems, including for public infrastructure such as public transportation systems or public infrastructure for the use of EVs and the lack of financing for the civil society to access EV technology might become a barrier.

Aside financial barriers there are also policy barriers. Policy barriers include the lack of capabilities or an appropriate mechanism for municipalities to enforce the measures involved in the establishment of a LEZ or ULEZ. A main criticism regarding the transport for London would be that they do not have established clearly defined priorities for "low emissions" neither of commercial vehicles nor for a long-term policy framework for alternatively powered commercial vehicles. Critics state that beyond Euro 6 / VI standards, there is no consistent definition of what constitutes low-emission or ultra-low emission for commercial vehicles. Another example for a policy barrier may be the lack of political will on either country or municipal level. In Switzerland, the mayor of Zurich wanted to establish a LEZ. National regulations in Switzerland, however, prevented the municipality from acting independently in this case (Soot Free Cities 2018).

The intention of this thesis is to give a broad overview on the issue of private mobility and available technologies, their current level of development and to what extent they could be beneficial in the attempt to create a more sustainable transport sector. While the focus is indeed on private mobility, where EV play a key role, one must also bear in mind that there are branches in the transport sector that are rather difficult to electrify but still are the source of an important share of GHG emissions. These sectors include aviation, heavy duty fright and shipping. The ETC Report suggests alternative fuels such as biofuels and hydrogen could eventually become viable substitutes for fossil fuels, especially for long distance aviation and shipping. This is a subject left for further investigation.

A third barrier could be industrial barriers, led by the lack of trust in the technology providers. Modern technologies are sometimes also seen as too risky or not adapted to the customer's needs (due to a lack in infrastructure). To overcome this low level of trust the critical threshold level must be reached, that has been previously mentioned.

The Energy Transition Commission Report (ETC Report) lays out policy enablers that would support and maybe even speed up the transition to clean power train solutions (Energy Transitions Commission 2017, 16).

Along with the individual incentives and strategies implemented by governments and municipalities, another indicator of where the mobility transition is heading to, may be found in the names of individual ministries and the sectors they are combining. Taking for instance the example of Austria. The Austrian ministry responsible for environmental affairs, including forestry, agriculture and fisheries used to be called "Federal Ministry for Agriculture, Forestry, Environment and Water management".[1] Since 2018 it changed its name into "Federal Ministry of Sustainability and Tourism" including the previously mentioned sectors as well as Energy. In France, under the new government of President Emanuel Macron, the former Ministry for Environment (Ministere de l'environnement) is now called Ministry for an Ecological and Solidary Transition (Ministere de la Transition ecologique et solidaire). In Denmark, environmental issues are divided amongst the Ministry of Climate and Energy and by the Ministry of Environment. In the UK, the Department of Energy and Climate Change also shows the merging of energy and climate related issues.

Such developments in public institutions are indicators for a change in mindset, which is critical to bring about a change in perception of technologies that have been an integral part of life. The automobile is more than a product. For some it is a lifestyle. A certain

[1] German original name is "Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft"

group of consumers must be reached to acquire a critical threshold. Only once that threshold is reached the technology has been sufficiently tested by the consumers and declared ready for large scale deployment. Public incentives, while financially very attractive, are not necessarily strong enough to encourage the transition in powertrains, or not the only reason for selecting an alternative powertrain. To this end a consumer survey was conducted to analyse consumer choice behaviour. The results of the survey are presented in the concluding chapter.

CHAPTER 5
Discussion and Conclusion

The objective of this thesis is to analyse the effectiveness and viability of alternative technologies to the Internal Combustion Engine specifically regarding the two prevalent alternative technologies currently in the market, i.e. Battery Electric and Fuel Cell Electric. In other words, is electricity the next powering source for passenger and light duty vehicles or is it a transition fuel paving the way for another alternative fuel?

This thesis has therefore in the previous chapters focused on laying out a comprehensive overview of different factors, both technical and non-technical, that make up these two very different but potentially revolutionary technologies. While there do exist further alternative powertrains, such as biofuel powered vehicles and FCEVs using methanol instead of hydrogen, this thesis has focused on discussing only BEVs and hydrogen FCEVs.

When Tesla first presented their Model S in 2012, the first fully electric car to ever top the monthly new car sales in all of Europe consistently in 2015-16 (Winton 2016), and the success of this 21st century car seemed unbound, many believed that the future of the automobile had been set. The future of the automobile, as touted by many, is allegedly the electric vehicle, led by Tesla.

Public incentives and new legal frameworks, especially on an EU-level, have indicated that a new mobility system will be put in place. In the EU's mobility package for instance, new CO_2 emission levels will be set at a level below the current 95g per kilometre driven by a passenger light duty vehicle (European Commission 2014). This Regulation will phase out the current testing cycle and replace it with a globally standardized approach (WLTP), while it will also seek to change the absolute CO_2 value to a percentage approach (European Commission 2017b). These policy changes coupled with a shift in global manufacturing incentives such as cheaper battery production costs and shifting consumer tastes and priorities can all reasonably be attributed to major European car manufacturers to increasing their investments in alternative powertrains. That way recognized, and popular car brands would offer their clients viable alternatives too. This can be evidenced by the number of new models and variants that are already out in the market or are planned to be launched by major auto makers such as Audi, Mercedes, Jaguar etc.

By the end of 2018 the automobile manufacturer Audi will introduce their E-Tron model, a BEV SUV, which is slightly larger than an Audi Q5 and has a distance range of up to

500 km and 435 BHP. By July 2018, a BEV by Jaguar, the i-Pace, will challenge comparable Tesla models as the Jaguar as it is relatively cheaper with 78,000 Euro. From 2019 a series of other automakers will present their latest alternative vehicles. BMW will introduce their i4 in addition to an electric version of the SUV X3, Volkswagen will present an entire I.D. series of electric vehicles with distance ranges of up to 600km. From 2019 Mercedes will also start to produce EVs in the frame of their EQ electric series. Many other car manufacturers are also presenting new models that are gradually more appealing in design and cover a broader range of consumer demands related to speed, size and comfort.

EVs seem to be here to stay and to gradually replace ICEV (Berkeley 2017). Nevertheless, the final call on the alternative powertrain market has not yet been made. FCEVs remain a viable competition with regard to other areas in the transport sector including shipping, heavy duty vehicles and aviation. The most potent barrier with FCEV seems to be the efficient production of hydrogen as a fuel; however, what seems to be interesting to note here is that there already exists more than 82 such Hydrogen stations in Europe alone and automakers such as Mercedes and Hyundai are coming out with models based on Fuel Cell technology which points towards a brighter future for hydrogen as a fuel source ("European Alternative Fuels Observatory" 2018).

SURVEY ON POTENTIAL EV CONSUMERS

To test the research question from a consumer choice perspective, a brief survey was conducted. The purpose of the survey was to identify the role of the consumer in the transition of the automotive industry and to what extent the availability of alternative powertrain technology given certain factors have influenced consumer choice. A total of 96 people answered a questionnaire consisting of 17 questions related to their consumer preferences on the choice of powertrain. The raw data of the survey can be found in Annex- I.

Survey Results

70.8% of the participants of the survey were aged 25 or above (mostly between 25 and 35). Almost 45% of participants had a postgraduate degree or more (7% had a Matura or equivalent and 48% were graduates). Given the age range, earnings were quite balanced. While half of the participants who indicated earnings were still having a yearly income of less than 36,000 Euros while the other half scored above that level. 36,000 Euro was used as a threshold as it gives a good indication of the type of contract. 36,000 Euro can be on average considered as standard salary for trainees and high educated interns (work contracts in Europe).

The turnout of the type of participants is quite promising. The age group and educational level are representative of future prospective buyers of premium cars. Now, it was of interest to know what powertrain they would prefer or if they had any preferences at all. Plotting user experiences against technology preferences, the data indicated that consumers are in general indifferent to the technology options as such (provided that their basic needs and comfort are met). Interestingly, 62% (60 participants) were indifferent when it came to choose between alternative powertrains. Moreover, amongst those who had never tested an alternatively powered car, those who had an opinion on the powertrain, would favour fuel cell technology and even those who had tested BEVs were almost equally split between indifference and BEVs.

Table 5.1 showcases two main indicators in a matrix representing consumer preference of an alternative vehicle technology vis-à-vis experience test driving such a vehicle.

Table 5.1 Consumer Preference Survey

	Alternative Powertrain Buying Preference			
Type of Powertrain Tested	**Battery-Electric Vehicle**	**Fuel-Cell**	**Indifferent**	**Grand Total**
Both Battery Electric and Hybrid Electric			1	**1**
Battery Electric Vehicle	8	3	7	**18**
But I don't know what type it was	1	1	4	**6**
Hybrid Electric Vehicle	2	1	7	**10**
Plug-in Hybrid Electric Vehicle	1		1	**2**
No Experience driving Alternative Powertrains	6	13	40	**59**
Grand Total	**18**	**18**	**60**	**96**

Even though almost 20% of the participants admitted to never having heard of FC-technology, it was a clear trend that most preferred alternative powertrains to ICEVs if the choice was given. This aligned with the pattern that low tailpipe emissions and zero tailpipe emissions ranked second and third after the price in their individual perception of importance of considerations to take during a car purchasing process.

32 participants earned an income of more than 36,000€ with close to 70% having a Post Graduate Degree or higher. Out of these 32 participants, 43% had test-driven an alternative powertrain and 1 participant owned a BEV. Out of the 43% test drivers – 50% were indifferent to their final preference between BEV and FCEV, while 28% of the test drivers opted for a BEV and 21% opted for FCEV. This goes to show that amongst the middle to high income earning segment of this survey with a High-Education level, most have not even consciously test driven an alternative powertrain. While amongst those that did, half of them were indifferent to the choice. Moreover, if one were to investigate consumer preferences for buying a car in relation the similar group of participants i.e. Middle to High Income earning individuals; more than 60% of the participants were most sensitive to the price of a car and were similarly sensitive to low-tailpipe emissions and cost of fuel while choosing to buy a vehicle.

Overall, the concern for a decarbonized mobility system seems to be representative. However, this concern may not result in an actual modification in car purchasing behaviour. Price remains the most important variable, as proven by the survey. Unfortunately, the survey lacks to give further insight on what seems to be included in the term price by the individual customer. Such an analysis would require a more extensive survey, conducted in person with all participants. For this thesis these resources were not given. Nevertheless, conversations with some of the participants enabled to conclude that the term price is relative. Purchasing prices of a car are often put in relation to similar models. They also include future costs of ownership. A higher overall price for an EV does not necessarily imply the immediate opting for an ICEV.

Many private car owners have two sets of demands. Firstly, the convenient regular middle- to short-distance shifting from home to the workplace and other frequently visited destinations. Secondly, the convenient and relatively fast transportation of a small group (e.g. family, friends) to middle- or long-distance leisure destinations. For the latter case, the vehicle must offer storage room, have the ability to travel long distances within a respectable amount of time and provide comfort for the passengers.

Due to uncertainties regarding achievable distances with EVs, a representative group of people are opting for two cars (Barlag 2015, 14). One zero tailpipe emission producing BEV for the usage on regular and known routes and a second hybrid or ICEV that is free from range uncertainties. Uncertainties with regard to future discriminations of ICEVs in cities including differentiated parking costs, the introduction of LEZs or ULEZs, are additional incentives to own a BEV as a second car.

Driving and owning a car are not a simple activity nor product - for many it is a lifestyle. The current lack of variety in the choice of alternative powertrain models, is another reason why the ICEV will not be disappearing in the immediate future. During the preparations for the survey, a participant admitted that they were really considering the purchase of a BEV. Finally, they opted for an ICEV. What tipped the scale was the fact that no BEV on the market would offer a panorama-rooftop. For others it was the fact that their trusted car-brand had not yet come out with a viable EV model. At the beginning of this chapter the launch of a variety of new models by a series of popular automobile manufacturers was mentioned. This increase in choice coupled with an enhanced deployment of charging infrastructure and the inclusion of additional technologies such as PV-roofs that would extend the range could have a significant impact on consumer behaviour and remains to be observed in the future.

The race for the future leading passenger light duty vehicle technology is at its height. European economies have signed up for ambitious Nationally Determined Commitments (NDC), which they should comply with. Many reductions can be achieved in the automotive sector. To this end, LEZs and similar concepts are trusted methods to encourage an increased use of no CO_2 emitting BEVs. Understandably, European car manufacturers find themselves in a tricky situation. Their production processes are still calibrated to the traditional manufacturing of ICEVs and their components. They are also facing fierce competition from the Asian market, especially with respect to EVs. The fact that the core element of EVs, the battery, is not yet economically feasible produced in Europe, poses additional difficulty and a potential threat. On the producer side, the fear of future bans on ICEVs cannot be a reason for decreasing car sales. Therefore, major automobile manufacturers have given appealing leasing options and a redemption guarantee, should customers not be allowed to use their newly acquired cars in the near future.

It is in the interest of European car manufacturers that policies paving the way for a transition in the automobile sector remain technology neutral. This is of key importance at this stage, especially from a European point of view, as the legal landscape should not hamper the regional car producers to remain major players.

WHY ALTERNATIVE POWERTRAINS

It is a viable question to ask oneself why alternative powertrains are investigated in the first place. There are a host of reasons. Greater diversification of energy and powering sources constitutes one reason. In the EU some 450 million tons (Mtoe) of oil is consumed on average every year (European Commission 2015a). Of those approximately 47.5% is consumed by the road transport sector (European Commission 2015a). The total amount of energy consumed in Europe is 70% dependent on oil. The share of oil imported into the EU lies at 73% (BiophysEco 2017). These are significant numbers that all depict the dependence on oil and consequently on oil exporting economies. A 2016 Bloomberg study estimates that a continued 60% growth of EVs would result in a decreased oil demand of 2 million barrels less per day by 2023 or 2028, depending on the methodology applied, as shown in Figure 5.1 (Bloomberg 2016). This reduction in oil demand would be similar to the drop in oil demand that lead to the oil crisis in 2014 (Bloomberg 2016).

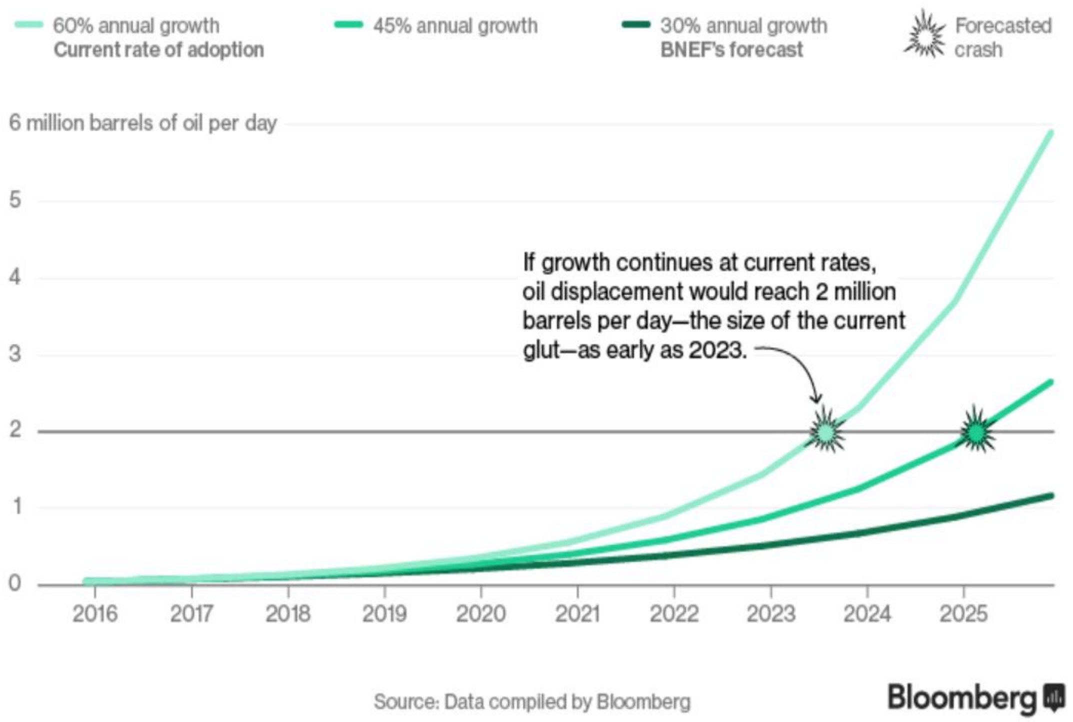


Figure 5.1: Predicting the Big Oil Crash

The amount of oil displaced by EVs depends on when EV sales take off. Two scenarios for rising EV sales.

A diversification of powering sources would indeed relief the dependence on oil but could have short to middle term repercussions on economies at large. When supporting a transition in the automotive sector decision makers should be aware of economic spill over effects and prepare mitigating strategies.

The second reason for preferential treatment for alternative powertrains is related to the global strategy to decarbonize energy production and consumption as much as possible. A decarbonized road transport system is especially beneficial in urban agglomerations and benefits air quality. Alternative powertrains do also emit hardly any noise pollution, which significantly contributes to living quality in densely populated areas. Yet, and this seems ironic, sensors need to be installed into BEVs so that they produce an adequate noise once they detect a foreign object (such as a pedestrian crossing the street) as a warning signal for the respective object.

While considerations related to a greater independence on oil, on a geopolitical level and lower noise emissions are not to be neglected, it is the prospect of significantly reduced local air pollution and emission of that drive the switch towards alternative powertrains. Bearing this intention in mind, a set of scientific papers and analyses agree that the switch to alternative powertrains would only be environmentally justifiable if energy production itself was decarbonized. Due to the inexistence of tailpipe emissions, BEVs are considered clean vehicles. However, CO_2 generation during production and end-of-life processes must also be accounted for. To provide a comprehensive overview of a BEV's carbon footprint Life Cycle Assessment (LCA) are conducted examining the CO_2 throughout the various stages of a BEV.

LIFE CYCLE ASSESSMENT

A Life Cycle Assessment is a comprehensive methodology that seeks to give the overall environmental impact of a technology in question by analysing their impact along various stages of the respective technology.

Life Cycle Assessment of a BEV

For an electric vehicle, four main stages can be identified, including the 1) powertrain production stage (i.e. of battery, motor, electronics), 2) Well-to-Tank (WTT) stage (fuel supply chain), 3) Tank-to-Wheel (TTW) stage (energy conversion in the vehicle, 4) Glider related processes (manufacturing, maintenance and recycling) and finally 4) (Messagie 2017, 8).

1) Powertrain production

The mechanics of a Battery Electric Vehicles do not require a lot of parts and far less moving parts as compared to an ICEV (Hummel, et al. 2017). The main element of a BEV's powertrain is the battery. Investigations show that the production of a lithium battery alone accounts for about 15% of a BEV's environmental footprint (Messagie 2017, 8). Of course, this share can be subject of slight variations depending on what overall life time driven distance of the vehicle. A shorter total distance completed would increase the share of impact of powertrain production. The review paper on the environmental impact of lithium batteries (Peters et al. 2017) unveils that the production of lithium batteries may generate between 40 and 350 kg $CO_2/kWh_{\text{battery capacity}}$ with an average of 110 kg $CO_2/kWh_{\text{battery capacity}}$, depending on the chemistry technology incorporated in the battery. Lithium-Iron-Phosphorus (LFP) batteries would score as high emitters while Lithium-Manganese-Oxide (LMO) batteries would generally realize lower emission levels during their production. While the consideration of compounds that contribute to global warming is important, toxicity levels should also be considered. In this respect, LFP batteries have a very low toxicity level as they do not incorporate nickel or cobalt. The mining of those two elements pose a large environmental burden. This indicates that in a scenario of global deployment of BEVs the environmental impact thereof will be different according to the geographic region. Countries possessing raw materials essential for the production of batteries such as Chile or the Democratic Republic of Congo, would be more impacted. On the other hand, the extraction of such resources is also likely to gradually decrease with an increased manufacturing of batteries as high recycling rates and consequently the reemployment of resources is anticipated. Thereby the step of producing/ extracting primary resources can be skipped.

2) Well-to-Tank

The largest share of the environmental footprint generated by a BEV can be contributed to the production of electricity. Under the EU-28 energy mix status of 2015, the Well-to-Wheel impact accounted for 70% of the total BEV environmental impact (Messagie 2017, 8). The level of the carbon footprint of the Well-to-Tank stage is entire dependent on the composition of the energy mix. A variety of primary energy sources make up the energy mix, including coal, oil, gas, nuclear, biomass, wind, solar and hydro power. Since the WTT stage is of such overall significance it decides upon whether or not investments in support of BEVs should be allocated. Currently, the average European carbon footprint of electricity lies at 300 g CO_2/kWh (year 2015) with a maximum in Germany and Poland of 410 g CO_2/kWh and 650 g CO_2/kWh respectively. Lowest carbon footprints are observed in Sweden with some 20 g CO_2/kWh (Messagie 2017, 10). The European Commission is predicting that the average European carbon footprint of electricity will be gradually decreasing due to an increase of the share of renewables in the total energy mix. Table 5.2 gives a brief overview on how the European Commission forecasts the development of impact of electricity consumption aligned with an increase of the share of renewables.

Table 5.2 Prediction of carbon footprint in European Energy Consumption (EU Commission 2018)

Year	Share of renewables in total energy mix [%]	Average carbon footprint of electricity [g CO_2/kWh]	GHG emissions reductions below 1990 levels [%]
2015	18	300	
2020	21	260	-26
2030	24	200	-35
2050	31	80	-48

The carbon intensity of a national electricity grid is of utmost importance to a justified deployment of any electric vehicle. Table 5.2 shows the evolution of an overall decrease of carbon intensity within Europe. However, countries that have a less favourable energy mix would hardly contribute to an overall decarbonization of the transport system. Therefore, the national mix of energy must be analysed and adapted accordingly prior or simultaneously to improving energy production. Figure 5.2. shows the respective environmental efficiencies of BEVs in eight different EU member states. The Figure also indicates the specific burden of each stage of the life cycle of a BEV. It is evident that Well-to-Wheel carries the largest burden, second is the production of the batteries and processes towards the end of the vehicle's life such as maintenance, reparation and recycling. For obvious reasons there are no Tank-to-Wheel emissions – a major advantage of BEVs. The manufacturing of the powertrain is marginal in emissions, which are independent of the propulsion technology.

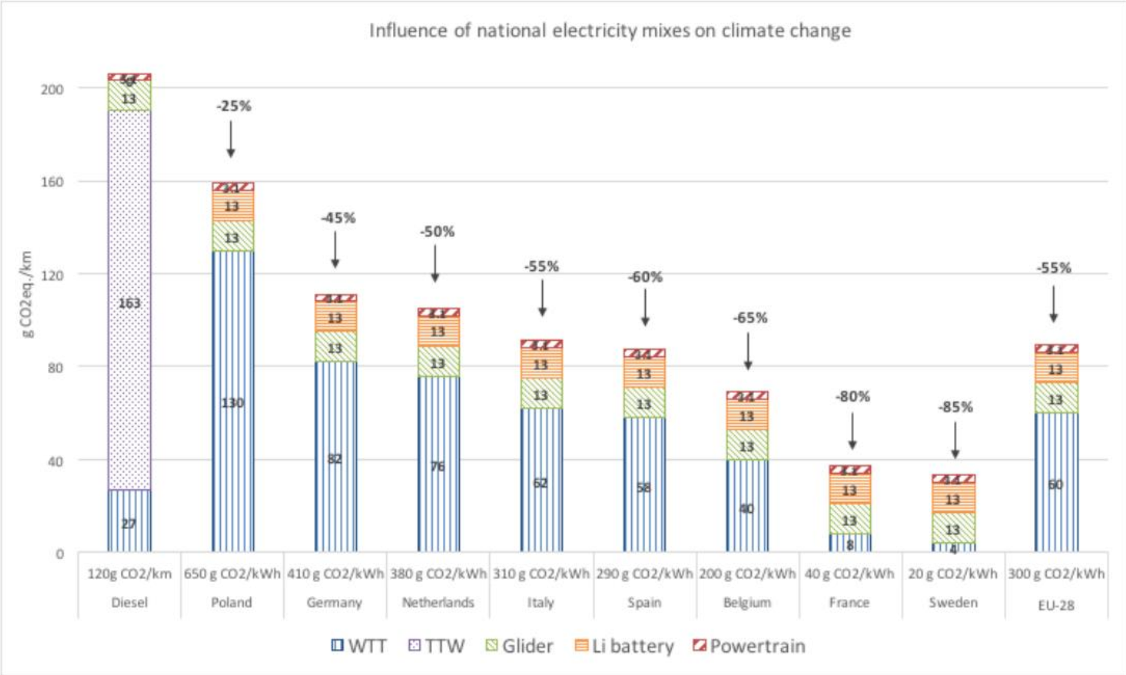


Figure 5.2: Influence of the carbon footprint of national electricity grids – comparison of LC-GHG emissions of BEVs, according to the electricity mixes given by the European Commission (Messagie 2017, 11)

Failure to circumvent current trends of increased use of coal generated energy such is the case in Germany would could lead to negative feed backs on the environment by EVs. The Energiewende package foresees the shutdown of all nuclear powerplant by 2020. There is a fair chance that the share of renewables would consequently decrease in Germany, should it be neglected to open up new renewable energy production facilities. Figure 5.3 depicts the effects of the various energy sources on the Well-to-Tank efficiency as well as the anticipated improvement of the overall EU carbon footprint in the energy mix.

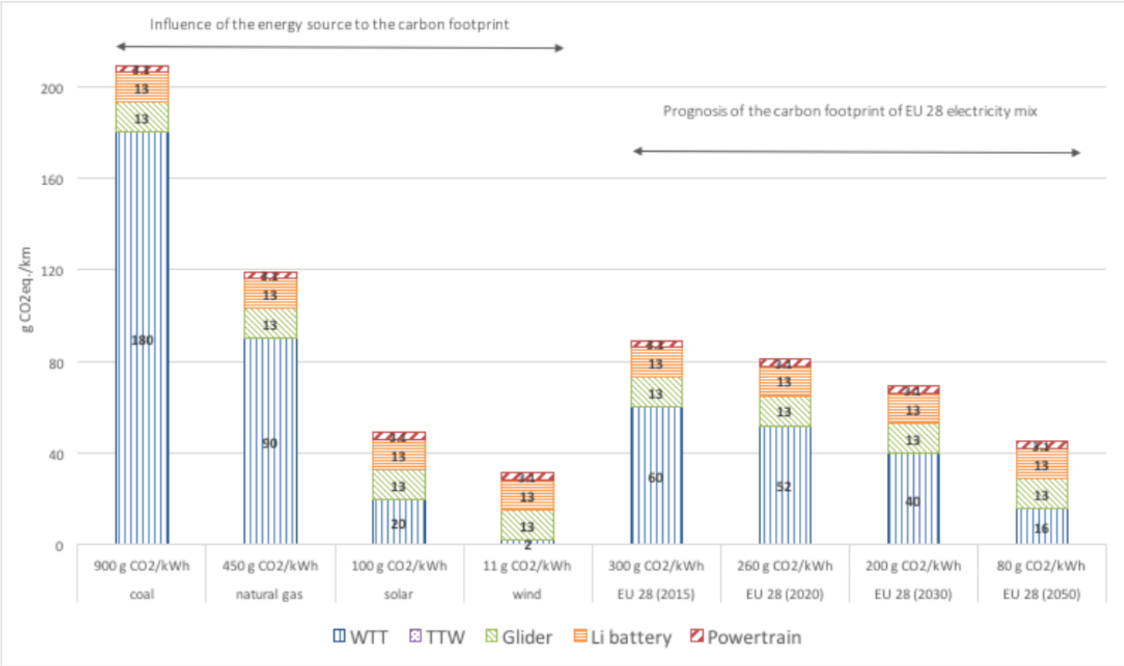


Figure 5.3: GHG emissions of EVs depending on the energy sources and the prognosis of the reduction of carbon intensity – based on data from European Commission (Messagie 2017, 12)

3) Tank-to-Wheel

This stage can be considered as part of the Well-to-Wheel process. For clarification reasons Wall-to-Tank and Tank-to-Wheel were shown as individual stages to really highlight the importance of an adapted energy mix for investments into a large-scale electrification to be justifiable. Strictly speaking, there are TTW emissions even for BEVs. They are of noncarbon nature and include the creation of particulate matter in the air, for example by tire wear. Yet, if a Well-to-Wheel perspective was to be taken, then driving patterns would also need to be taken into. Constant driving over an extended period shows a greater Tank-to-Wheel efficiency, while frequent stop-and-go driving patterns as they exist in urban areas require a higher input of fuel. Therefore, it is believed that electrified vehicles are of great advantage in urban areas as local air quality would be less impacted. Figure 5.4 gives a comprehensive overview of the respective carbon footprints in three selected driving patterns. The results of Figure 5.4 show that electrified vehicles do play a key role in an urban context.

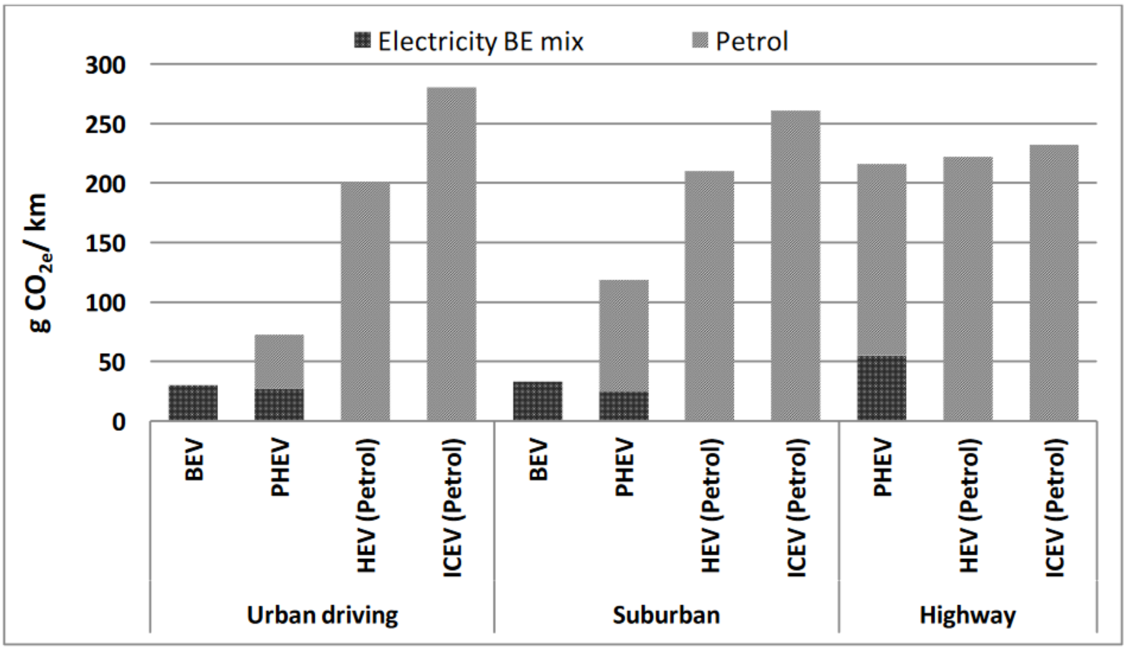


Figure 5.4: Impact of real world driving and traffic conditions on the WTW environmental performance of cars (Messagie 2017, 4)

4) Glider related processes

This stage includes the manufacturing of the autobody, maintenance, repair and recycling. The manufacturing of the autobody of a BEV is not much different to the one of an ICEV. With respect to repair and maintenance, BEVs require less thereof due to the existence of fewer moving parts. (Hummel, et al. 2017).

The Life Cycle Assessment showed that there is in fact an advantage to the electrification of vehicles. Especially in an urban context, do BEVs emit much less than the traditional ICEV, accounted over the entire life cycle. The key to a successful deployment of BEVs lies in the renewability of the energy mix. Moreover, improvements in the manufacturing stage, such as the further reduction of weight of the car body would result in further efficiencies, for both BEVs and ICEVs. Finally, battery technology also ought to be improved, including on a technical/chemical level and with a mindset of enabling the recycling thereof. Currently recycling rates, especially for lithium are rather low due to significant differences in commodity price and costs of recycling. The purchase of new lithium is at present cheaper than the recycling thereof (Gardiner 2017)

Life Cycle Assessment of an FCEV

To provide an equilibrated comparison between technologies, an LCA for FCEVs was equally considered. The author has thus far shown that the electrical efficiency of a fuel cell is inferior to the one of a BEV, some 40% compared to more than 85%. It has also been shown that during the electricity generation in a fuel cell the additional by-products are heat and water. Consequently, when the produced heat is used as well, the total efficiency of fuel conversion may reach up to 90% (Notter et al. 2015, 2). This is a relevant piece of information to estimate the overall efficiency as that automatically generated heat can be used for heating of the interior of the vehicle without requiring additional fuel. The author considered two scientific papers discussing the efficiency and environmental footprint of fuel cell technology (Notter et al. 2015; Dhanushkodi et al. 2015). Both agree that the data on FCEV fuel efficiency is still low especially in comparison to available data on BEVs. The previous LCA showed that the production of the battery of a BEV accounted for 15% of its total environmental footprint (Messagie 2017, 8). Looking at fuel cell technology, the environmental burden is firstly dependant on the FC technology used as they incorporate different raw materials and secondly on the sources of energy production, in this case on the energy sources enabling the production of hydrogen. While platinum (used as a catalyst) only accounts for about 1% of the total mass of a FC it causes 89.4% of the total environmental footprint (Notter et al. 2015, 6). The mining and refining of platinum is very energy intensive. Moreover, the usage of certain chemicals during the platinum mining process is also a cause for the release of toxins impairing the health of humans, such as the disposal of sulfidic tailings (Notter et al. 2015, 8). Thus, FC-technologies containing less platinum and resorting to other materials would largely benefit the overall environmental footprint of fuel cell technology.

The paper concludes by stating that the *conditio sine qua non* of a justifiable introduction of FCEVs is the clean production of fuel, meaning the generation of hydrogen (or other gases) from renewable energy sources. The paper also indicates that the relative competitivity between BEVs and FCEVs depends on the type of renewable used for electricity or hydrogen production respectively due to electricity conversion rates (Notter et al. 2015, 14). Figure 5.5 depicts how both alternative powertrains accumulate much of their environmental burden during the production and disposal process, namely of the battery and the fuel cell. It is also clearly visible that there is a problem shift of environmental impact from ICEVs to alternative powertrains consisting of the shift of environmental impact from operation (ICEV) to production (BEV and FCEV). Moreover, under the viewpoint of a European electricity mix from 2007 (this mix is considered in Figure 5.5) where the share of renewables accounted for 10% (EEA 2015), the powering of a FCEV has an even greater environmental impact than the usage of an ICEV. This is because the production of electricity to produce hydrogen and reconversion into electricity for the propulsion of

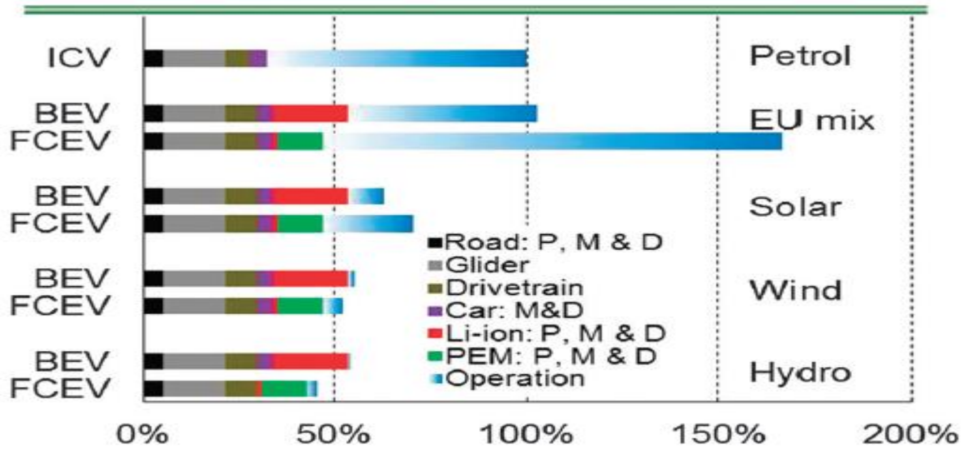


Figure 5.5: Environmental burdens expressed as ReCiPe (a LCA method) points for a transport service of 1km travelled by an ICV, BEV and FCEV (Notter et al. 2015)

the FCEV is by large less efficient than the direct use of the non-renewably produced electricity in a BEV. In the 2007 European energy mix scenario ICEVs and BEVs have the same environmental burden.

However, under the premise that energy is largely produced from renewables or that fuels for FCEVs are produced with the aid of renewables, then FCEVs are very competitive. The burden is comparable to the one caused by BEVs, there are zero local emissions and larger distances can be covered. With a 5kg tank of hydrogen at least 500km can be covered. Refuelling times are similar to traditional petrol fuelling processes. Additionally, the deployment and improvement of fuel cell technology would largely contribute to an even more diversified energy structure. After all, fuel cell technology can also accept other gases than just hydrogen, such as methanol to just name one other example. Fuel cell technologies would enforce power-to-gas storage technologies, which are considered efficient and reliable storage methods especially under a renewable energy production scenario ("Versorgungssicherheit mit Power-to-Gas" 2018). Furthermore, resorting to power-to gas technologies allows to use existing infrastructure such as gas pipeline networks for transportation purposes. This would lower the costs of infrastructure build up.

CHALLENGES OF ELECTRIFICATION

The Energy Transition Commission Report (ETCR) states that the infrastructure choices made over the next five to ten years will largely determine whether or not we can stay within a 2°C pathway and suggests that progress is needed in energy productivity and share of energy derived from zero-carbon energy sources, through accelerating the transition, amongst other, in the transport sector, where a lot of potential lies (Energy Transitions Commission 2017, 67). A higher share of renewables in the total energy mix, does not pose a challenge on a technical level. The main challenge lies in the efficient storage of renewably generated energy. Irregular peak loads remain up until date a difficulty to feed into the grid and so do electricity surpluses produce by individual households with their PVs. Simply put, efficient storage technology is a crucial component in the energy transition and by extent in the mobility transition.

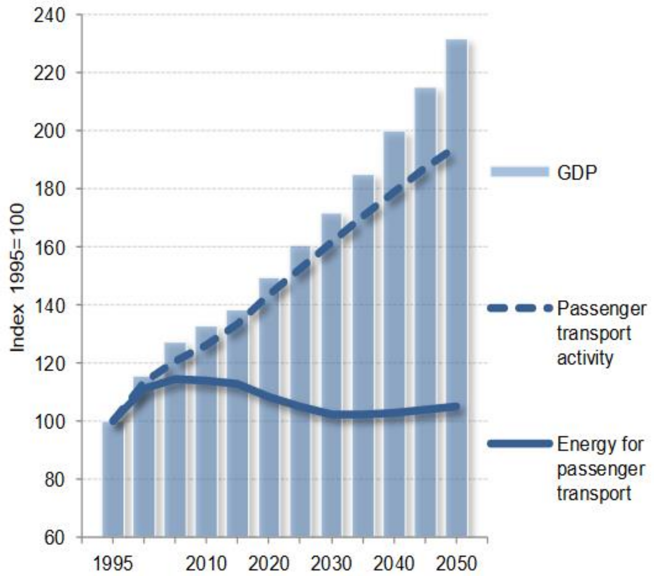


Figure 5.6: Trends in transport activity and energy consumption (European Commission et al. 2016)

The European Commission estimates a growth in transport activity until at least 2050. It predicts that growth will reach its peak before 2030. In line with this, it is believed that the use of electricity in the transport sector will also be increasing, though steadily due to a more pronounced electrification of the mobility sector. However, the growth in road vehicle electrification is sobering: a 2% growth in 2030 and 4% growth in 2050 (European Commission et al. 2016). Figure 5.6 depicts this self-confident rise in passenger transport activity, following the trend of GDP growth. At the same time, energy consumed in the field of passenger transport will be going down. This could on the one hand be attributed to greater vehicle efficiencies as well as to a change in transportation mode. Upgraded public transportation systems in an urban context could also be a cause for an increased passenger transport activity coupled with a decreasing energy requirement for passenger transportation.

What is also interesting to note is that the potential transition in fuels for vehicles will be gradual and slow. Figure 5.7 shows the share of fuels in the transport sector at large between 2010 and 2050. While the share of electricity and hydrogen is slowly growing it also implies a slow decrease of fossil fuels in the vehicle propulsion mix. This progress might be too slow to be pushing for alternative powertrains as investments for vehicle manufacturing must be going hand in hand with investments for infrastructural adaptations. Nevertheless, the 90% share of oil in the transport sector in 2030 and the predicted share of 86% in 2050 are valid for the entire transportation sector, including aviation and shipping, which are hard to electrify domains of the transportation sector (European Commission et al. 2016, 13). This does not exclude an increased electrification rate for passenger and light duty vehicles in urban areas. The already existing relatively high share of electricity in the final energy demand in transport can be explained by the high electrification rate within branches such as the railway system which is now largely electrified.

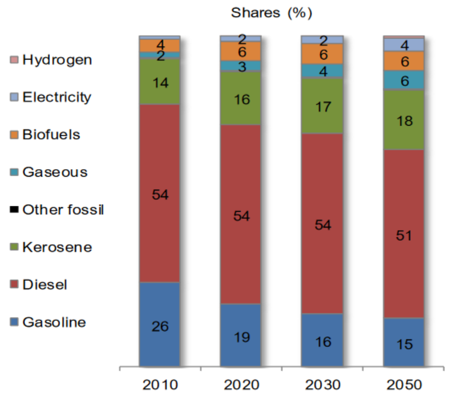


Figure 5.7: Final energy demand in transport by fuel type (European Commission et al. 2016)

As explained in a previous chapter, R&D is also conducted in the area of vehicle to grid (V2G) or power to grid (P2G) technologies. In Amsterdam a pilot project implementing V2G technology has been introduced (Bijman 2018). Within the Amsterdam Smart City Project PEV-owners are incentivized to charge their vehicles with cheap electricity from the grid during low demand hours and feed the grid with electricity during peak load hours. The intention is to test whether PEVs can support the stabilization of grids, may operate as a back-up should there be electricity failures and if PEVs can become relatively cheap mobile storage units of energy to be transported to specific locations in need of electricity. Should the V2G technology prove to be efficient, large, costly and time-consuming investments into the upgrading of power grids can be circumvented. PEVs would consequently positively contribute to a decentralized energy production and storage system.
A rival to the classic EVs is the fuel cell technology. Fuel cell technology, powered by hydrogen, as explained in a previous chapter is still at an early stage in its development. There is however, potential in this technology should the production of hydrogen become less energy intensive or require less investments. The advantage of FCEVs is that driving behaviour is not impacted. While tank to wheel efficiency is inferior to the one of BEVs it requires less resources in production, compared to the battery. Issues related to long driving ranges are also non-existent. However, the safe storage of hydrogen on board and in fuelling stations remains a concern for some. Hydrogen too would be a potential storage system of renewable energy surplus. However, in this case a more centralized approach is taken, as from an efficiency and economic point of view, large electrolysis

facilities would make more sense. Moreover, existing gas-pipeline infrastructure can be used to distribute hydrogen. It remains debatable which option would be more attractive.

CONSEQUENCES AND THREATS

The automotive industry has never existed as an independent industrial branch. Throughout its existence it was closely connected to energy supply, infrastructural projects and R&D in many other sectors. A change in paradigm in the automotive sector can therefore hardly occur without affecting other areas in an economy.

European car manufacturers have mastered the production of premium passenger vehicles. The notion "Das Auto"[2] is globally known and represents premium quality (Economist 2012). A transition in the automotive industry comes with a shift in expertise. According to a recent study commissioned by the Austrian Automobile Club (ÖAMTC), some 450,000 workplaces in Austria alone are directly related to the automobile industry. This accounts for 11% of the non-self-employed people in Austria (ÖAMTC 2018b). At least 10,000 workplaces depend on the manufacturing of ICEs in the Styrian automobile cluster ACStyria. In the automotive hub, Germany, expertise and the number of workplaces dependent on the ICE is even more significant, at least 800,000 people work in the car manufacturing industry (Statista 2016). In 2016, already some 43% of all EVs produced worldwide were manufactured in China (Hertzke, Müller, and Schenk 2017). This implies a significant shift of workplaces and expertise to other areas. It is still too early to give a concrete prediction about the impact of electrification on the job market. Currently, there is no extensive research available on this question. It is, however, known that EVs require far less moving parts. While a Chevy Bolt (one of the first commercially deployed EVs) contains 24 moving parts in its powertrain, a comparable ICEV, such as a VW Golf, contains as many as 149 moving parts (Hummel et al. 2017, 5). Moreover, according to the report, almost 60% of the components of an EV come from outside the traditional auto supply chain. Traditional tier-1 suppliers are doubtlessly among those to be hit the hardest in the transformation of the automotive sector. Batteries, which account for 42% of tier-1 supplies are largely provided by traditional electronics companies, who up until recently had little contact with the automotive sector, such as LG. It is critical to do further investigation on the impact of the shift of expertise and on the introduction of new players, such as electronics suppliers.

[2] "Das Auto"is the slogan of Volkswagen and appears at the end of every VW commercial.

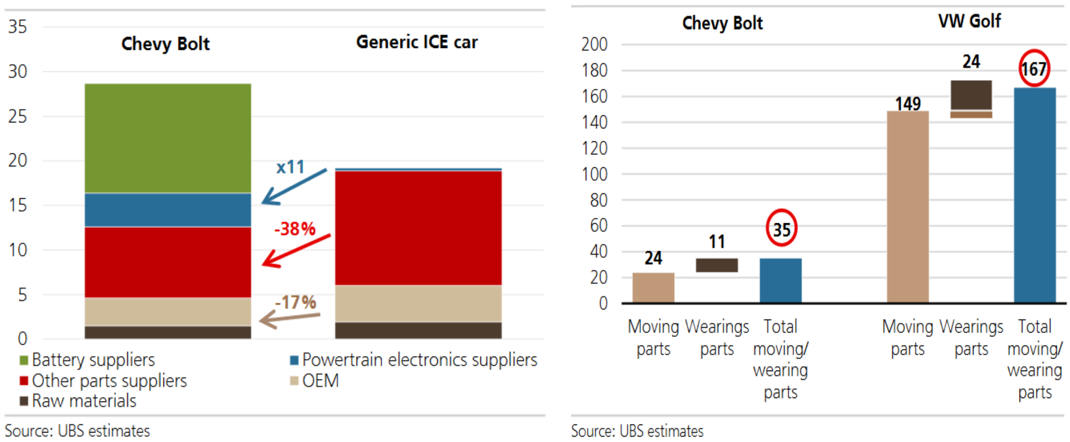


Figure 5.8: Comparative Electric Car v. ICE Tear down (Hummel et al. 2017)

The fact that Mercedes had announced to completely electrify their Smart fleet from 2020 is for instance a concern for car part suppliers, who will lack follow-up commissions form 2020 (VDA Arbeitskreis Finanzen 2018, 5).

There is evident threat of the emergence of a “Green Paradox”. The Green Paradox, a notion coined by the German Economist Hans-Werner Sinn, describes the reverse effect of policies aimed at the protection of the environment (Sinn 2012). For Sinn, climate policies announcing an end of fossil fuels would at least in the short- to mid-term lead to an increase in CO_2 emissions, as owners of fossil resources would wish to check in their profits that they would have expected in the future (Sinn 2012, 79). A Green Paradox in the larger sense could also occur from abrupt changes in the automotive industry. As seen in a previous chapter, ICEV bans have so far only been introduced or announced for urban areas. Uncertainties and lack of trust in alternative powertrains do still run deep among potential consumers. Prevented from using ICEVs in urban areas for short and/or regular journeys, consumers might buy a second vehicle with a clean and alternative powertrain. Despite their zero tailpipe emissions, EVs have a large environmental footprint during production. In the short- to middle term uncertainties in fuelling/charging infrastructure and policies are likely to lead to a Green Paradox. In addition, the second car requires parking space. New mobility systems foresee an overall reduction in passenger vehicles, which might only become a reality in the long run, once the new ICEV has been nominated.

Talking about an overall transition in the mobility system towards a sharing concept, car manufacturers might be able to overcome the shift through the introduction of new services. The shift from a product-based car industry towards a service industry might be the source of a new value chain in the automotive sector. Daimler and BMW have already announced the cooperation of their car sharing services Car2go and Drive Now (Reuters 2018). These car-sharing services do already use EVs on a broad scale. Their presence in densely populated areas is of tremendous value with regard to marketing and via these services they may even reach user groups that previously would not have been reached, such as customers who do not travel enough to require their own vehicle. Against this backdrop, car manufacturers could build up a two-segment structure. One segment which is laid-out for short distance car sharing services and one for larger distances. The basic concept would be "Mobility-passes" that are purchased by the customers. Depending on the mobility package bought, a selection of cars can be "rented" in an uncomplicated way. With the existence of comparatively low monthly fees, the accumulation of a broader range of customers could result in attractive profits.

The large-scale deployment of BEVs is also dependent on an efficient and easy payment system. Electricity prices are volatile and are more prone to adapt their price over a brief time frame according to demand and supply. This price volatility would be even more pronounced under a renewable energy system, which is a precondition to an effective and solutions -orientated implementation of EVs. To overcome the issue of effective payment systems, smart meters need to be introduced, another investment necessary for the deployment of EVs. In addition to smart meters, new financial concepts could also facilitate transactions. Aligned with blockchain technology a digital "electricity currency" could be introduced that follows two systems of value and exchange. Used as an exchange medium for electricity, it has a stable value. On the other hand, it is floating currency when exchanged for fiat money. With such a concept, V2G systems could be supported.

V2G or P2G systems are a consequence of an increased feed of renewables into the total energy mix. To evaluate the potential of electricity as a substitute for fossil fuels the composition of the energy mix is of essence. PEVs charge their batteries with electricity from the grid. This electricity had to be previously produced. The energy mix in Europe in not homogeneous over the countries. Scandinavian countries lead in having the highest percent share in renewables in their energy mix with 53% in total energy consumption (including electricity, heating and transport) in Sweden. In other European countries the share is lower is significantly lower, such as in Germany with some 17% renewables in their energy consumption mix (IEA et al. 2018). Such significant differences do have a substantial impact on the efficiency and benefit of an EV. With a lower share of renewables in the energy mix, the carbon footprint of a BEV increases to the extent that the overall environmental footprint of the BEV is greater than that of an ICEV.

With the aid of a life cycle analysis (LCA) the environmental burden of either technology can be evaluated and compared. On a large scale, three levels of the lifecycle can be distinguished: extraction of resources and production, operation, and end-of life/recycling. For each stage a comparison between BEVs and ICEVs was done. The result shows that ICEVs require less resources in production than BEVs while operation is less carbon intensive for BEVs, provided it is used in a high renewables energy mix environment. This makes electricity only partly a viable substitute for fossil fuels.
When it comes to the extraction of resources, there are not only environmental issues to consider but geopolitical ones too. BEVs require a distinct set of resources to produce their batteries. Some of the resources, including cobalt are found in combat-stricken regions or where legislation is weak with regards to environmental protection.

CONCLUSION

This thesis seeks to analyse whether electricity was an ideal substitute for fossil fuels for the use in passenger vehicles. To answer this question a three-pronged approach was taken. The private passenger automotive sector needs to be viewed from a holistic perspective, as it is so intrinsically incorporated to everyday life. The three-pronged approach included technology, policy measures and socio-economic considerations.
On a technological level, vehicles using electricity as powering source have proven to be significantly more efficient than propelling systems based on an internal combustion engine, especially with regards to tank-to-wheel efficiency. Moreover, electric powertrains produce less tailpipe emissions and require less maintenance due to a lower amount of moving parts in the powertrain system. However, distances to be covered with one charge of an EV are still shorter than distances coverable with one tank of an ICEV. In addition, charging with respect to charging infrastructure and standardization thereof still poses a barrier to large scale EV deployment. Related to charging infrastructure is of course the status of electricity grids. More EVs mean more pressure on the grid, unless smart and interesting systems are developed to normalize charging behaviour. From a technical point of view and given the specific efficiencies in urban driving, electricity could indeed be the new leasing powering source. It could, however, also be a transition fuel, facilitating the switch to fuels such as hydrogen until production of the latter can be achieved relatively cheaply.
The possible transition towards a decarbonized mobility system can hardly be achieved without the aid of public incentives and restrictions. Financial benefits attributed to low-carbon emitting vehicles in combination with limited access to certain areas in urban regions have proven to be quite successful. Restrictions, while contributing to higher air

quality standards especially in city centres, may also bring about negative effects. After all, positive discrimination still discriminates those who cannot afford another vehicle and might also lead to a shift of commercial activity away from city centres to outer districts. Policies play a very important role in incentivizing a transition towards alternative fuels and pronounce the effect of individual preferences. Consumer preferences are largely a factor of economic or financial considerations and individual values. Both are linked to government policies. Up until date, vehicles with alternative powertrains are still more costly in purchase than comparable ICE-models. Interesting financing schemes and the non-application of certain fees make EVs the cheaper option in some regions, such as in Scandinavia. The analysis has shown that there is viable prospect of electricity to be future fuel and to gradually replace fossil fuels. However, at least a decade will pass until uncertainties regarding the perception of the technology will have been overcome. Moreover, it is possible, that electricity will have to share the powering market with hydrogen or other gases for promising power-to-gas technologies. The parallel implementation of two alternative technologies may be expensive at first, however by resorting to existing infrastructure and regarding electricity and hydrogen as complementary sources of energy a new era could be started. Fuel cell technology, especially with respect to the decarbonisation of hard to electrify sectors, is here to stay. It is even possible that both technologies could co-exist and complement one another. Today, petrol and diesel are two technologies that exist simultaneously in the transport sector. This could also be envisaged for the co-existence of BEVs and FCEVs. From a technical point of view, the provision of hydrogen and electricity from one and the same fuelling station is feasible and equally is the incorporation of fuel cell stacks and a battery in one and the same vehicle. The complementary use of both technologies would lead to greater energy independence and energy security while also reducing the exposure to price volatility.

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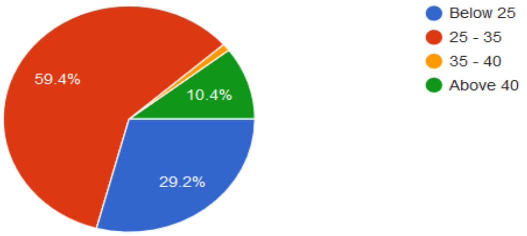
List of Tables and Figures

TABLES

ANNEX I
CONSUMER PREFERENCE SURVEY RESULTS

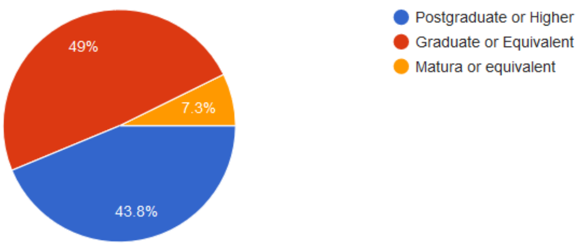
What is your Age?

96 responses



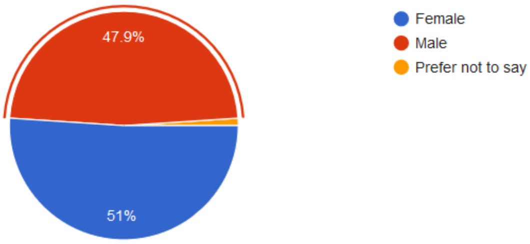
What is your Highest Academic Degree?

96 responses



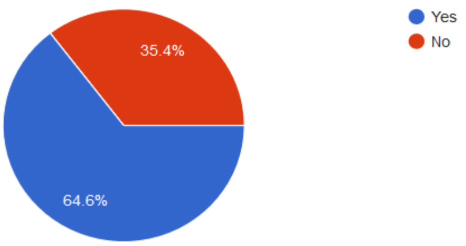
What is your Gender?

96 responses



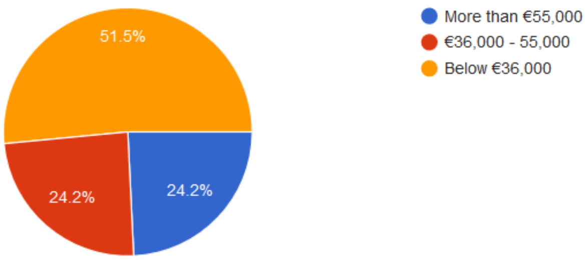
Are you currently earning a fixed income?

96 responses



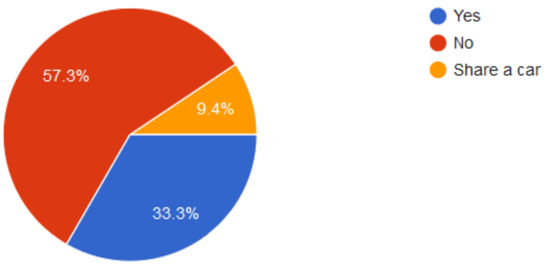
If yes, how much do you earn annually (gross)?

66 responses



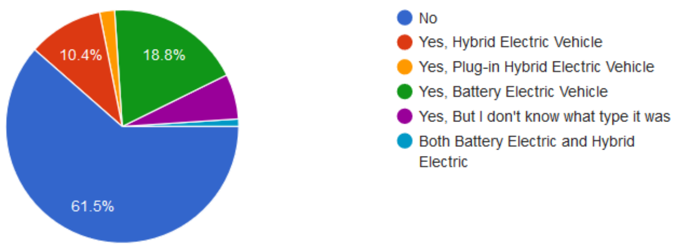
Do you own a car?

96 responses



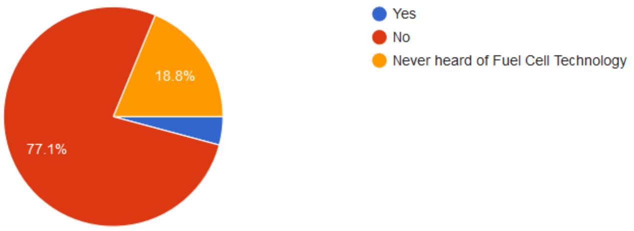
Have you ever driven/tested an Electric Vehicle (EV)? If yes, please indicate the type of EV you drove.

96 responses



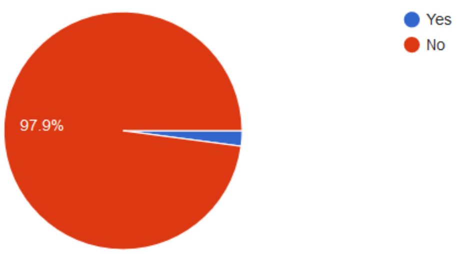
Have you ever driven/tested a Fuel Cell Electric car (FCEV)?

96 responses



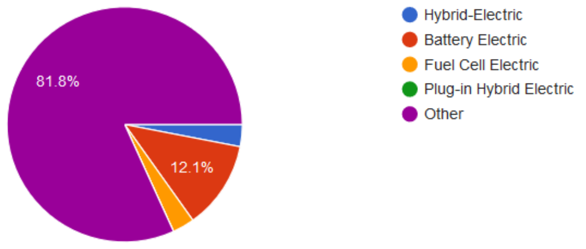
Do you own an electric vehicle?

96 responses



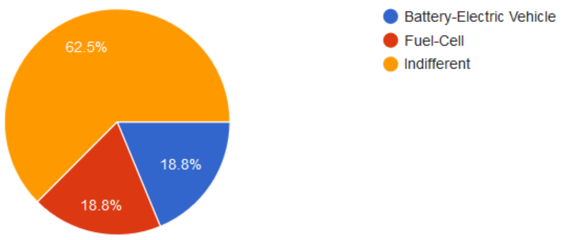
If yes, which type?

33 responses



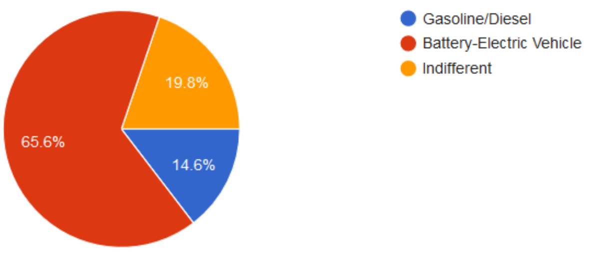
Would you prefer Battery Electric or Fuel Cell Electric Vehicle?

96 responses



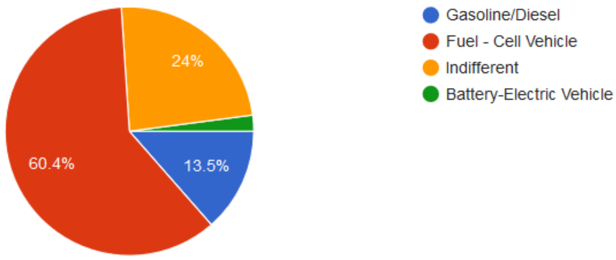
Would you prefer Gasoline/Diesel or Battery Electric Vehicle?

96 responses



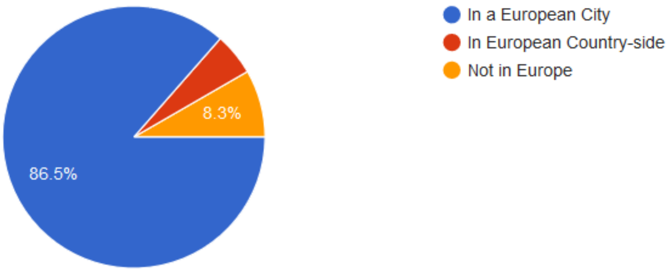
Would you prefer Gasoline/Diesel or Fuel-Cell Electric Vehicle?

96 responses



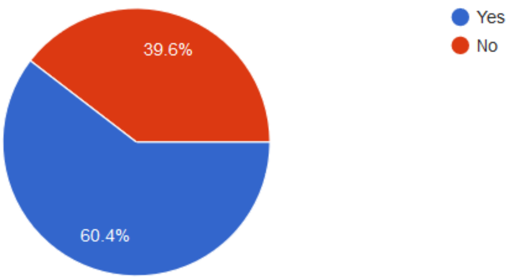
Where do you live?

96 responses



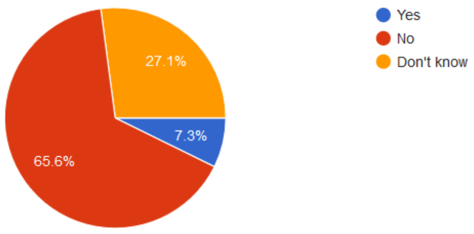
Do you plan on buying a car in the next 5 years?

96 responses



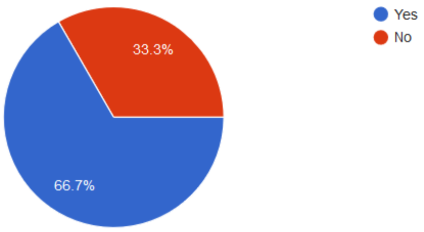
Does the city you live or work in have a Low Emission Zone (LEZ)? (For instance: London has certain parts of the city designated as LEZ; where one has to pay a fee if their car technology is considered to be polluting - diesel commercial vehicles for example)

96 responses



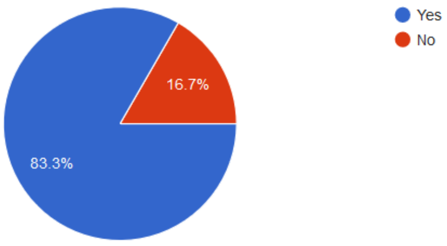
Does the possibility of introducing low emission zones in your city effect your choice of car technology, if you were buying a new car (i.e. choosing an alternative fuel source to power the vehicle)?

96 responses

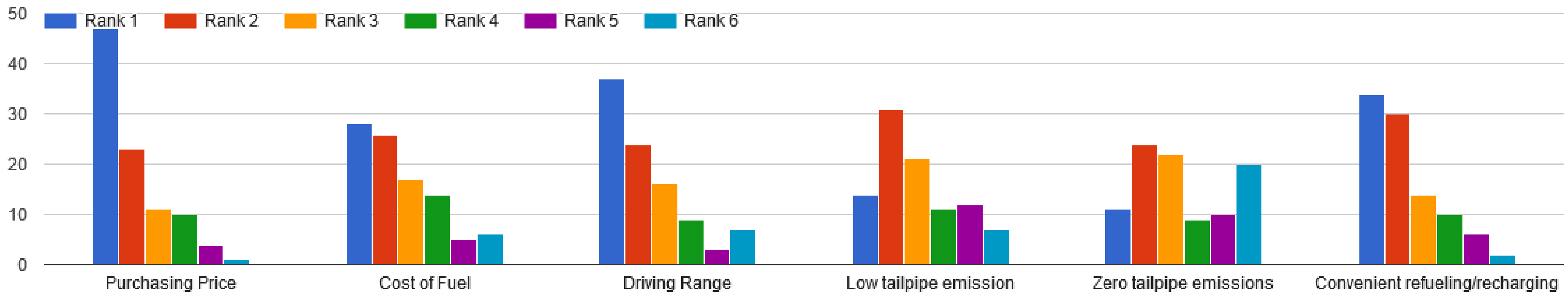


Does the existence of tax benefits for low emission vehicles affect your choice of vehicle?

96 responses



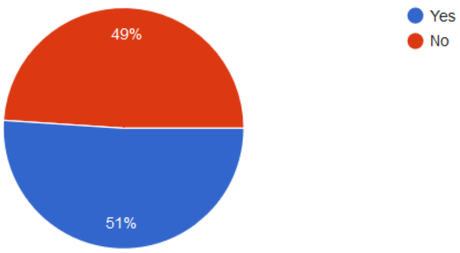
Please rank the following options according to your perception of importance when buying a new car (1 being the most important criteria)



G

Would a fluctuating oil price affect your choice of vehicle?

96 responses



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ANNEX II
COMPARISON OF BATTERY TECHNOLOGIES FOR EV USE
(Yong et al. 2015)

Battery type	Nominal voltage per cell [V]	Energy density [Wh/kg]	Volumetric energy density [Wh/L]	Specific power [W/kg]	Life cycle	Self discharge [% per month]	Memory effect	Operating temperature [°C]
Lead acid (Pb-acid)	2.0	35	100	180	1000	<5	No	-15 to +50
Nickel-cadmium (Ni-Cd)	1.2	50 - 80	300	200	2000	10	Yes	-20 to +50
Nickel-metal hydride (ni-MH)	1.2	70 - 95	180 - 220	200 - 300	< 3000	20	Rarely	-20 to +60
ZEBRA	2.6	90 - 120	160	155	>1200	<5	No	+245 to 350
Lithium-ion (Li-ion)	3.6	118 - 250	200 - 400	200 - 430	2000	<5	No	-20 to +60
Lithium-ion polymer (LiPo)	3.7	130 - 225	200 - 250	260 - 450	>1200	<5	No	-20 to +60
Lithium-iron phosphate (LiFePO4)	3.2	120	220	2000 - 4500	>2000	<5	No	-45 to +70
Zinc-air (Zn-air)	1.65	460	1400	80 - 140	200	<5	No	-10 to +55
Lithium-sulphur (Li-S)	2.5	350 - 650	350	-	300	8 - 15.	No	-60 to +60
Lithium-air (Li-air)	2.9	1300 - 2000	1520 - 2000	-	100	<5	No	-10 to +70