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Recent developments in alternative fuel vehicles, infrastructure and their prospects in replacing internal combustion engine vehicles.

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Abstract

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Internal combustion engine vehicles are a major source of pollution. To prevent a devastating impact on the environment, steps need to be taken to transition from combustion engine vehicles to cleaner alternatives. The availability of fossil fuels is also rapidly declining. These reasons make a fast transition to alternative fuel vehicles a necessity.

Currently, two technologies are the most likely successors to internal combustion engines: battery electric and fuel cell electric and were therefore focussed on in this thesis project. Their perspectives in replacing the internal combustion engines were explored.

In this thesis project, the recent developments in battery electric vehicles, fuel cell electric vehicles and their infrastructure were reviewed. Life cycle assessments of various vehicle technologies were explored and compared. The impact of energy generation on the life cycle emissions of alternative fuel vehicles were studied.

Keywords	battery electric vehicles, fuel cell electric vehicles, BEV, FCEV, life cycle assessment, LCA, hydrogen vehicles, electric vehicles

List of abbreviations

ICE – Internal Combustion Engine
ICEV – Internal Combustion Engine Vehicle
EV – Electric Vehicle
BEV – Battery Electric Vehicle
FCEV – Fuel Cell Electric Vehicle
GHG – Greenhouse Gas
GWP – Global Warming Potential
LCA – Lifecycle Assessment
WTW – Well To Wheel
WTT – Wheel To Tank

Contents

1 Introduction

The purpose of this thesis was to explore the perspectives of alternative fuel vehicles and to analyse how much of an actual improvement in terms of environmental impact a switch to different technologies would bring. The available and planned infrastructure as well as steps taken by different countries to promote more environmentally friendly means of transportation were examined.

This chapter will briefly show how the internal combustion engine vehicles (ICEVs) have developed in recent years, how the internal combustion engine (ICE) technology has matured, what the main emissions of ICEVs during the use phase are, their environmental effect, and what emission standards are currently implemented in Europe.

1.1 Internal Combustion Engine Vehicles

An internal combustion engine is a heat engine where the combustion of fuel happens in a combustion chamber (typically a cylinder) with the presence of an oxidizer. In this process, chemical energy is transformed into mechanical energy, which is used to exert force on a moving part which is typically a piston, turbine blade, rotor or nozzle. The first successful combustion engine was created by Étienne Lenoir around 1859. [1]

As seen in the Figure 1, ICE efficiency has seen a rapid increase since 1980’s due to better engine designs. A typical modern car is about 80% more efficient in terms of distance travelled per volume of fuel used than a typical car from 1970’s. Such an increase in efficiency happened due to an increase in engine efficiency and advancements in car design.

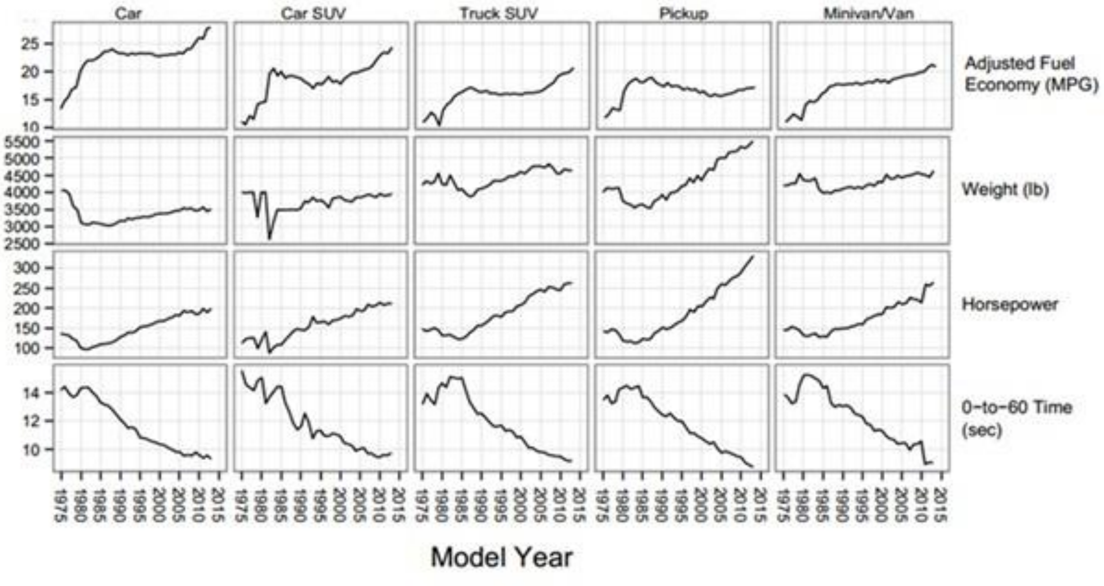


Figure 1. ICE efficiency for various vehicles, 1975 – 2015. [2]

As can be seen from the graph, presented in Figure 2, 1975-1982 saw a very large increase in fuel economy.

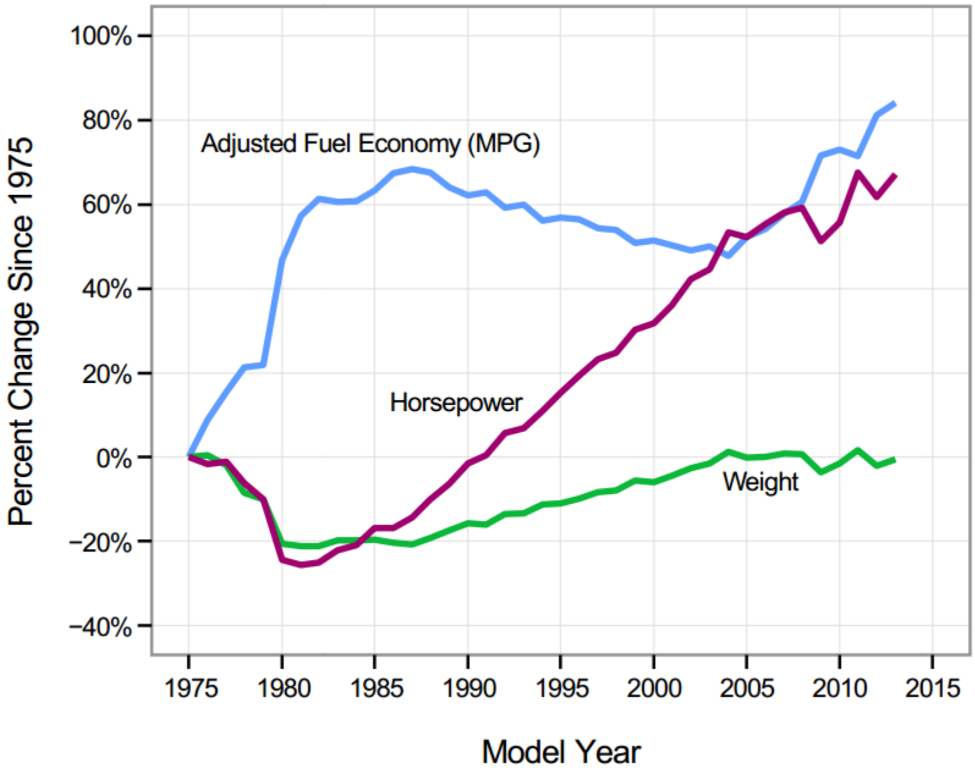


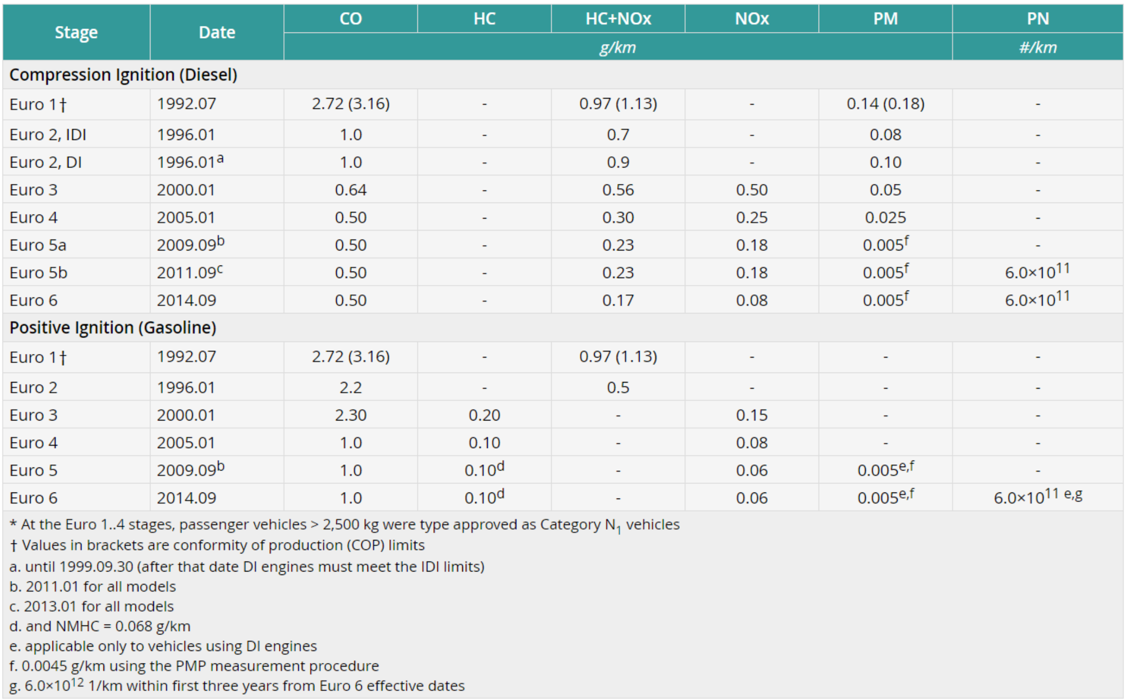
Figure 2. Percent change in ICE performance, 1975 – 2015. [3]

This happened due to various laws being passed that focused on enforcing manufacturing rules that set the minimum required fuel economy. Such laws were, for example, Corporate Average Fuel Economy (CAFE) standards established in 1975 by the US Congress and Energy Policy and Conservation Act of 1975. [3]

1.2 Emission standards

An emission standard is a piece of legislation that specifies maximum amounts of pollutants released in the atmosphere from specified sources. In Europe, emission standards for passenger cars and light commercial vehicles are set by the European Commission, which can be seen in Table 1.

Table 1. European emission standards for passenger cars. [4]



Stage	Date	CO	HC	HC+NOx	NOx	PM	PN
		g/km					#/km
Compression Ignition (Diesel)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	0.14 (0.18)	-
Euro 2, IDI	1996.01	1.0	-	0.7	-	0.08	-
Euro 2, DI	1996.01[a]	1.0	-	0.9	-	0.10	-
Euro 3	2000.01	0.64	-	0.56	0.50	0.05	-
Euro 4	2005.01	0.50	-	0.30	0.25	0.025	-
Euro 5a	2009.09[b]	0.50	-	0.23	0.18	0.005[f]	-
Euro 5b	2011.09[c]	0.50	-	0.23	0.18	0.005[f]	6.0×10^{11}
Euro 6	2014.09	0.50	-	0.17	0.08	0.005[f]	6.0×10^{11}
Positive Ignition (Gasoline)							
Euro 1†	1992.07	2.72 (3.16)	-	0.97 (1.13)	-	-	-
Euro 2	1996.01	2.2	-	0.5	-	-	-
Euro 3	2000.01	2.30	0.20	-	0.15	-	-
Euro 4	2005.01	1.0	0.10	-	0.08	-	-
Euro 5	2009.09[b]	1.0	0.10[d]	-	0.06	0.005[e,f]	-
Euro 6	2014.09	1.0	0.10[d]	-	0.06	0.005[e,f]	6.0×10^{11} [e,g]

* At the Euro 1..4 stages, passenger vehicles > 2,500 kg were type approved as Category N_1 vehicles
† Values in brackets are conformity of production (COP) limits
a. until 1999.09.30 (after that date DI engines must meet the IDI limits)
b. 2011.01 for all models
c. 2013.01 for all models
d. and NMHC = 0.068 g/km
e. applicable only to vehicles using DI engines
f. 0.0045 g/km using the PMP measurement procedure
g. 6.0×10^{12} 1/km within first three years from Euro 6 effective dates

The European Commission specifies maximum emissions for carbon dioxide per kilometer traveled (g CO_2/km), carbon monoxide (CO), total hydrocarbons (THC), nonmethane hydrocarbons (NMHC), nitrogen oxides (NOx), hydrocarbons and nitrous oxides (HC+NOx) and particulate matter (PM). [4]

1.3 Environmental impact

Air pollution has a major negative environmental impact. It causes or contributes to a number of problematic environmental effects, such as acid rain, eutrophication, haze, negative effects on wildlife, ozone depletion, crop and forest damage and global climate change. [5]

ICE vehicles are a major source of air pollution and greenhouse gas emissions. Transportation accounts for 17% of global CO_2 emissions [8], 58% NOx emissions, 18% NMVOC emissions, 21% SOx emissions, 22% – 27% of PM emissions and 30% of CO emissions. [6,7]

2 Alternatives to ICE Vehicles: Battery Electric and Fuel Cell Electric

2.1 Battery electric vehicles

Electric vehicle is a vehicle that uses electric or traction motors for propulsion.

The first electric car prototype was made by Ányos Jedlik, a Slovak-Hungarian priest in 1828. The first rechargeable battery electric car was built by an English inventor Thomas Parker in 1884. Electric cars reached their peak market share of 38% around 1900-1910, while steam and gasoline cars were at 40% and 22% respectively. Electric cars had many advantages over steam and gasoline cars: they were silent, odorless, reliable, simple to drive, and easy to start. Both steam and electric cars, however, had inferior range compared to that of gasoline cars. Establishing a road infrastructure and improvements in car technology has led to ICE cars eventually dominating the market. [8]

By the end of 2014, global EV stock was estimated to be over 665 000, which represents 0.08% of the global passenger car fleet. By the end of 2012, this number was approximately 180 000. [10]

Global EV sales have gone from around 5000 units per year in 2010, to 300 000 in 2014, as can be seen in Figure 3.

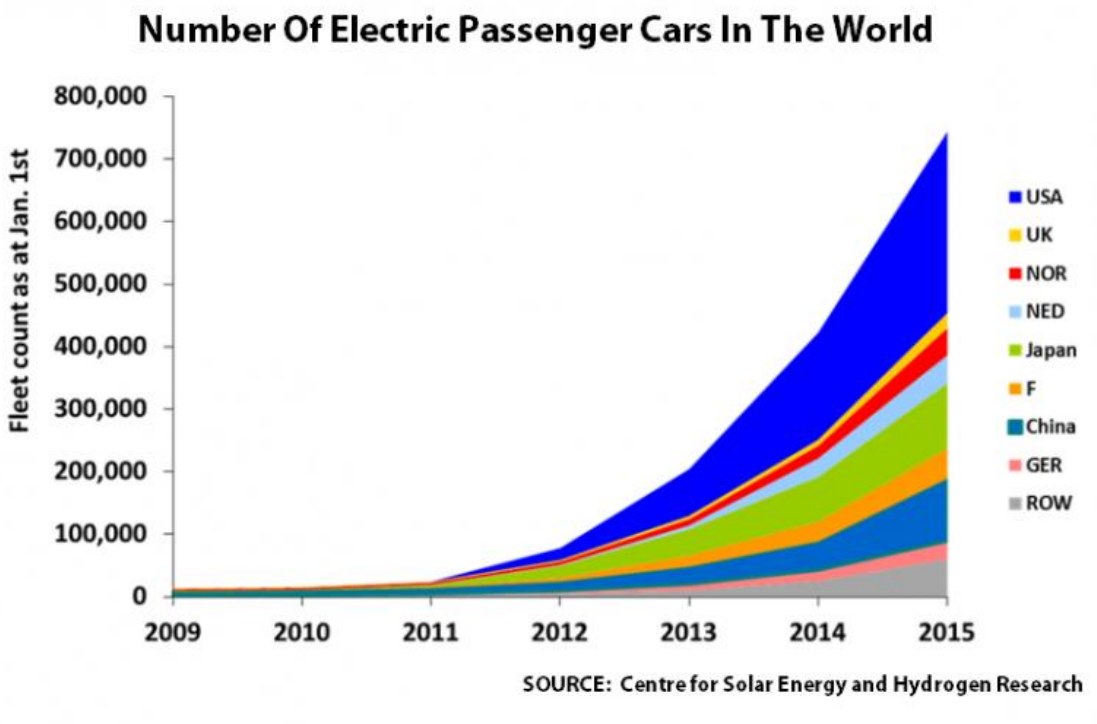


Figure 3. Number of electric passenger cars in the world. [10]

These numbers only include passenger cars and not busses, motorcycles or heavy-duty vehicles. China alone has almost 180 million two-wheel EV. In 2015, there were 46 000 electric busses and 235 million electric two-wheelers deployed. [9] [10]

In 2010, there were only 2-3 battery electric vehicles (BEV) models available to consumers. By the end of 2015, this number has reached 13 models. Also 16 plug-in hybrids (PHEV) were available in 2015. [11] There is a strong correlation between model variety and total sales.

2.2 Electric vehicles initiative (EVI) and EV deployment goals

The world population and energy consumption is growing. Current methods of energy generation produce large quantities of greenhouse gases which will lead to a catastrophic global temperature increase if left unchecked. In 2009 transportation accounted for 1/5 of global energy use and ¼ of CO_2 emissions, half of which were produced by passenger vehicles. International Energy Agency’s (IEA) published a report called *Energy Technology Perspectives 2012*, in which it estimated that the global vehicle stock and fuel consumption will more than double by 2050. Electric vehicles represent one of the best ways of reducing CO_2 emissions. [12]

EV require an ecosystem that would make them a convenient and affordable alternative to ICV. Many cities and regions around the world prepare for the coming mass EV market. A number of initiatives and incentives are being employed to encourage mass EV adoption. Financial incentives include “rebates or tax credits on vehicles (often paired with national government purchase subsidies), exemptions from vehicle registration taxes or license fees, discounted tolls and parking fares, as well as discounts for recharging equipment and installation”. [12] Nonfinancial incentives include “preferential parking spaces, access to restricted highway lanes, and expedited permitting and installation of electric vehicle supply equipment (EVSE).” [12]

Below are a number of examples by country and city.

2.2.1 Holland

Holland’s is planning to implement the following changes: “The plan contains a range of activities to stimulate electro-mobility in focus areas and viable market segments, strengthen international collaboration and partnerships, and roll out communication, research and monitoring. Besides this general economic policy, the national government offers opportunities to stimulate electro-mobility and aims to participate in European projects and welcomes opportunities for cooperation with other countries.” [12]

In 2011 a CAR2GO service was launched in Amsterdam. It is a public car rental service with electric vehicles available for pick up and drop off at any public parking spot inside the business area. In 2014, the city has passed the milestone of 1000 public charging stations and another 1000 semi-public or private charging points. The Amsterdam City Council aims to have 4000 charging points in the city by 2018. In 2011, the first in Europe fully electric taxi company (Taxi Electric) was launched in Amsterdam. From October 2014, all taxis travelling from Amsterdam Airport Schiphol are electric. [12]

2.2.2 Spain

National EV incentives include subsidies for purchase, discount registration tax, free parking in controlled parking lots, lower electricity tax, free charging on all municipal points on public roads (discontinued in 2012), free parking for Barcelona residents with 100% EVs and car parks with 2% of the spaces reserved for EV owners.

In Barcelona, e-bikes are available for the guests to rent with charging points available at the hotels. The stations were available free of charge till 2013. A sharing service for electric cars is also available. A person can use his mobile phone to open and use, for a fee, a number of electric cars available in strategic locations. It is essentially a car rental service, but it is easier to use due to it working with a mobile phone.

Barcelona has also partnered with chargelocator.com, a service that allows its users to find nearest, available and cheapest charging spots via a mobile app. [12]

2.2.3 Japan

In Kanagawa, K.P.G. – Kanagawa EV Promotion Council was established in 2006. It is a collaboration between the government of Japan, industry and academia, established to promote electric vehicles. K.P.G. provides subsidies, tax breaks and incentives. The national government subsidizes 50% of the cost difference between the cost of EVs and gasoline vehicle. K.P.G provides the other half of this subsidy, grants an automobile tax release for 5 years and 100% tax release for buying a car. Also 50% toll discounts are in place on express highways.

Hakone, a town with many hot springs and over 20 million visitors a year, is taking steps transitioning into a low carbon community. To achieve this goal, it is implementing a number of steps: EV sharing, EV rentals, charging spots at parking places, hotels, restaurants golf resorts, museums, hot springs; e-taxis, e-bikes, e-busses. [12]

2.2.4 USA

In many cities, on-road vehicles are majorly polluting the environment. In Los Angeles, on-road vehicles account for 43% of all emissions, including CO_2. Los Angeles has the highest Ozone levels in USA, 137 days a year over the national safety limit. These are some of the reasons why the state of California is taking steps to promote the adoption of electric vehicles. The federal government offers a tax credit of up to $7,500 for PEV purchases. “The California Air Resources Board (CARB) is revising the Zero Emission Vehicle (ZEV) mandate to include GHG reduction; and the Low Carbon Fuel Standard (LCFS) will mandate a 10 percent reduction in average fuel carbon intensity for all fuels distributed by 2020.” [12]

The state of LA offers up to $2500 rebate on EV purchases. EV’s are allowed in high occupancy lanes regardless of the number of occupants. Los Angeles International Airport is using a fleet of all electric shuttle busses. These busses not only reduce emissions but result in savings of up to $500,000 over the lifetime of each bus. The port of LA utilizes a fleet of all-electric drayage trucks. [12]

“Los Angeles is working with a regional collaborative–comprised of utilities, cities, and regional government agencies–known as SoCal EV, share regional EV data and research, jointly pursue grant funding opportunities, and coordinate a regional approach to the deployment of PEV charging infrastructure.” [12]

These are but a few examples of the developments in EV adoption. Most countries are taking significant steps in promoting EV usage and developing the supporting infrastructure.

In terms of commercial efforts, Tesla motors a USA-based company deserves a mention as it offers free fast charging stations for Tesla vehicles. As of April 2016, there are 617 fast charging stations around the world. This is very significant because fast charging offers the possibility of long distance travel. The battery of Tesla Model S (90kWh) takes about 30 minutes to charge to 70% capacity when using the fast charging station, which offers 170 miles (274 km) of range. Fast charging is not a unique feature of the Tesla Company and many companies offer fast charging services around the globe. However, Tesla is the only company, as of 2016, to offer fast charging for free for their vehicles. [14]

3 Comparison of BEV to ICEVs (LCA)

3.1 Introduction

Road vehicles with internal combustion engines are large contributors in the pollution of cities. In large cities, ICE vehicles are the most problematic in terms of their negative environmental impact. Due to a very large amount of road vehicles in the big cities, the road traffic often becomes congested which leads to a large decrease in the speed of traffic flow and an increase in stop-and-go traffic. This leads to a large increase in fuel consumption, emissions of pollutants and greenhouse gases. According to a study made by World Business Council for Sustainable Development (2004), the amount of light road vehicles could increase from approximately 700 million to 2 billion over 2000-2050. This means a very large increase in gasoline and diesel demands, environmental impact and GHG emissions.

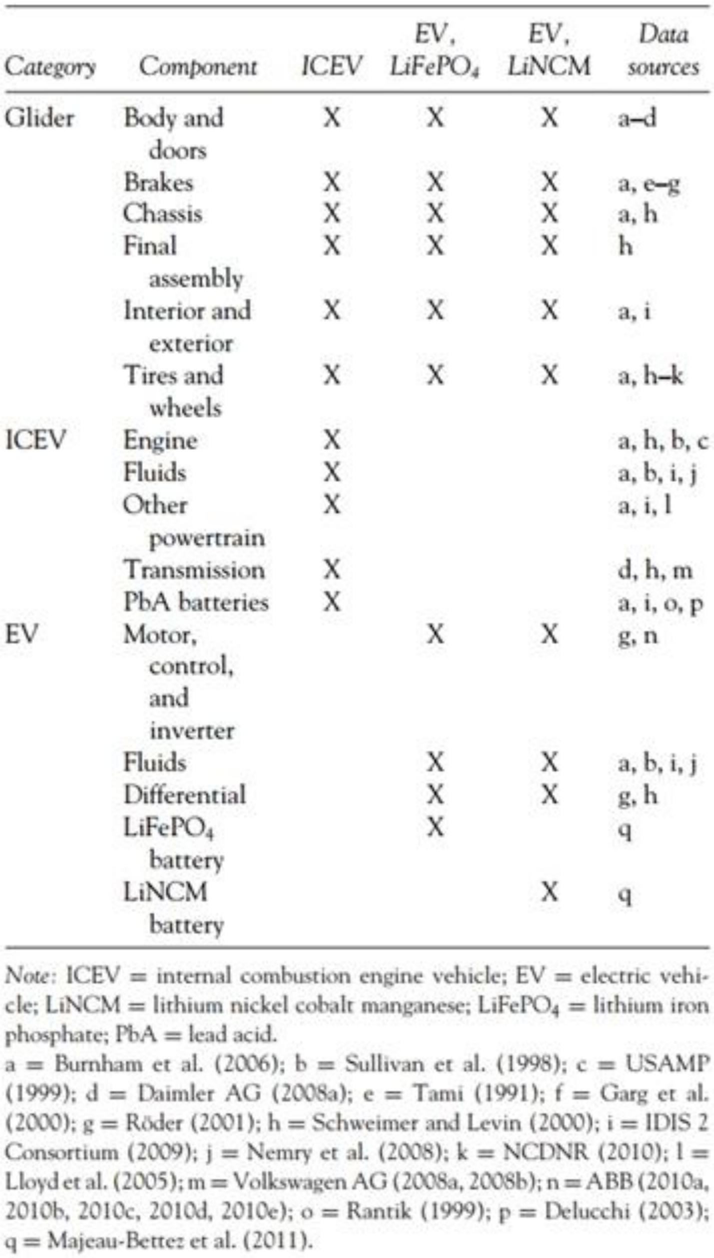
Taking Moscow as an example, a city with the population of approximately 15 million in 2014. There were around 4 million ICE vehicles on the road in 2014. There was an estimated deficit of 400 kilometers of city roads in relation to the total amount of road vehicles. This leads to a global road speed of less than 28 km/h. During rush hours, approximately 400,000–550,000 vehicles are traveling on the roads at the same time. Yearly, the road vehicles consume over 4.5 million tons of fuel, which is equivalent to around 1.2 tons of pollutants emitted and 14 million tons of CO_2 produced. The total environmental damage caused by road vehicles is estimated to be 1.5-1.8% of GDP. The situation is expected to get worse in the future with the number of road vehicles constantly growing and expected to reach 5.5 million in 2020. [15]

3.2 LCA of BEVs vs ICEVs

A comparison between ICEVs and EV needs to include all significant differences between them. Such differences include engine, fluids, powertrain, transmission PbA batteries, motor, control, inverter, differential, and $LiFePO_4$ and LiNCM batteries. The phases of the LCA include vehicle production, use and end of life, including all the supply chains needed. In the use phase, the energy and fuel consumption were tracked. “Use phase energy requirements were based on Mercedes A-series ICEV and Nissan Leaf

EV, comparable vehicles in terms of mass, size and power. For the end of life, the treatment and disposal of the vehicles and batteries were modeled.” [16]

Table 2. A list of vehicle components included in this LCA. [16]



Category	*Component*	*ICEV*	*EV, LiFePO$_4$*	*EV, LiNCM*	*Data sources*
Glider	Body and doors	X	X	X	a–d
	Brakes	X	X	X	a, e–g
	Chassis	X	X	X	a, h
	Final assembly	X	X	X	h
	Interior and exterior	X	X	X	a, i
	Tires and wheels	X	X	X	a, h–k
ICEV	Engine	X			a, h, b, c
	Fluids	X			a, b, i, j
	Other powertrain	X			a, i, l
	Transmission	X			d, h, m
	PbA batteries	X			a, i, o, p
EV	Motor, control, and inverter		X	X	g, n
	Fluids		X	X	a, b, i, j
	Differential		X	X	g, h
	LiFePO$_4$ battery		X		q
	LiNCM battery			X	q

Note: ICEV = internal combustion engine vehicle; EV = electric vehicle; LiNCM = lithium nickel cobalt manganese; LiFePO$_4$ = lithium iron phosphate; PbA = lead acid.
a = Burnham et al. (2006); b = Sullivan et al. (1998); c = USAMP (1999); d = Daimler AG (2008a); e = Tami (1991); f = Garg et al. (2000); g = Röder (2001); h = Schweimer and Levin (2000); i = IDIS 2 Consortium (2009); j = Nemry et al. (2008); k = NCDNR (2010); l = Lloyd et al. (2005); m = Volkswagen AG (2008a, 2008b); n = ABB (2010a, 2010b, 2010c, 2010d, 2010e); o = Rantik (1999); p = Delucchi (2003); q = Majeau-Bettez et al. (2011).

For the vehicle production assessment, the GREET 2.7 vehicle cycle model served as a starting point and was adapted to match the Mercedes A-Class and included the data from industry inventories and reports. For the EV assessment, Nissan Leaf 2010b was used.

As for the use phase,

> The energy requirements were based on the industry performance tests. “Use phase energy requirements were assumed to be 0.623 megajoules/kilometer (MJ/km)4 for the EV, 68.5 milliliter/kilometer (mL/km)5 for the gasoline ICEV, and 53.5 mL/km for the diesel ICEV, based on the Nissan Leaf (Nissan 2010a), the Mercedes A-170, and an average of the Mercedes CDI A-160 and A-180 results (Daimler AG 2008a). These vehicles were selected because of their comparable sizes, masses, and performance characteristics. [16]

For the end of life phase, vehicle lifetime was 150,000 km, which is lower than usually used in studies. Ecoinvent v2.2 was used for the end of life treatment.

Figure 4 evaluates 6 technologies in terms of 10 environmental LCA. Those are “LiNCM or $LiFePO_4$ EV powered by European average electricity (Euro), and LiNCM EV powered by either natural gas (NG) or coal (C) electricity, and an ICEV powered by either gasoline (G) or diesel (D).” Impacts are sorted by life cycle stages and normalized for largest impact. Different impacts of the two EV versions are only due to different battery manufacturing.

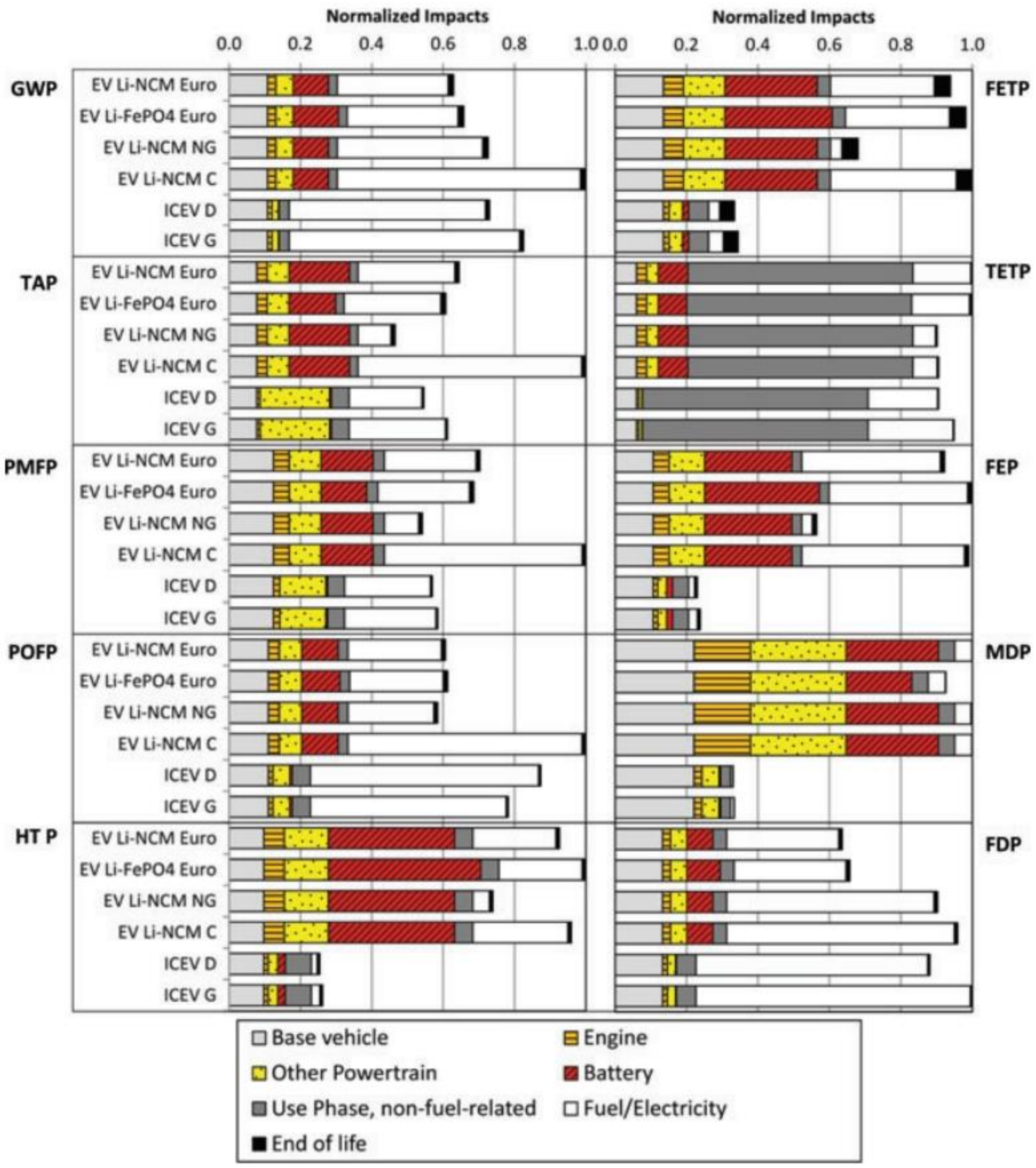


Figure 4. Results for the various environmental impacts of different engine technologies.

The acronyms used are explained below:

- GWP (global warming potential).
- TAP (terrestrial acidification potential).
- PMFP (particulate matter formation).
- POFP (photochemical oxidation formation potential).
- HTP (human toxicity potential).
- FETP (fresh water eco-toxicity potential).
- TETP (terrestrial eco-toxicity potential).
- FEP (freshwater eutrophication potential).

- MDP (mineral depletion potential).
- FDP (fossil depletion potential).
- ICEV (internal combustion engine vehicle).
- EV (electric vehicle).
- $LiFePO_4$ (lithium iron phosphate).
- LiNCM (lithium nickel cobalt manganese).
- C (coal).
- NG (natural gas).
- Euro (European electricity mix)

3.3 LCA results

For all cases, HTP (human toxicity potential), MDP (mineral depletion potential), and FETP (freshwater eco-toxicity potential) are caused mostly by the supply chain of manufacturing. The use phase is the most significant contributor for GWP (global warming potential), TETP (terrestrial eco-toxicity potential) and FDP (fossil depletion potential). End of life treatment is a very minor contributor in all cases. The production phase of EV has the most negative environmental impact potential. For ICEV, it is the use phase, except TAP (terrestrial acidification potential).

Global Warming Potential (GWP)

In all cases analyzed, the use phase contributes the most to the GWP impact through fuel consumption or energy generation. When the average European electricity is used, “electric vehicles reduce the global warming potential by 20 - 24% compared to gasoline ICEV and by 10 – 14% compared to diesel ICEV.” When the electricity is produced by natural gas, LiNCM EVs reduce GHG emissions by 12% compared to gasoline ICEVs and are at the same level with diesel ICEVs. Electric vehicles powered by coal produced energy increase GWP by 17% to 27 % compared to diesel and gasoline ICEVs.

Nearly half of the EVs life cycle GWP comes from its production, which equals to approximately 87 – 95 grams of CO_2/km, which is nearly double the 43 g CO_2/km of the ICEV production. Battery production is about 35% to 41% of the EV production phase GWP and the electric engine is about 7% - 8%. Other parts, especially those with high aluminum content, such as inverters and the battery cooling system, represent 16% - 18% of the EVs GWP.

EVs with LiNCM batteries have a slightly smaller GWP impact than $LiFePO_4$ EVs because of their greater energy density. [16]

Due to that fact that the most GWP of EVs life cycle comes from the production phase, the longer the vehicle is in use, the greater GWP reduction it has. Assuming 200,000 km traveled, the GWP reduction would be 27% - 29% relative to gasoline powered vehicles and 17% - 20% relative to diesel powered vehicles. Assuming 100,000 traveled, the GWP reduction becomes 9% - 14% compared to gasoline vehicles and around equal compared to diesel vehicles. The same goes for other environmental impact categories, because the vehicle production phase of EVs has the most environmental impact.

The *TAP (terrestrial acidification potential)* is similar between EVs and ICEVs. The main source of TAP in EVs production phase is the production of nickel, copper and aluminum that are required for the manufacturing of the motor and battery. For ICEVs the main source of the production phase TAP is the manufacturing of the catalytic converter.

For the use phase, more than 70% of the TAP is the sulfur dioxide (SO_2) emissions. Due to the fact that in Europe the average means of energy production involve burning hard coal and lignite, the use of electricity does not significantly impact the overall SO_2 emissions of EVs compared to ICEVs. Notable improvements only appear when using electricity sources with similar or lower sulfur content than natural gas.

The *PMFP (particulate matter formation potential)* is similar to the TAP scenario, where in the use phase the main source of pollution comes from the production of nickel, copper and aluminum. SO_2 emissions are the main source of the PMFP in all the life cycle phases as well. An electricity source with comparable or lower sulfur content is required here as well to achieve significant reduction to the emissions of EVs compared to ICEVs.

The *POFP (photochemical oxidation formation potential)* is significantly lower in EVs, showing 22% to 33% reduction compared to ICEVs, when using standard European electricity. The releases of nitrogen oxides (NOx) are the main cause of the POFP. NOx are mostly released during combustion and also blasting in mining procedures.

The *HTP (human toxicity potential)* is 180% to 290% greater in EVs compared to ICEVs. The main reasons for that are the additional copper and nickel requirements. 75% of the HTP arise from the disposal of the sulfidic mine tailings and the rest from the disposal of the waste from lignite and coal mining.

The *FETP (freshwater ecotoxicity potential) and FEP (eutrophication potential)* show significant improvements in the EVs case when natural gas combustion or a cleaner method is used as the source of electricity.

The *TETP (terrestrial ecotoxicity potential)* appears mostly from the use phase, from zinc emissions in tire wear and from copper and titanium emissions from break ware. For this reason, there is not a significant difference between EVs and ICEVs with regards to the TETP.

The *MDP (metal depletion potential)* in EVs life cycle is approximately three times that of ICEVs due to EVs reliance on different rare metals, but this number is uncertain, due to the reference research not being focused on MDP.

The *FDP (fossil depletion potential)* may decrease by 25% to 36% with EVs using the average European electricity. However, use of natural gas or coal as the source of electricity does not lead to significant reductions. [16]

4 FCEV (Fuel Cell Electric Vehicles) and FCEV vs EV

4.1 Introduction

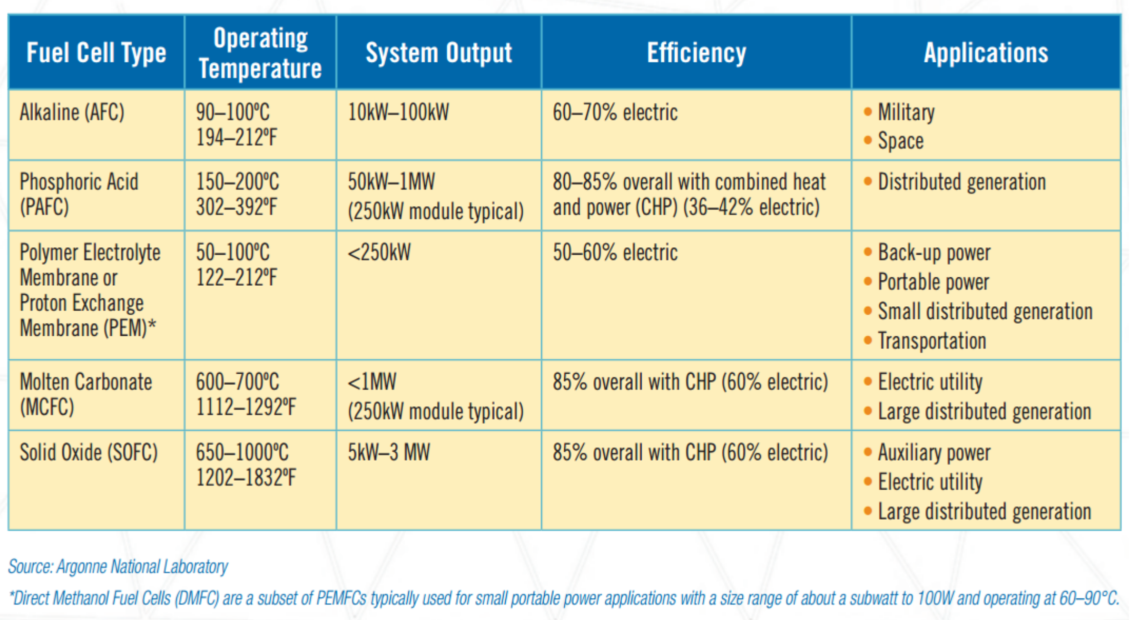
Hydrogen is an energy source with very high potential for future use in automotive and other industries. Our planet has a practically unlimited supply of hydrogen in contrast to the fossil fuels. A unit of mass of hydrogen contains nearly 3 times as much chemical energy as gasoline [17]. It can be widely used in the transport industry. Using hydrogen as an energy source has the potential of reducing the environmental impact of energy generation when compared to fossil fuels. Combustion of hydrogen produces mostly distilled water vapor and a small amount of nitrogen oxide (NO_2), while the combustion of fossil fuels has a much heavier environmental impact. However, using hydrogen fuel cells provides greater opportunities due to higher efficiency. In contrast to gasoline ICEs, fuel cells are two to three times more efficient: 20% vs 40% - 60%. The byproducts of hydrogen fuel cells are water vapor and heat, which makes them extremely eco-friendly in the use phase.

4.2 Fuel cell operation principles

According to the U.S. department of energy:

> A single fuel cell consists of an electrolyte sandwiched between two electrodes, an anode and a cathode. Bipolar plates on either side of the cell help distribute gases and serve as current collectors. In a Polymer Electrolyte Membrane (PEM) fuel cell, which is widely regarded as the most promising for light-duty transportation, hydrogen gas flows through channels to the anode, where a catalyst causes the hydrogen molecules to separate into protons and electrons. The membrane allows only the protons to pass through it. While the protons are conducted through the membrane to the other side of the cell, the stream of negatively-charged electrons follows an external circuit to the cathode. This flow of electrons is electricity that can be used to do work, such as power a motor.
>
> On the other side of the cell, oxygen gas, typically drawn from the outside air, flows through channels to the cathode. When the electrons return from doing work, they react with oxygen and the hydrogen protons (which have moved through the membrane) at the cathode to form water. This union is an exothermic reaction, generating heat that can be used outside the fuel cell.
>
> The power produced by a fuel cell depends on several factors, including the fuel cell type, size, temperature at which it operates, and pressure at which gases are supplied. A single fuel cell produces approximately 1 volt or less — barely enough electricity for even the smallest applications. To increase the amount of electricity generated, individual fuel cells are combined in series to form a stack. (The term “fuel cell” is often used to refer to the entire stack, as well as to the individual cell.) Depending on the application, a fuel cell stack may contain only a few or as many as hundreds of individual cells layered together. This “scalability” makes fuel cells ideal for a wide variety of applications, from laptop computers (50-100 Watts) to homes (1-5kW), vehicles (50-125 kW), and central power generation (1-200 MW or more).” [18]

Table 3. Performance of various types of fuel cells. [18]



Fuel Cell Type	Operating Temperature	System Output	Efficiency	Applications
Alkaline (AFC)	90–100°C 194–212°F	10kW–100kW	60–70% electric	• Military • Space
Phosphoric Acid (PAFC)	150–200°C 302–392°F	50kW–1MW (250kW module typical)	80–85% overall with combined heat and power (CHP) (36–42% electric)	• Distributed generation
Polymer Electrolyte Membrane or Proton Exchange Membrane (PEM)*	50–100°C 122–212°F	<250kW	50–60% electric	• Back-up power • Portable power • Small distributed generation • Transportation
Molten Carbonate (MCFC)	600–700°C 1112–1292°F	<1MW (250kW module typical)	85% overall with CHP (60% electric)	• Electric utility • Large distributed generation
Solid Oxide (SOFC)	650–1000°C 1202–1832°F	5kW–3 MW	85% overall with CHP (60% electric)	• Auxiliary power • Electric utility • Large distributed generation

Source: Argonne National Laboratory

**Direct Methanol Fuel Cells (DMFC) are a subset of PEMFCs typically used for small portable power applications with a size range of about a subwatt to 100W and operating at 60–90°C.*

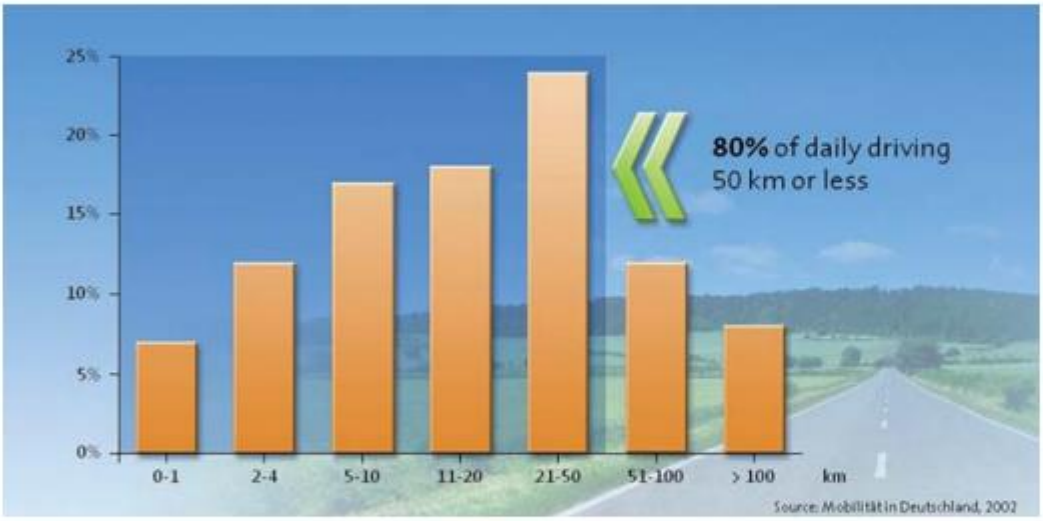
4.3 FCEVs perspectives

This section attempts to answer the question whether one technology such as battery electric vehicles has to replace internal combustion engine ones, or whether it could co-exist with another technology such as hydrogen fuel cell vehicles. Due to a vast difference in stored energy per mass, these two technologies may coexist and occupy different market segments.

A typical modern vehicle can achieve a 500 km range, or can exceed 1000 km in case of some diesel vehicles. A 500 km range diesel tank system would weigh close to 43 kg and has a storage volume of less than 50 l. To achieve a similar range with the current Li-ion battery technology, the energy storage system would have to weigh approximately 850 kg. Also, it may take anywhere from an hour to 12 hours to recharge a 100 kWh battery, depending on the charging rate, whereas refueling a gas tank takes minutes.
A hydrogen powered vehicle tank system could weigh approximately 125 kg to achieve the same 500 km range. The Figure 5 shows a visual representation of the numbers discussed.

Figure 5. Energy storage system weight and volumes for various energy carriers. [19]

Figure 6 illustrates that in Germany, nearly 80% of daily vehicle travel distances are shorter than 50 km, while only approximately 7% of trips require distances longer than 100 km. In other words, for a daily commute, BEVs have the potential to suit the vast majority of people in Europe.



Source: Mobilität in Deutschland, 2002

Figure 6. Daily driving distances in Germany. [19]

The current state of these technologies is such that hydrogen is better suited for vehicles that require long range. However, for shorter ranges, battery electric vehicles are suited better, because they do not require the necessary infrastructure that is currently not in place for hydrogen distribution in most parts of the world. To charge a battery electric vehicle, one may simply use a power outlet at home or use a power outlet widely available at the parking stations in most European countries. Even though the charging time is significant, an overnight charge is likely to last a full normal working day.

5 FCEVs Compared to Various Vehicles

5.1 FCEVs and hydrogen

While the use phase emissions of FCEVs do not present an environmental concern, the methods of hydrogen generation certainly do. As is the case with BEVs, if fossil fuels are used to produce electricity, or in this case produce hydrogen, only limited benefits can be seen in terms of the environmental impact if any.

Currently, more than 95% of hydrogen produced worldwide is derived from fossil fuels, 49% is derived from natural gas via steam methane reforming, 29% is produced from oil, most of which is used in gasoline refineries, and 18% is produced from coal, mostly for the manufacturing of ammonia. The remaining 4% is produced via electrolysis. [20]

Four stages of the life cycle were considered. Well to tank stage (WTT) includes the extraction of raw materials and fuel production. The manufacturing stage includes the production of components and vehicle assembly. The use stage includes the tank-to-wheel (TTW) path and maintenance of the vehicle. The end-of-life stages includes the end of life treatment. The full life cycle was considered here and not the more typical well-to-wheel assessment, because the latter does not take as many factors into account, such as battery manufacturing, end-of-life treatment and assembly, and thus creates a bias towards zero-tailpipe emission vehicles. [20]

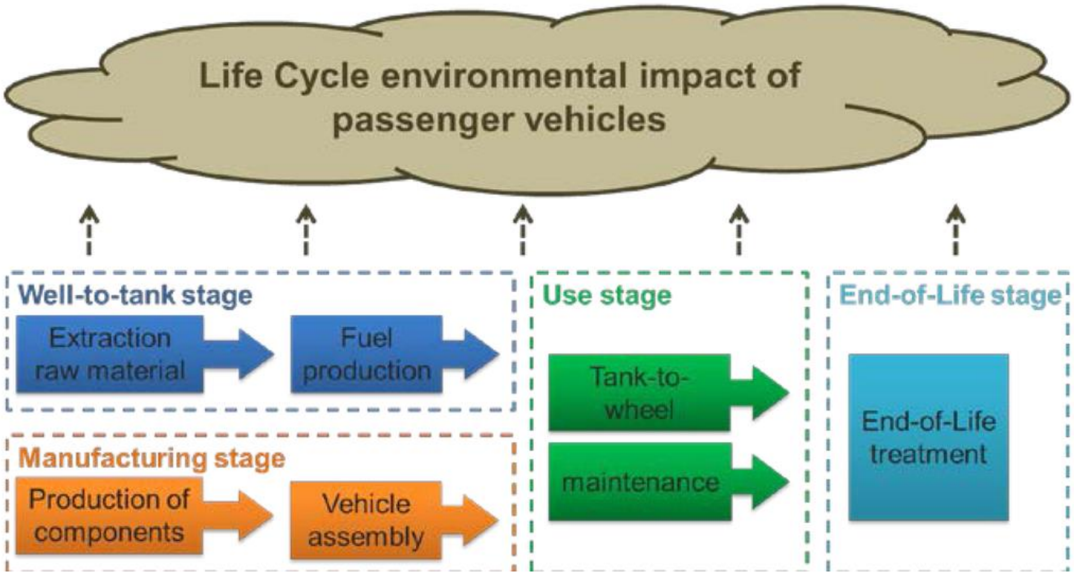


Figure 7. Life cycle environmental impact of passenger vehicles. [21]

According to Eberle, Muller and Helmolt,

> “The vehicle specific data such as the fuel type, fuel consumption, Euro standard, weight and direct emissions are retrieved from an extensive vehicle database based on data mainly gathered by the Belgian federal service in charge of vehicle registration. An attributional LCA modeling framework has been used.
>
> The functional unit (FU) is a quantified description of the performance of product systems, for use as a reference unit. It allows comparing two or several product systems on the basis of a common provided service. In this paper, the functional unit is defined as driving 1 km in Europe. The functional unit takes all life cycle stages of the vehicle into account and assumes an average lifespan of 13.7 years and a total life mileage of 230,500 km. The total life time refers to the age of the average vehicle going to the end-of-life treatment in Belgium.” [21]

5.2 LCA of the FCEVs

5.2.1 Climate change

As can be seen in Figure 8, the FCEV has a higher negative climate change impact than the BEV, which is slightly lower than the diesel vehicle manufactured in accordance with the Euro 5 standard. The largest part of the climate change impact is due to the fact that both the energy and hydrogen manufacturing are heavily dependant on fossil fuels. Due to the same reason, the environmental impact will be drastically lowered when renewable energy sources are used to generate the fuel.

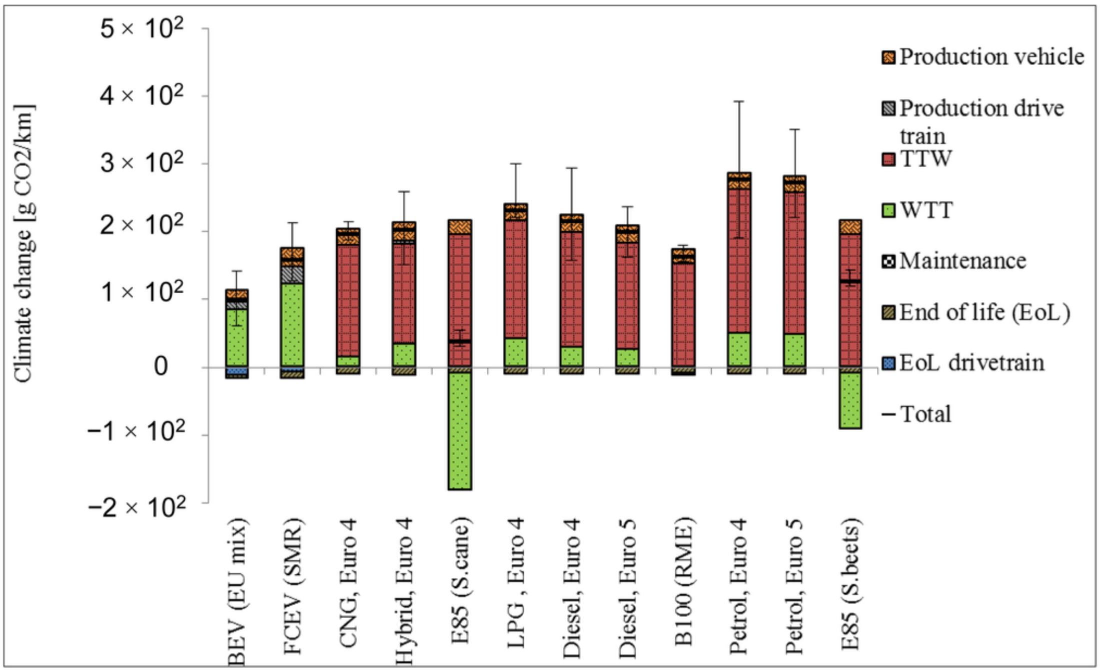


Figure 8. Climate change impact for various vehicles. [24]

Some of the acronyms used are SMR (steam methane reforming), CNG (compressed natural gas), LPG (liquified petrolium gas), RME (rapeseed methyl ester (biodiesel)).

5.2.2 Respiratory effects

The Figure 9 shows the respiratory effects impacts for various vehicles.

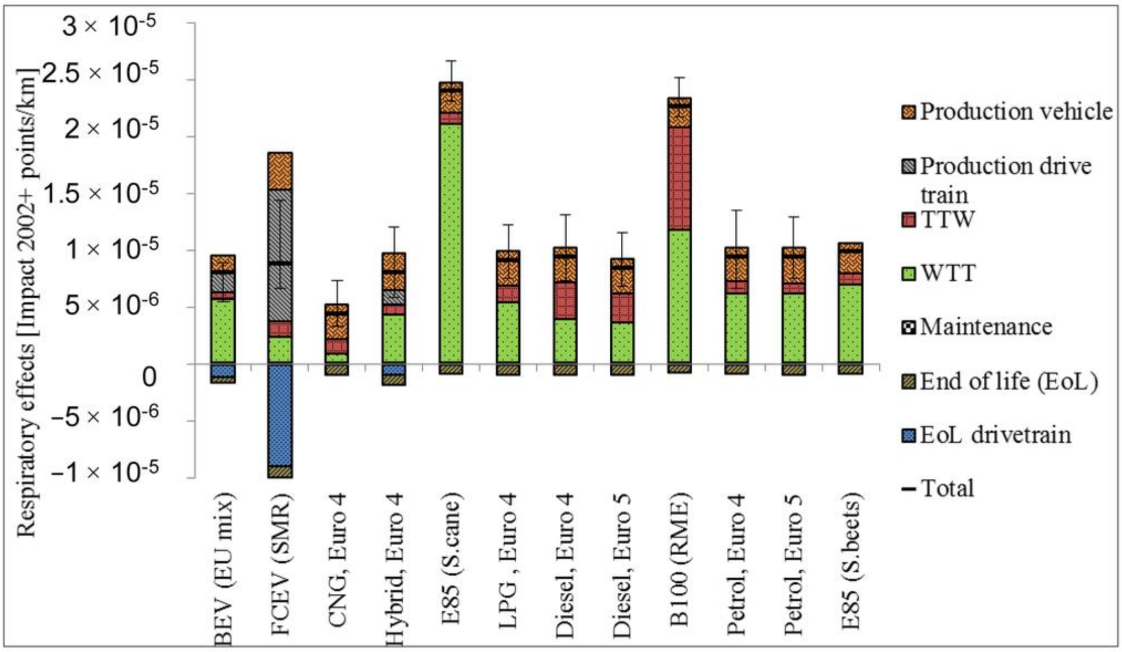


Figure 9. Respiratory effects impact for various vehicles. [24]

Most of the pollutants of the WTT phase of sugar cane are produced during the field burning and include methane, particulates and carbon monoxide. In case with the RME vehicle, the use of nitrogen fertilizers lead to nitrogen oxide and ammonia emissions. The condensed natural gas shows the best result in this category due to the lower environmental impact of gas production in this case.

5.2.3 Acidification

The respiratory effects impact results can be seen in Figure 10.

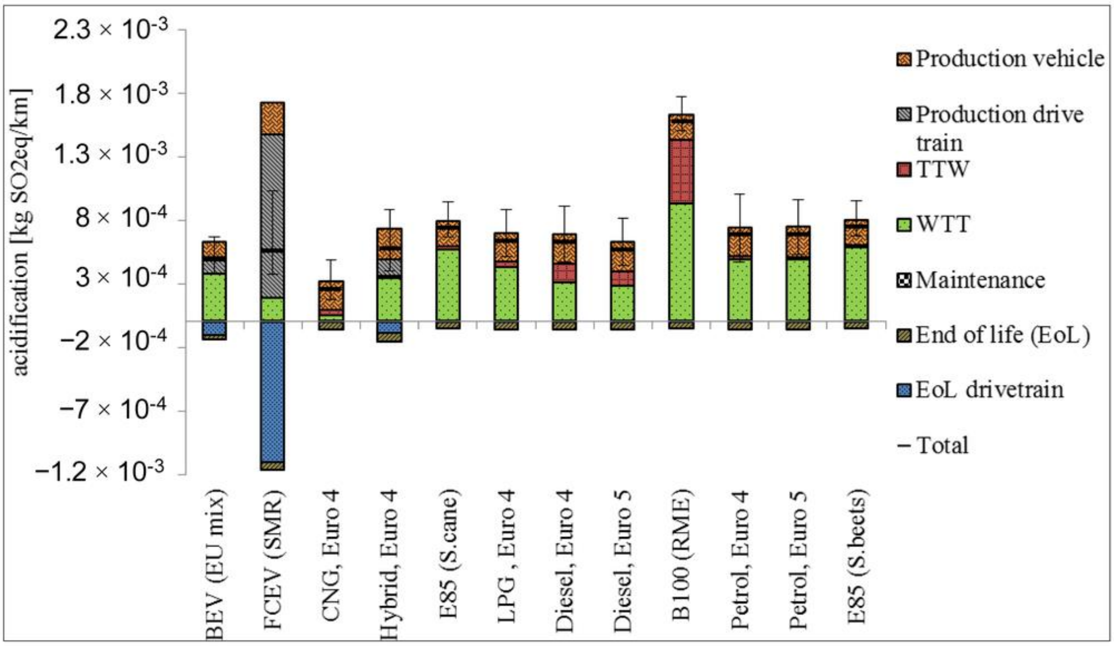


Figure 10. Acidification impact for various vehicles. [24]

The rapeseed methyl ester (biodiesel) vehicle shows the worst results in this category due to nitrogen, sulfur, fluoride and chloride. In the FCEV, the production of platinum has a large environmental impact, however it is offset by the fuel cell recycling.

5.2.4 Mineral Resource Depletion

In this category, the FCEVs have the largest impact due to the fuel cell production requirements. BEVs show the best result; however, the bigger the battery used, the more impact it will have. The energy generation phase has a significant impact on the BEVs as well.

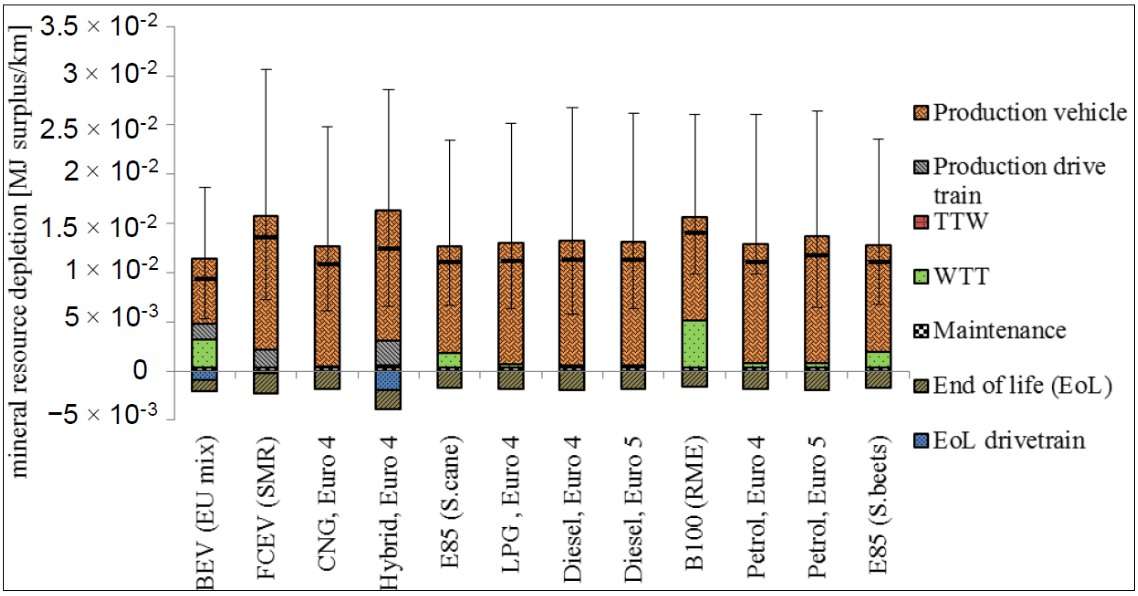


Figure 11. Mineral resource depletion for various vehicles. [21]

These results show the importance of recycling vehicular components such as batteries and fuel cells (FCEV, hybrid, BEV, etc.). [21]

5.3 Hydrogen Vehicle Fuelling Infrastructure

The fuelling infrastructure currently faces problems. A hydrogen refuelling station that produces hydrogen onsite would cost approximately $0.6 million to $3 million to install, for SMR reforming, and $2 million to $11.8 million for electrolysis. Truck delivery of hydrogen is around 10-20% more expensive. [22] Compared to Tesla’s supercharges station, which costs around $270,000 to install [23], the difference in costs is massive.

Another problem is that hydrogen refuelling infrastructure is highly less developed than the electricity charging station infrastructure. Currently, a person can use the existing and fast growing number of EV charging stations in most cities of the developed countries. At the same time, there is a very limited amount of hydrogen fuelling stations currently available. For example, there will be about 50 retail stations for hydrogen in the US, and their concentration is very uneven, mostly focused in California. [24] On the other hand, there were 12,271 charging stations and 30,847 outlets in February 2016, in the US. [25]

6 Conclusion

The general perception of alternative fuel vehicle technologies is often such that they bring a definite improvement over ICEVs in terms of their environmental impact and that the only question is how big this improvements is. This thesis has showed that the matter is more complicated than it may seem.

Alternative fuel vehicle technologies are not always more ecological and in fact their negative environmental impact can be greater in some areas. This thesis has shown that in order to utilise the full ecological potential of BEVs and FCEVs, the whole life cycle needs to be taken into account. One of the main findings is that a switch to sustainable energy generation is required to fully utilize the potential of alternative fuel vehicles.

At the moment of writing this thesis, hydrogen vehicles are overshadowed by battery electric vehicles. While FCEVs have a great potential due to high energy density of hydrogen, in their current state they are less economical and consumer friendly than BEVs. The required infrastructure for fuelling and repairs is underdeveloped and unavailable in most cities. While there are many BEVs available to choose from, only few FCEVs are available and at a higher price point than many BEVs.

Due to the collective effort of many countries, the number of BEVs is growing exponentially and their convenience and price rapidly approach conventional vehicles. The same cannot be said about FCEVs as their development is currently at a significantly earlier stage, which makes their future uncertain.

7 References

[1] Encyclopedia Britannica. History of technology [online]. [Cited 2016 Jun 21]; Available from: URL:
http://global.britannica.com/technology/history-of-technology

[2] Matt Smith. Performance and Fuel Economy Trends [online]. [Cited 2016 Jun 21]; Available from: URL: http://sites.lafayette.edu/egrs352-sp14-cars/performance-and-fuel-economy-trends/

[3] Union of Concerned Scientists. A Brief History of U.S. Fuel Efficiency Standards [online]. [Cited 2016 Jun 22]; Available from: URL: http://www.ucsusa.org/clean-vehicles/fuel-efficiency/fuel-economy-basics.html#.Vwnwr6REkuV

[4] EU Emission Standards for Passenger Cars [online]. [Cited 2016 Jun 23]; Available from: URL: https://www.dieselnet.com/standards/eu/ld.php

[5] Department of Environmental protection. Health & Environmental Effects of Air Pollution [online]. [Cited 2016 Jun 23]; Available from: URL: http://www.mass.gov/eea/docs/dep/air/aq/health-and-env-effects-air-pollutions.pdf

[6] US Environmental Protection Agency. Global Greenhouse Gas Emissions Data [online]. [Cited 2016 Jul 3]; Available from: URL: https://www3.epa.gov/climatechange/ghgemissions/global.html

[7] Pastorello. Emissions of air pollutants from transport [online]. 11 Sep 2015 [Cited 2016 Jun 23]; Available from: URL: http://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-air-pollutants-8/transport-emissions-of-air-pollutants-9

[8] History of Electro-technology Conference (HISTELCON), 2012 Third IEEE. Available [online]. [Cited 2016 Jun 23]; Available from: URL: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6487583

[9] Edeltstein. Electric Car Price Guide: Every 2015-2016 Plug-In Car, With Specs [online]. Jan 27, 2016 [Cited 2016 Jul 15]; Available from: URL: http://www.greencarreports.com/news/1080871_electric-car-price-guide-every-2015-2016-plug-in-car-with-specs-updated/page-3

[10] International Energy Agency. Global EV Outlook 2013 [online]. 2013 [Cited 2016 Jul 19]; Available from: URL: https://www.iea.org/publications/freepublications/publication/GlobalEVOutlook_2013.pdf

[11] Car list [online]. 2016 [Cited 2016 Jul 25]; Available from: URL: http://www.plugincars.com/cars?field_isphev_value_many_to_one=electric+%2B+gasoline

[12] Organisation for Economic Cooperation and Development/International Energy Agency. EV CITY CASEBOOK 2013 [online]. 2013 [Cited 2016 Jul 25]; Available from: URL: http://www.cleanenergyministerial.org/Portals/2/pdfs/EV_City_Casebook_LR.pdf

[13] Electric transport facts & figures [online]. [Cited 2016 Aug 3]; Available from: URL: http://www.iamsterdam.com/en/media-centre/city-hall/dossier-electric-transport/electric-transport-facts-figures

[14] Supercharger [online]. 2016 [Cited 2016 Aug 3]; Available from: URL: https://www.teslamotors.com/supercharger

[15] Azarov, Kozlov, Kutenev, Terenchenko. Economy of Modern and Perspective Automobile Constructions in their Full Life Cycle [online]. 2013 [Cited 2016 Aug 8]; Available from: URL: http://www.aae-press.ru/f/78/46.pdf

[16] Hawkins, Singh, Majeau-Bettez, Strømman. Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles. Journal of Industrial Ecology DOI: 10.1111/j.1530-9290.2012.00532.x Volume 17, Issue 1, 158–160, 16 January 2013.

[17] U.S. Energy Information Administration. TODAY IN ENERGY [online]. Feb 14, 2013 [Cited 2016 Aug 15]; Available from: URL: http://www.eia.gov/todayinenergy/detail.php?id=9991

[18] U.S. Department of Energy. Hydrogen Fuel Cells [online]. October 2006 [Cited 2016 Sep 4]; Available from: URL: http://californiahydrogen.org/sites/default/files/doe_fuelcell_factsheet.pdf

[19] Eberle, Rittmar. Sustainable transportation based on electric vehicle concepts: a brief overview. Energy Environ. Sci., 2012, 5, 8780, 2010, 3, 689-699

[20] Hwang. Sustainability study of hydrogen pathways for fuel cell vehicle applications. Renewable and Sustainable Energy Reviews 19, 2013, 220–229

[21] Messague, Boureima, Coosemans, Macharis, Mierlo. A Range-Based Vehicle Life Cycle Assessment Incorporating Variability in the Environmental Assessment of Different Vehicle Technologies and Fuels. Energies, 2014, 7, 1467-1482

[22] Melania, Penev. Hydrogen Station Cost Estimates [online]. 2015 [Cited 2016 Oct 15]; Available from: URL: http://www.nrel.gov/docs/fy13osti/56412.pdf

[23] ARK INVEST. Supercharger: A Charge Could Cost Half the Price of Gas [Online]. July 11, 2016 [Cited 2016 Oct 15]; Available from: URL: https://ark-invest.com/research/supercharger-cost-comparison#fn-6240-2

[24] Alternative Fuels Data Center. Hydrogen Fueling Stations [online]. 2016 [Cited 2016 Nov 10]; Available from: URL: http://www.afdc.energy.gov/fuels/hydrogen_stations.html

[25] The Statistics Portal. Number of public electric vehicle charging stations and charging outlets in the U.S. as of February 2016 [online]. 2016 [Cited 2016 Nov 10]; Available from: URL: https://www.statista.com/statistics/416750/number-of-electric-vehicle-charging-stations-outlets-united-states/