Department of Mechanical and Aerospace Engineering
MSc in Mechanical Engineering

Master of Science’s Thesis

Decarbonization scenarios for medium and heavy-duty transportation

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Executive Summary

Global warming caused mainly by greenhouse gases emission and health damages due to air pollutants are two crucial issues of the modern society, particularly in the last decade. The transportation sector is a key contributor to both sector and is responsible for 7.8 Gt of carbon dioxide in 2015 and more than half of the global energy emission of Nitrogen oxides (NO_x).

This thesis is focused on medium and heavy-duty trucks (MHDT) decarbonization in California. While MHDT are a small percentage in terms of population with respect passenger cars (less than 5% of passenger car vehicles in unit), the overall emission (GHG, NOx, Sox, $PM_{2.5}$) is only lower by a factor of three. The emission per vehicle is then much higher, as is the annual miles travelled by each vehicle.

In this project we consider battery electric trucks (BET) and fuel cell hydrogen electric trucks (FCET) technologies since they are the only technologies which have zero tailpipe emissions and thus their carbon emissions are constrained by the means of electricity or hydrogen fuel production. A technical comparison considering the most important parameters for medium and heavy-duty vehicles has been developed. We find that battery weight in BET is more sensitive to increased driving range than FCET by up to two orders of magnitude.

The volume of the hydrogen tank for high values of miles range will be also lower than the battery one, due to the high pressure of the hydrogen (350 or 700 bars have been considered). Furthermore, dealing with truck trailers, drayage trucks and buses the volume is not considered as a constraint

Using the EMFAC2017 model, developed by the California Air Resource Board (CARB), a reference case to 2050 has been defined taking into account current policies, and a stock analysis including fuel shares has been performed for Class 3-8 trucks using the LEAP software tool.

A cost analysis has also been developed, comparing diesel technology, BET and FCET for different manufacturing rates (100, 1000, 10000 trucks/year) and varying the battery size and fuel stack power by truck class. Sensitivity analysis has been also performed, varying the mileage range between refueling (300, 600, 1000, 1500 miles) and the cost of the various system components the system

Finally, due to the fact that no zero-emission truck policies have been enacted, another goal of this work is to analyze different future scenarios in order to identify zero-emissions truck adoption scenarios required to have a significant impact on reducing greenhouse gases and air pollutant emissions. For this purpose, three different adoption scenarios (low rate, medium rate and high rate of adoption) have been developed in LEAP.

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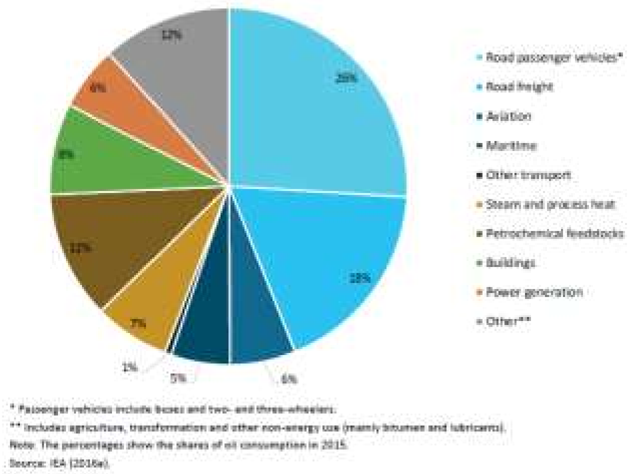
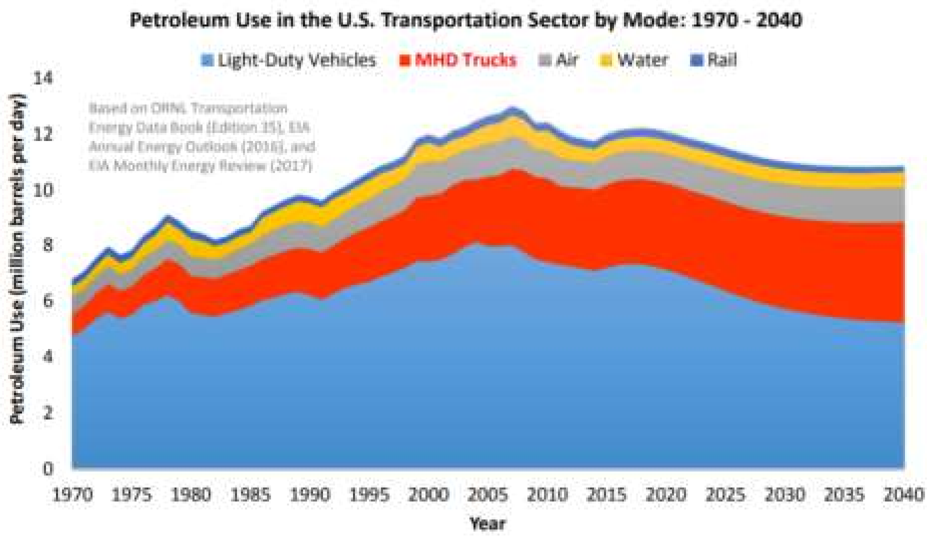
1 Introduction

1.1 Energy impact for transportation sector

The road freight transportation, which encompasses everything related to goods transfer, is a key enable of global economic activity and play a role of cardinal importance in the energy system. Globally, road freight transport consumption has grown by more than 50% over the past one-and-a-half decades, from around 23 exajoules (EJ) in 2000 to 36 EJ in 2015. Today, road freight transport makes up 32% of total transport-related energy demand [6]. This makes road freight transport an important contributor of oil demand, and much more in a predicted future scenario from [28] as shown in Fig 1.1



(a)



(b)

Figure 1.1 (a) Sectoral consumption of oil in 2015 – Global overview [6], (b) Petroleum use in the U.S. Transportation sector by mode: 1970-2040 [28]

From fig. 1.1(b) it is possible to notice that medium and heavy-duty vehicles (MHDVs) are the second largest and the fastest growing energy (petroleum) consumer.

Road freight transport is the primary user of Diesel among all sectors, which means that it accounts for 50% of total Diesel energy demand and 80% of net increase Diesel demand [6]. The huge use of Diesel in the freight transport sector has been emphasized in Fig 1.2.

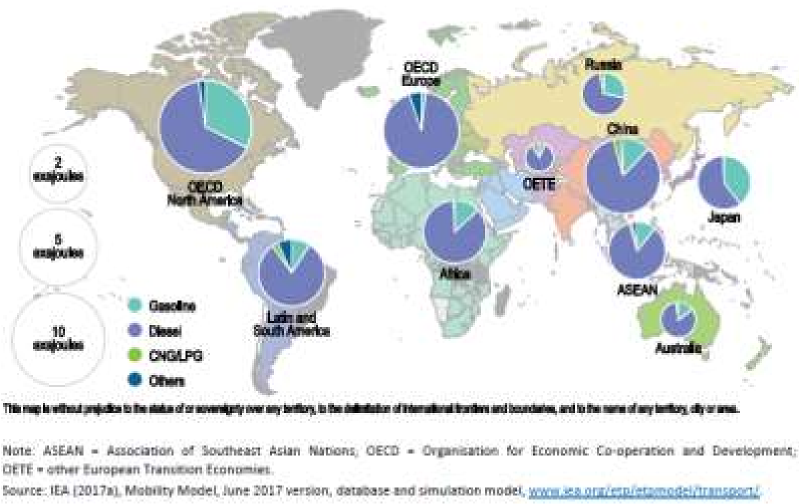


Figure 1.2 Global energy consumption of road freight vehicles, 2015 [6]

As far as Green House Gases are concerned, HDT accounts for 40% of road transportation, 75% of all freight (not only road) and from 2000 there has been 40% growth in CO_2 emission from all road transport and most it is ascribable to large trucks. HFTs contributed some 600 megatons (Mt) (or 65%) to global CO2 emissions growth from road freight vehicles, and MFTs another 300 Mt (33%) [6].

1.1.1 Emissions overview

The medium-heavy duty trucks contribute in GHG emission is evidenced in fig 1.3, where CO2 emission has been depicted over time [27].

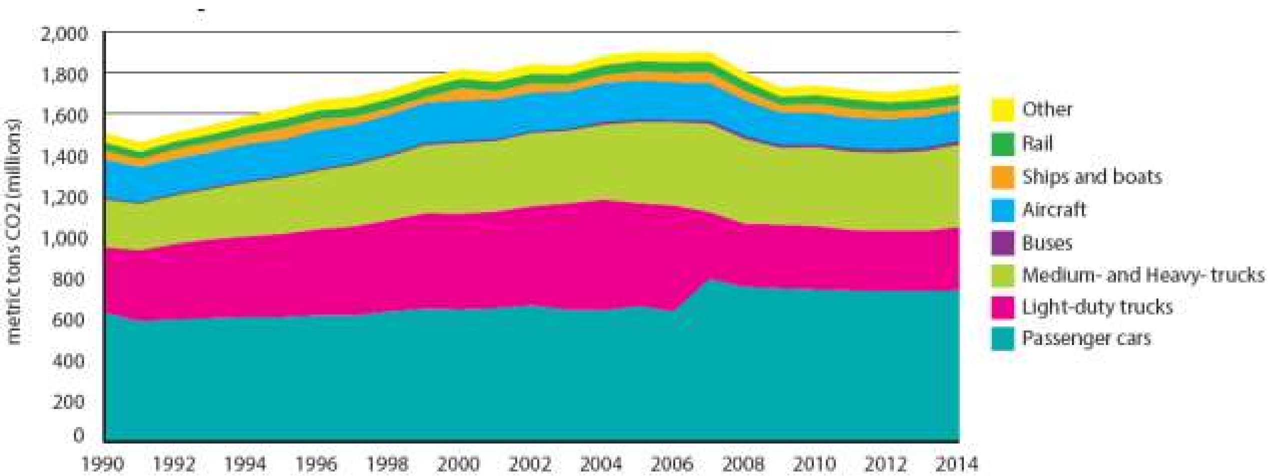
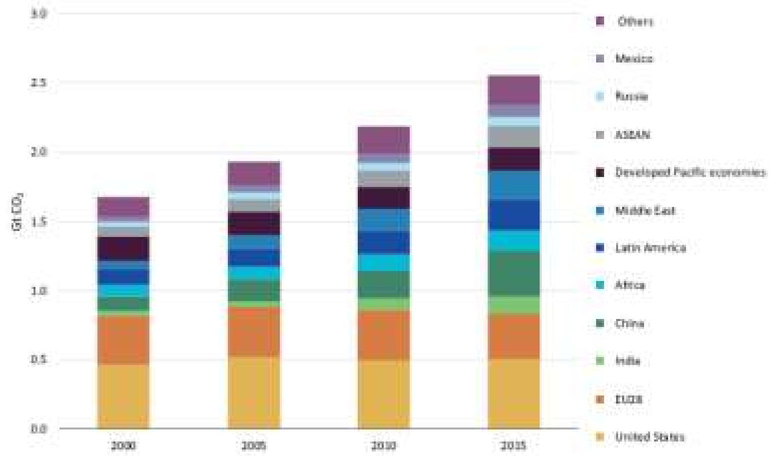


Figure 1.3: CO2 Greenhouse gas emissions by mode from 1990 to 2014 [27]

The GHG emission increase during the last decade can be seen clearly in Fig 1.4, which accounts only for the tailpipe emissions.

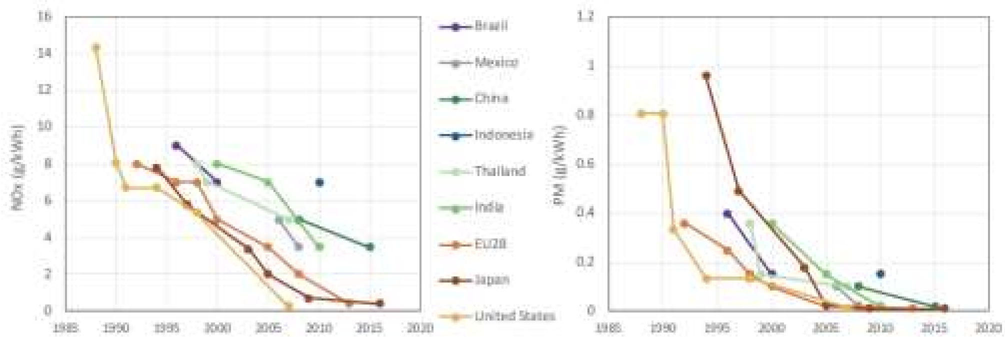
Increasing energy efficiency will be important to address carbon dioxide emissions. On the other hand transitioning a significant percentage of the sector to zero emission vehicles (ZEVs) will be necessary to meet climate change goals by the end of the century. This is especially important considering that the U.S. Energy Information Administration projects an 80% increase in truck miles between 2010 and 2050 [6]



Note : EU28 = European Union. Developed Pacific economies = Australia, Japan, Korea and New Zealand.
Source: IEA (2017a), Mobility Model, June 2017 version, database and simulation model, www.iea.org/etp/etpmodel/transport/.

Figure 1.4 Global tailpipe CO_2 eq emissions from road freight transport [6]

Besides GHG emission, air pollutant plays a key role in the human health sector: it accounts for 6.5 million death each year, making it the world's fourth-largest threat to human health behind high blood pressure, dietary risks and smoking. The transport sector contributes more than 50% in NOx emissions, 12 % SO_2 emissions and 7% of $PM_{2.5}$ (freight transport contributes in 35% of NOx, 50% of $PM_{2.5}$ and 4% SO_2 due to Diesel low SO_2 emission) [6].



Note: Other countries with pollutant emission standards for trucks in the range of those shown here include Argentina, Australia, Chile and Korea.
Source: ICCT and DieselNet (2016).

Figure 1.5 Global time evolution of air pollutant emission (NOx and PM) [6]

Policy makers in many countries have been active in limiting air pollution emission, the results are shown in fig 1.5 which evidences a strong reduction in the air pollutant emission in the last decade.

1.1.2 Focus on United States and California

Given this general overview on the current global energy demand and emissions related to transportation, this work will be more focalized on the United Stated, in in the California area. California area is one of the most active regions on limiting air pollution and GHG emissions. Over the next fifteen years California will need to build upon its successful efforts to meet critical air quality and climate goals.

These include the following [15]:

• Attaining federal health-based air quality standards for ozone in 2023 and 2031 in the South Coast and San Joaquin Valley, and fine particulate matter (PM2.5) standards in the next decade;

• Achieving greenhouse gas (GHG) emission reduction targets of 40 percent below 1990 levels by 2030, with continued progress towards an 80 percent reduction by 2050;

• Minimizing health risk from exposure to toxic air contaminants;

• Reducing our petroleum use by up to 50 percent by 2030;

• Increasing energy efficiency and deriving 50 percent of our electricity from renewable sources by 2030.

All these policies can be summarized in the following plot (fig 1.6) [15]

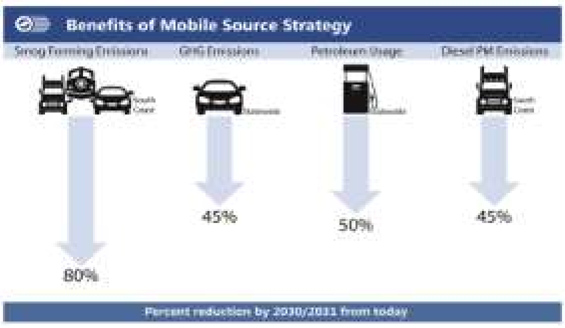


Figure 1.6 Mobile source strategy [15]

To achieve this goal the future use of Zero-emission vehicles in California will be a must, given the huge contribution that transportation sector gives to the overall emissions.

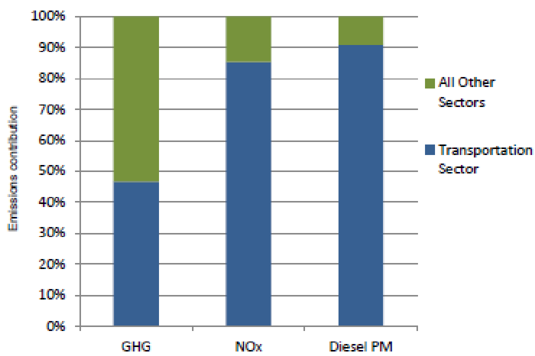
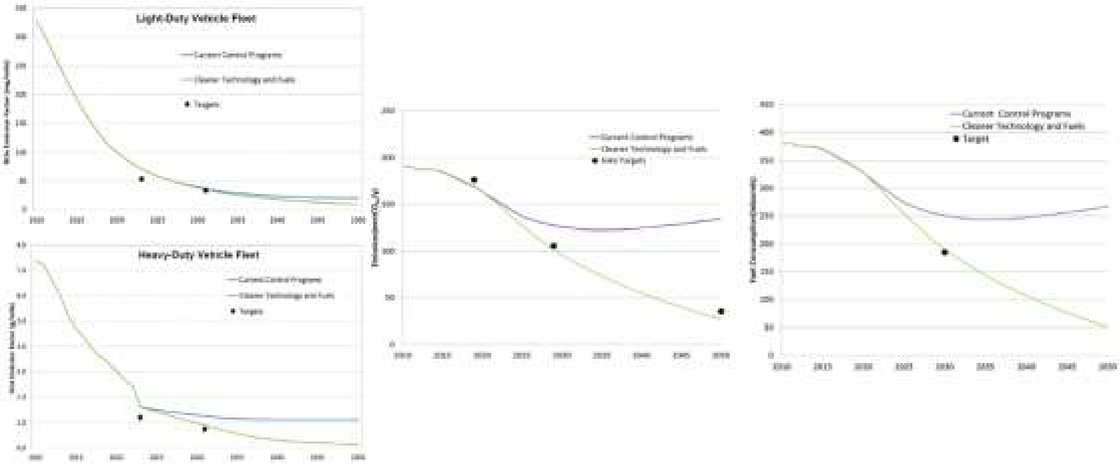


Figure 1.7 Emission contribution from mobile sources [15]

The impact of Zero-emission vehicles (ZEVs) on the GHG, air pollutant and fuel consumption are evident from the graphs presented below [16]



(a) (b) (c)

Figure 1.8 Time trend and future prospective of: Comparison between LDV and HDV NOx emissions (a), GHG emission trend (b), and Fuel consumption trend (c). Current vehicles and ZEV emission trends are compared. [16]

From the above graph it is evident that to meet the actual California target the introduction of ZEV is of cardinal importance.

1.2 Medium and heavy-duty transportation

The great importance in considering medium-heavy duty vehicles decarbonization is the extremely high ratio $\frac{Fuel\ use\ (emission)}{VMT\ (vehicle\ miles\ traveled)}$ that they have with respect to light duty vehicles, considering the actual technologies.
This aspect is much more evident considering future scenarios projections as has been done in [27] and as it is shown in the following graph

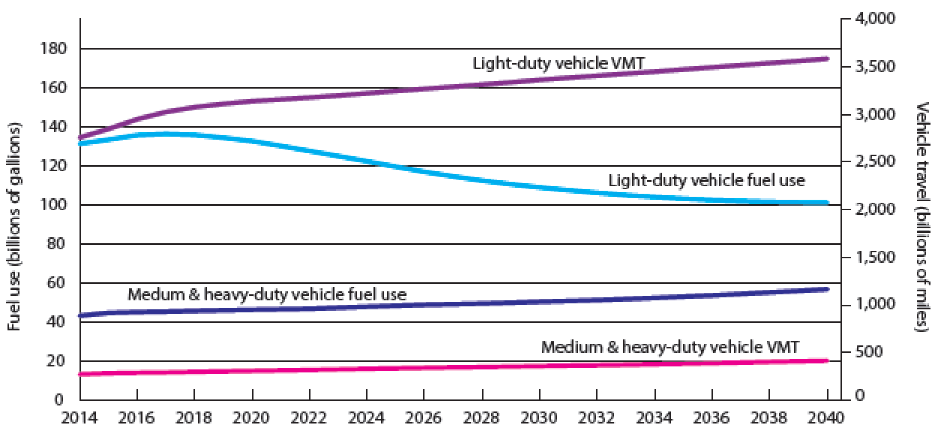


Figure 1.9: Vehicle fuel use and travel, projected to 2040 [27]

Heavy duty vehicles can be categorized by Gross Vehicle Weight Rating (GVWR) and broken out into classes. Moreover, also the vocation of the has been considered [8].

Class	Weight (1,000 lbs)	Vans					Work Vehicles						Freight			Other
		Step	Enclosed	Insulated	Open top	Other	Flatbed	Dump	Concrete	Tow	Utility	Garbage	Tank	Beverage	Tractor	Other
8	60+	2	4	2	8	1	33	200	122	2	2	32	19	0	[illegible]	29
8	50-60	1	4	1	22	1	41	160	49	4	7	73	28	0	314	21
8	40-50	1	14	4	69	2	81	187	17	3	11	48	51	2	279	24
8	33-40	2	18	6	58	1	100	103	2	11	51	26	41	8	152	15
7	26-33	5	87	40	78	4	204	181	0	16	71	20	130	46	64	40
6	19.5-26	127	294	60	89	20	475	425	0	78	106	14	96	82	31	104
5	16-19.5	109	175	23	19	7	157	80	0	21	70	6	14	5	0	49
4	14-16	98	80	7	17	11	185	114	2	36	46	2	13	3	0	69
3	10-14	234	258	21	11	43	345	204	0	65	117	5	13	4	0	152
Total		572	593	167	345	90	1,617	1,546	193	249	485	229	405	100	1,489	502

Figure 1.10 Vehicle population in the US in 2014 (1000s of vehicles) [8]

The Heavy-Duty sector is considered starting from 14000lb (so from class 4). This study will be mostly focused on the Class 8 Freight transportation.

1.2.1 New technologies

Some studies [6-14] then focalize on the new technologies which can be adopted to achieve the Government target in terms of emissions, the most common are:

- Natural gas (NG) = The most common is methane (CH_4). Liquified NG or Compressed NG are two ways for storage, incomplete combustion is an important issue of methane (less biomethane). Only 1% of global trucks stock in 2015. The unit costs of compressed gas storage are lower than they are for liquefied gas storage. These costs have been estimated here at USD 1.4 per MJ of storage capacity for CNG (based on indications available from JEC (2008) for car storage tanks) and USD 2.4 per MJ of storage capacity for LNG (based on recent claims from manufacturers – see Clevenger [2014]). When applied to an MFT with a range of 700 km, these claims translate into a cost increment of USD 10 000 per vehicle and USD 17 000 per vehicle, respectively. The cost increment increases to USD 22 000 per vehicle and USD 40 000 per vehicle, respectively, in the case of an HFT. NG but LNG has 12 times more energy density than CNG. There is no important reduction in GHG (yes using biomethane) but reduction in CO, NOx, PM2.5, hydrocarbons (better air quality). NG Trucks emits less noise than current Diesel ones.
- Biofuels = can be produced from wastes or crops: biodiesel, HVO, biomethane are the most used; deployment depends on volume of fuel production, suitable freight vehicles, fuelling infrastructure; benefits in GHG emission which highly depends on production pathway; benefits in air quality and support in agriculture (crops).
- Electricity = The key performance indicators are: gravimetric and volumetric battery energy density, specific power, durability, temperature management; efficiency is much higher with respect to diesel, taking advantage also of the regenerative braking system; a big issue is the Electric Road System: conductive catenary lines or inductive power transfer (with coils), the proximity is a big issue for coils; no tailpipe pollution, upstream pollution depends on generation and delivery of electricity
- Hydrogen = Fuel Cell Vehicles: they are essentially battery electric vehicle powered with a fuel cell which uses H_2. Hydrogen has a high energy density but low volumetric density, so the issue of storage is of cardinal importance; H_2 is a flexible energy carrier

(electricity=>H2=>electricity); FCV are 0 emission in tailpipe and upstream pollution depends on H_2 production, transportation and distribution

Among all these new technologies opportunities the only ones which guarantee zero emission from the tailpipe are battery electric vehicles and fuel cell electric vehicle, constraining the emissions only in the fuel production phase.

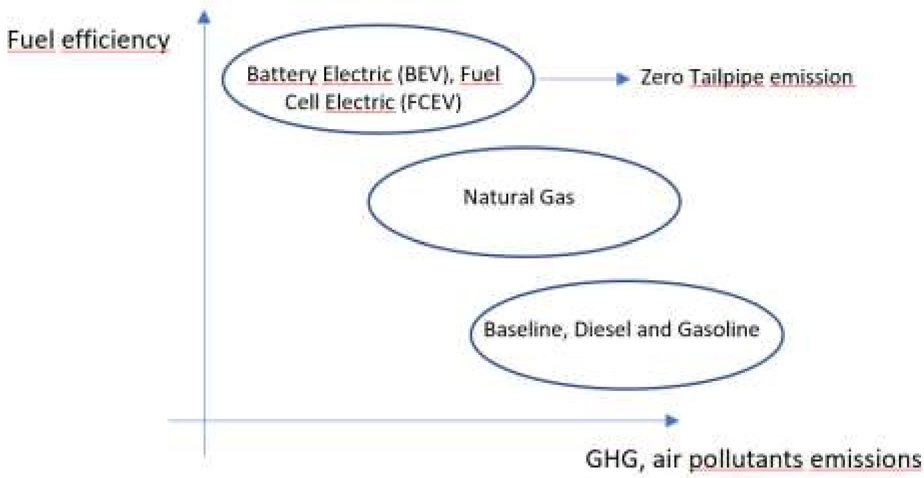


Figure 1.11: New technologies comparison

This is the reason why on this report the attention will be focused on battery electric and fuel cell electric medium and heavy-duty vehicles.

2 Battery electric and fuel cell electric trucks

2.1 Battery electric trucks

2.1.1 Technical analysis

California Air Resources Board [17] and Sen Burak, Ercan Tolga, and Tatari Omer [14] presented a detailed overview in Battery electric trucks, the former is related on the technological aspect and the latter on the costs and emission comparison with other technologies.
In the figure below is presented a very simplistic way for describing the overall BEV functioning [17].

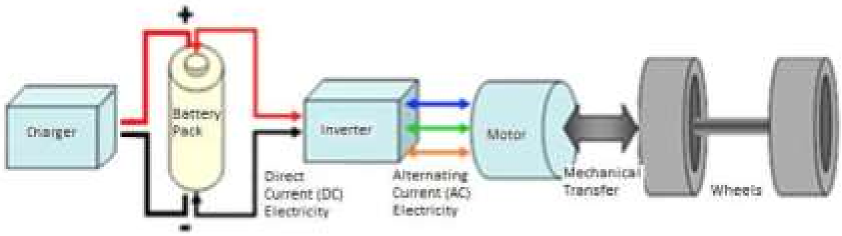


Figure 2.1 Simplistic overview of BEV components [17]

The key component of the Battery Electric Vehicle is of course the battery itself; its design become much more challenging when the Vehicle is a Heavy Duty one. One of the most important parameters for characterizing it is the energy density, which is then responsible of the battery pack sizing. This parameter is highly related to the battery chemistry as shown in fig. 2.2. Note that a factor of 10 is possible in gravimetric battery energy density.

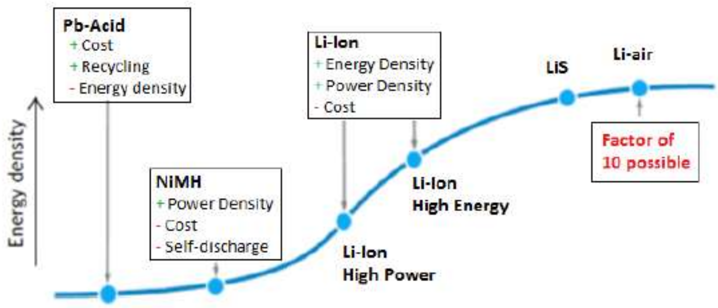


Figure 2.2 Gravimetric Energy Density of different battery chemistry [17]

The battery characteristics as size, charging time and range on a single charge are detailed in table 2.1 for electric buses and table 2.2 for two types of Heavy Duty Trucks.

Table 2.1 Battery all electric transit bus specifications

Model	40 foot	40 foot	60 foot	40 foot
Price	$800,000	$800,000	$1.2M	Not available
Battery Size (kWh)	100	360	590	300
Motor (kW)	220	90 or 180	360 (180 kW wheel motors)	160
Charge Time	<10 minutes	2 - 5 hr*	2 - 3 hr**	10 min gives 2 hours of operation***
Range on Single Charge	30-40	155	170+	80-120

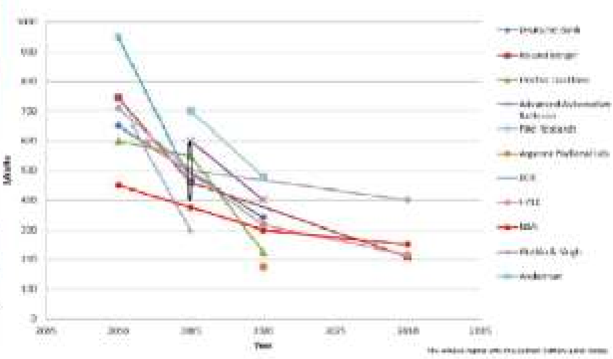
Table 2.2 Summary of BEV Heavy Duty Vehicle specification

Make	Weight	Range Miles	Battery Size kWh	Motor Size kW
Transpower (Drayage)	Heavy Duty	75	270	300
Motiv (Refuse)	Heavy Duty	80	220	230

The battery is also a driver for the overall Vehicle cost and the economy of scale can be of cardinal importance for the deployment of such a technology. This concept has been quantified in the table and graph presented below [17].

Components	BEV (Year 2012)	BEV (Year 2020)	BEV (Year 2030)
Glider	$79,000	$79,000	$79,000
350 kW motor	$9,000	$8,000	$7,000
Power Electronics	$12,000	$10,000	$8,000
350 kWh Battery System	$210,000	$111,000	$74,000
Total Vehicle Cost	$308,000	$208,000	$169,000
Baseline Diesel Truck Cost	$104,000	$108,000	$111,000
Incremental Cost	$204,000	$100,000	$58,000

(a)



(b)

Figure 2.3 Estimation of BEV Drayage Truck Costs over time (a) and Forecast of battery cost (b) [17]

The incremental cost of all the Vehicle with respect to the current Diesel one in 2030 will be almost one-quarter of nowadays, with a cost reduction of the Battery System of one-third.

A detailed analysis on the battery cost has been proposed by the U.S. Department of Energy [13], where different cost models are presented. They can be used to estimate current manufacturing costs in the absence of publicly available information (as in the automotive lithium-ion battery industry), and to analyse the cost impacts of various technology changes and improvements. The Clean Energy Manufacturing Analysis Centre (CEMAC) and Bloomberg New Energy Finance (BNEF) have created manufacturing cost models.
Moreover, price reductions may be driven in part by market conditions including global manufacturing overcapacity, supply contract structures, and strategic corporate [13].

2.1.2 Battery electric vehicle deployment status

In terms of deployment, the sale of electric-only vehicles started to grow only after 2010 and it is still really marginal also compared to hybrid technology, as shown in fig 16 [27]

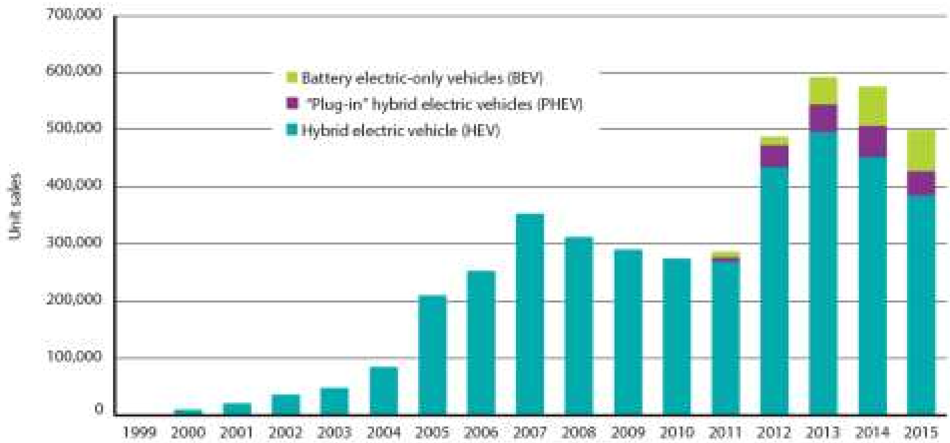
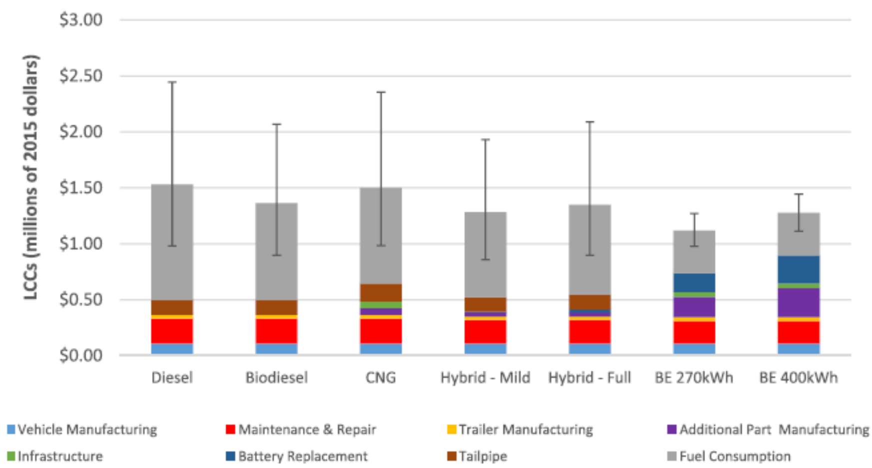
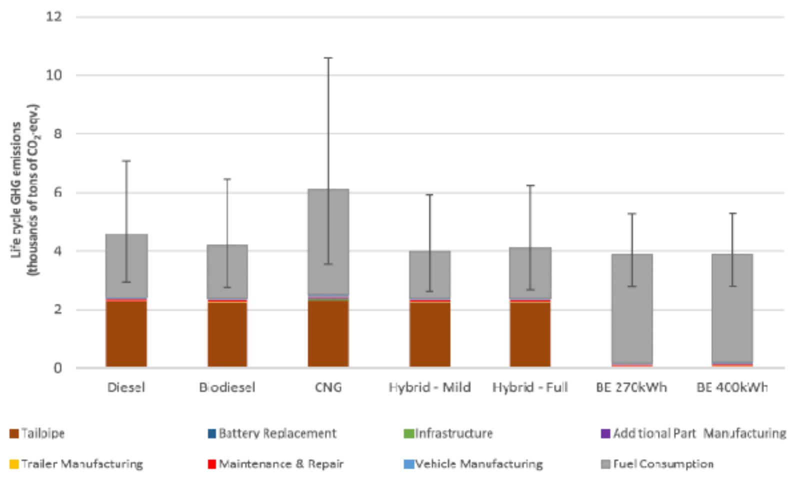


Figure 2.4: Sales of Hybrid, Plug-in Hybrid and Battery Electric Vehicles [27]

To evaluate the Battery Electric technology, it is worth comparing it with other possibilities, as has been done in [14].
Firstly, a Life Cycle Cost analysis, which includes both the vehicle related and the fuel related costs, has been performed.



(a)



(b)

Figure 2.5 Life cycle costs (a) and Life Cycle Green House Gas emissions (b) of heavy duty trucks [14]

Battery Electric trucks have the best overall performances out of all the considered trucks (Diesel, Biodiesel, Compressed Natural Gas, Hybrid) in terms of their Life-Cycle Cost and Green House Gas emissions.
It is worth to notice that even if the tailpipe emissions for BE trucks are zero, the total GHG emissions are comparable with the other technologies (except for Natural Gas emissions which are much higher). This happens because the GHG emissions from electricity generation are still high, being 70% higher than the conventional fuel production emissions.

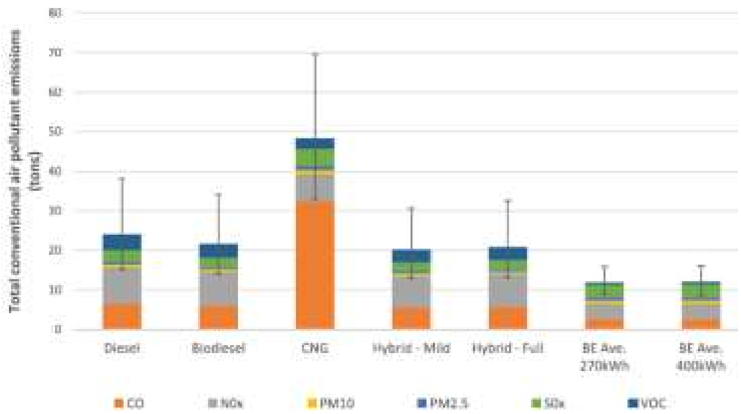


Figure 2.6 Life cycle air pollutant emissions of heavy duty trucks [14]

As far as air pollution is concerned, battery electric trucks are still the less pollutant and CNG trucks the most, due to the extremely high CO emission related to the use of natural gas.
The results shown in fig.2.5, 2.6, taken from [14], seems to disagree strongly with what has been doing in the recent years in the United States and in particular in California, enhancing natural gas production and usage for the automotive application in order to reduce GHG emission and meet climate goals.
An evidence of the beneficial GHG effect can be find in [28] where DOE has used GREET life cycle model in order to calculate the emissions from vehicles using different technologies.

2.1.3 Recent technological breakthroughs

Concerning the Heavy-Duty trucks, Tesla has recently launched the new ‘semi-truck’ which is a long range heavy duty truck fully electric. Here down are posted the specification of it [12]:
- Tesla Semi will go 0-60mph in 5 seconds, 20 seconds with 80,000 pounds
- Up-hill at 65MPH versus 45MPH for other semis
- 500 miles on a single charge, even with max load
- 4 motors
- Tesla Semi can add 400 miles of range in 30 minutes of charging
- Enhanced Autopilot: Automatic Emergency Braking, Automatic Lane Keeping, Forward Collision Warning
-Tesla Semi will have 1 million mile guarantee, while the brake pads will have “quasi-infinite” lifespan with regen braking
- $1.26/mile average cost versus $1.51/mile for diesel truck

These characteristics are a confirm that the Electric Battery technology is an extremely valuable path also for the Heavy-Duty sector.

2.1.4 Alternative infrastructure opportunities and costs

Due to the cost implications for large battery requirements, the challenge for the electrification of trucks, particularly in the Heavy Freight Transport segment, is one of how to reduce battery needs through the supply of electricity to vehicles while in motion [6].

Different types of infrastructures have been considered in [6] apart from plug-in recharge or battery swapping techniques, they are called Electric Road Systems.

Electric road systems (ERS) rely on vehicles that can receive electricity from power transfer installations along the road upon which the vehicles are driving. Furthermore, the vehicles using ERS can be hybrid, battery-electric, or hydrogen fuel cell vehicles and can conduct normal driving operations, such as overtaking and driving autonomously outside of the electrical roads. The main infrastructure concepts for ERS are:

- Overhead catenary lines, also requiring the installation of an overhead retractable pantograph on trucks.
- Inductive transfer of power, requiring the installation of coils that generate an electromagnetic field in the road as well as receiving coils for electricity generation on the vehicle.

Pilot applications in Germany, Sweden and the United States have begun installation of catenary lines along roadways (Siemens, 2016).

Inductive charging has many advantages over conductive charging, the main advantages include convenience due to the wireless charging, the lower risk of electrical shock, no limitations on the number of devices that can be charged (including cars, eventually), and low maintenance costs due to the lack of wear and tear of components. but also, several disadvantages, including lower efficiency, higher material requirements per lane-km, more invasive changes to the existing infrastructure, and more complex components. The efficiency of inductive power transmission is competitive with wired solutions only when the induction coils have a comparable size (less than a 50% difference) and are near (less than 10% of the size of the largest induction coil). The proximity

requirement is very difficult to comply with in the case of dynamic charging and therefore very likely to pose structural limits to actual efficiency potential.
In the Future of Trucks report [6] then presents a cost analysis for Heavy Duty Freight Vehicles and Fuel costs over five years of usage, including infrastructure.

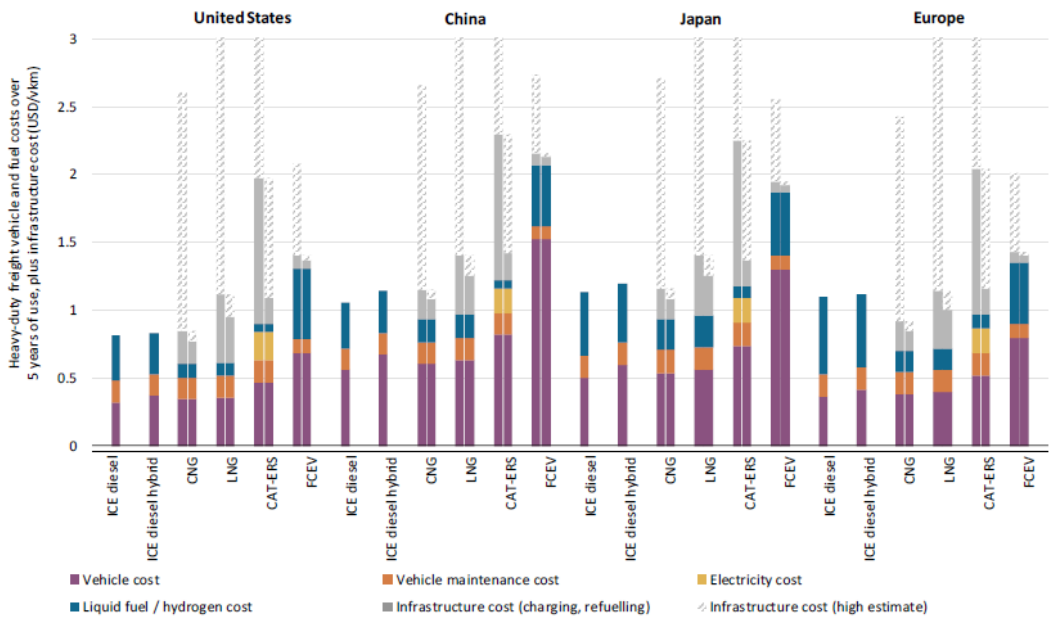


Figure 2.7 Heavy Duty Freight Vehicles cost (hitch and low infrastructure utilization assumptions) [6]

From the above graph it is possible to notice that the cost of infrastructure plays a key role in the overall cost of the technology.

2.2 Fuel cell hydrogen electric trucks

2.2.1 Technical analysis

A fuel cell electric vehicle (FCEV) is a vehicle propelled by hydrogen with the use of a fuel cell stack, which convert the hydrogen energy in electricity and water as the only emission at the tailpipe.

Like electric vehicles, the fuel cell electric vehicles use electricity to power an electric motor; the main difference instead is that in a fuel cell electric vehicle the power of the vehicle is only related to the dimension of the fuel cell and the energy to be stored on board by the size of the hydrogen tank, otherwise for fully electric vehicles both power and energy are related to the battery's size.

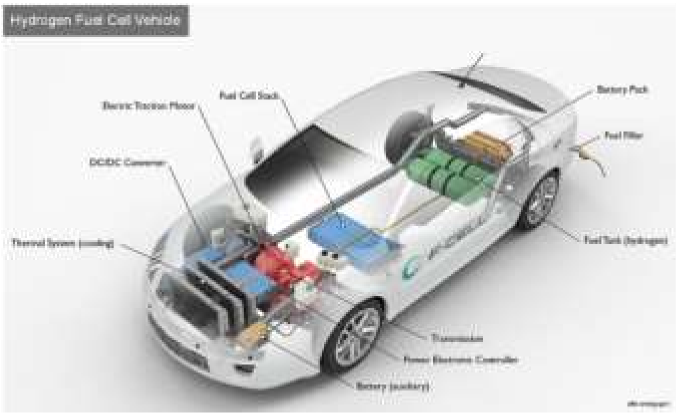


Figure 2.8: Fuel cell vehicle components detail [33]

It is possible to notice from fig.2.8 that the presence of a battery pack and an auxiliary battery is necessary also for a fuel cell electric vehicle. The auxiliary battery provides electricity to start the car and powers accessories, the battery pack stores energy from regenerative breaking and provides supplemental power to the traction motor.

The reason why this technology is of interest nowadays is that hydrogen has high energy density in terms of mass (kWh/kg), which implies the possibility to achieve higher range in the transportation field minimizing the increase of the vehicle's weight as shown in fig 2.9.

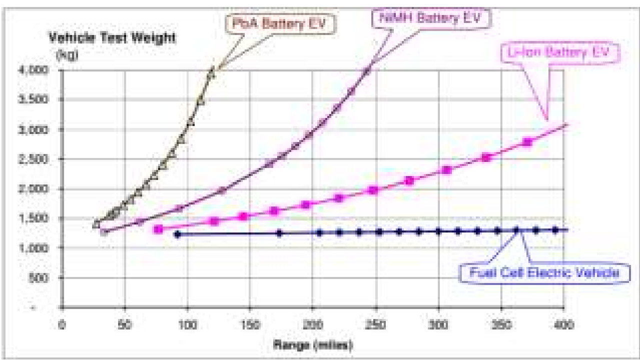


Figure 2.9: Weight increase with respect to range for light-duty vehicle application, the power trains are designed to provide a 0-97km/h acceleration in 10s

Another advantage of the fuel cell vehicle is the refueling time, which is the same of a combustion engine car and more than ten times lower with respect to the charging time of an electric vehicle nowadays in production.
The challenge for this application is the hydrogen production, distribution and storage. Hydrogen is extremely low dense at atmospheric pressure and to be stored it must be compressed at high pressures (typical pressure values are 350 bars or 700 bars).

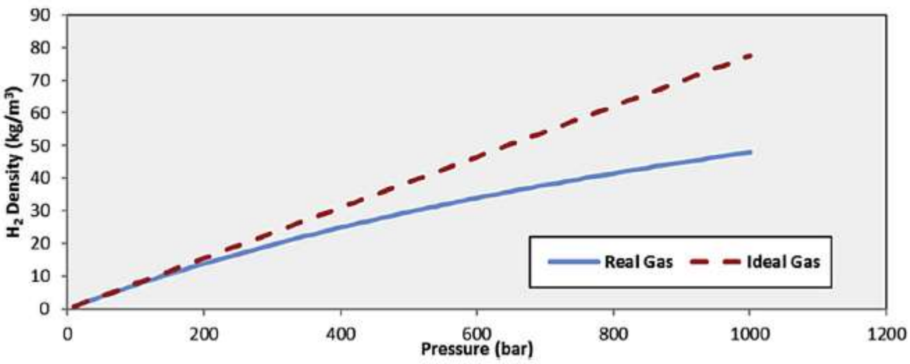


Figure 2.10: Comparison between ideal gas and real gas assumption for H_2 density

A quantification on the cost feasibility of hydrogen production and its infrastructure can be found in [37] and will be detailed in the following sections.

2.2.2 Components design

Jason Marcinkoski, James Kast and John Gangloff developed several studies on different aspects of this topic [8-11], firstly analysing the component size [9] and designing the hydrogen tank [10], then verifying the technical feasibility in terms of storage [8] and finally identify technical and economic targets that allow for commercialization of Fuel Cell Electric Trucks in the future.
The component sizing has been done to meet the functional requirements of a reference baseline vehicle (Diesel) and the paper [9] uses a class 4 (Medium Duty) truck. The same analysis can be extended to other classes of vehicles.

Figure 2.11 Schematic diagram for a medium fuel cell electric truck [9]

The major components (fig. 2.11) of the fuel cell truck has been sized to guarantee the same or better performance with respect to a current Diesel truck.

In the figure below, it is possible to detect the final results for a Class 4 truck component sizing

Mass estimates in kg	Baseline	FCHEV
Test weight	6809	6854
Chassis + Body	3417	3417
Cargo	2400	2400
Fuel	100	19
Fuel tank	40	435
Engine	305	
Fuel cell		125
Gearbox	142	10
Motor		145
Battery Low Voltage	83	83
Battery High Voltage		65

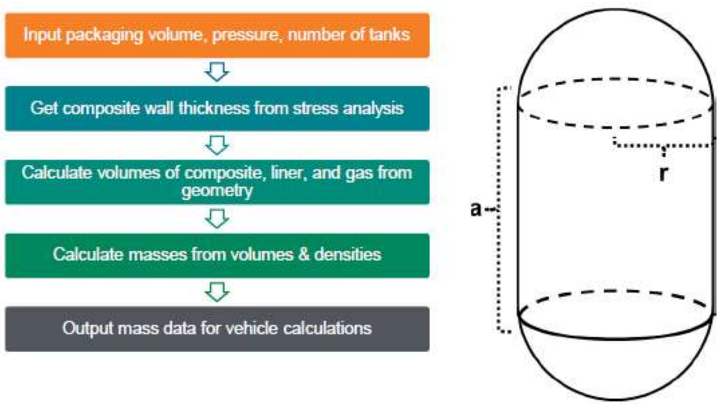
(a)

Selected component sizes	
Motor Continuous Power (kW)	151
Motor Rated Power (kW)	260
Fuel Cell Power (kW)	164
Battery Power (kW)	54
Battery Total Energy (Wh)	1426
Battery Volume (L)	53.4
Motor Speed Ratio	8.9

(b)

Figure 2.12 Mass difference between Baseline vehicle and FCET version (a) and result of the component dimension (b) [9]

The crucial part of the Fuel Cell vehicle design in the Hydrogen storage, being Hydrogen a low-density substance and therefore difficult to store.
Nowadays several pathways are being studied, starting from compressing or cryogenic liquefying Hydrogen to build molecular bonds with metallic or zeolitic fibers.
The study of Marcinkoski and his team is related on compressed hydrogen gas at 350 or 700 bar within Compressed Overwrapped Pressure Vessels (COPVs) [10].
The methodology that has been used for designing the COPVs is explained in the figure below:



(a) (b)

Figure 2.13 On-board truck hydrogen storage modelling flow chart (a) and capsule geometry typically used for Composite Overwrapped Pressure Vessels (COPV) (b) [10].

The results of this analysis bring to the understanding of the feasibility of Fuel Cell Electric Trucks: Heavy Duty Trucks can store 50-80kg of Hydrogen at 350-700bar. The vehicle ranges are equivalent to 50-85 gallons of Diesel for current trucks, which is comparable with most of the today application for which the fuel tank size is between 50-200 gallons.

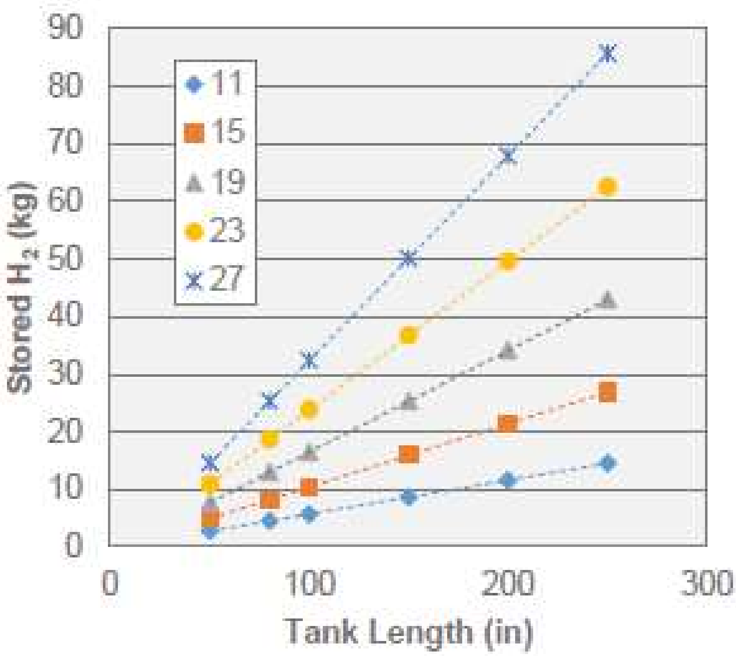
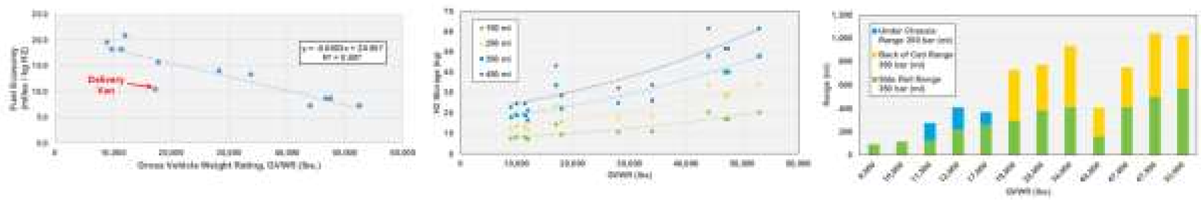


Figure 2.14 Mass of stored Hydrogen with respect to tank dimension for 700bar case. Each color and shape correspond to a constant diameter (in) [10]

The shape of the graph presented in fig.2.14 is the same if 350bar of pressure is considered, but with a reduction in the stored mass of H_2 of 60%.
The last part for the technical analysis of FCET is related to this question: will hydrogen fuel cell MHDVs be space or weight constrained given their range of operation? [8]
The team has developed a methodology for the study of hydrogen fuel cell electric trucks that ties the mass and dimensional constraints with the vehicle use and fuel economy. The results produce a design space for 12 example vehicles spanning many vehicle weight classes and vocational uses that make up large sections of the Medium and Heavy-Duty Vehicles market.



(a) (b) (c)

Figure 2.15 Autonomie-based simulation results for MHDV hydrogen fuel economy as a function of GVWR (a), Estimated amount of hydrogen storage needed to achieve a desired range for each representative truck, plotted as GVWR.(b) and Vehicle Range at 350 bar, based on compressed hydrogen storage tank location. (c) [10]

It is possible to achieve range of more the 1000 mile using 350 bar hydrogen storage tanks for the Heavy-Duty sector, this aspect is surely one of the crucial characteristic of the hydrogen fuel.

Given the technical feasibility of Fuel Cell Electric Trucks, the goal is then to compare performance of FCETs to conventional diesel trucks, and to identify technical and economic targets that allow for commercialization in the future. [11]

The summary information provided in Table 2.3 shows the final component sizes needed to meet or exceed the incumbent vehicle performance.

Table 2.3 Summary representative vehicle specifications [11]

Vehicle	Continuous motor power (kW)	Fuel cell power (kW)	Battery power (kW)	0–30 Acceleration improvement (%)	0–60 Acceleration improvement (%)
Class 2 Van	128	147	6	18	22
Class 3 Enclosed van	157	149	62	11	26
Class 3 School bus	175	180	76	10	16
Class 3 Service	146	165	4	37	23
Class 4 Delivery van	151	166	59	4	27
Class 5 Utility	210	253	8	134	17
Class 6 Construction	151	170	30	23	21
Class 7 School bus	146	145	56	20	13
Class 8 Construction	186	139	57	28	0
Class 8 Linehaul	349	363	47	24	15
Class 8 Refuse	256	273	94	16	27
Class 8 Tractor trailer	250	247	95	22	11

In all cases, vehicle performance is improved due to the operation of electric drivetrains.
Note that (table 2) many of the truck classes and vocations require 25 kg or less hydrogen storage to meet their daily range, and 180 kW or less fuel cell power to meet performance needs. The two long haul tractor trailers are the major exceptions that require significantly more hydrogen and fuel cell power to meet performance and daily range requirements with a single refuelling event.

Table 2.4 Representative vehicle range considerations from aggregate drive cycles data [11]

Vehicle	Onboard hydrogen storage (kg)	Average fuel economy (miles/kg of H_2)	Average range (miles)	% of cycles met by vehicle
Class 2 Van	7.2	23.6	170	100%
Class 3 Enclosed van	8.9	15.5	138	100%
Class 3 School bus	9.1	19.5	177	100%
Class 3 Service	6.7	15.7	105	100%
Class 4 Delivery van	19.1	11.9	227	100%
Class 5 Utility	8.5	11.1	94	95%
Class 6 Construction	13.5	13.5	182	96%
Class 7 School bus	11.3	11.1	125	99%
Class 8 Construction	25.3	9.2	233	100%
Class 8 Linehaul	63.7	5.5	350	40%
Class 8 Refuse	18.2	6.4	116	95%
Class 8 Tractor trailer	56.6	6.2	351	40%

Onboard hydrogen storage is able to satisfy the vehicle range requirements for at least 90% of daily routes based on data collected from U.S. census survey results and real world drive cycle data collection, except form class 8 long haul trucks.
Hydrogen storage can also be significantly increased on many larger trucks by taking advantage of unused storage space behind the cab and under the chassis, and by increasing the storage pressure, allowing to reach more than 1000 miles of range as sho.

2.2.3 Hydrogen production process

A key role for the deployment of Fuel Cell Electric Trucks is the hydrogen production and storage [1-5, 18-22].
There are several ways for Hydrogen production, the most common are steam methane reforming which is nowadays the most efficient process and water electrolysis which allows to produce hydrogen splitting water molecules using electricity.
A key role for the deployment of fuel cell electric trucks is the hydrogen production and storage [1-5, 19-22].

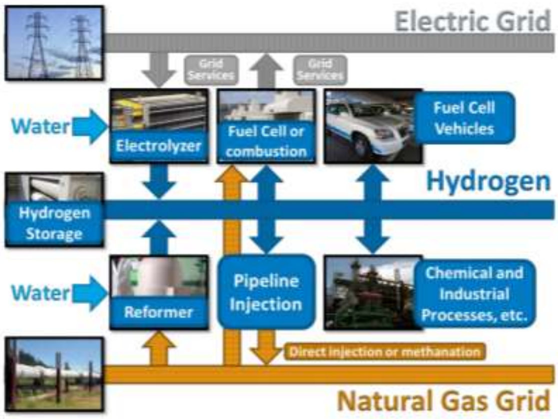


Figure 2.16 Hydrogen technologies configurations

There are several ways to produce hydrogen, the most common are steam methane reforming (SMR) and water electrolysis.
The SMR process can be viewed as an energy conversion process. It converts the energy stored in the hydrocarbon containing feed and combustion fuel to other energy forms, H2 and export steam.
The efficiency of this energy conversion process, therefore, can be defined as $\eta = \frac{E_{H2}}{(E_{raw} - Q_{exp})}$
where at the numerator there is the total energy content of the hydrogen which has been produced and the denominator the difference between the total energy content of feed and fuel (total energy consumption) and the thermal value of the export steam.
The efficiency limit is better as the export steam increases, ranging from 90.7 to 93.8% on the high heating value basis [20].
Another process is water electrolysis which produces hydrogen by splitting water molecules using electricity.
Three water electrolysis technologies are investigated: Alkaline Electrolysis Cells (AEC), Proton Exchange Membrane Electrolysis Cells (PEMEC) and Solid Oxide Electrolysis Cells (SOEC).
These technologies have different efficiencies, expressed as Voltage efficiencies on the high heating value basis: 62-82% for AEC, 67-82% for PEMEC and at least 110% for SOEC [22].

The second method of production is more appealing since it eliminates the carbon emissions during the process, leaving the electricity production the only emissions source.

Regarding this aspect the National Renewable Energy Laboratory in [2] has proposed a detailed analysis on the cost of Hydrogen from wind-based water electrolysis. From the emission point of view this process turns out to be extremely clean with respect to steam methane reforming.

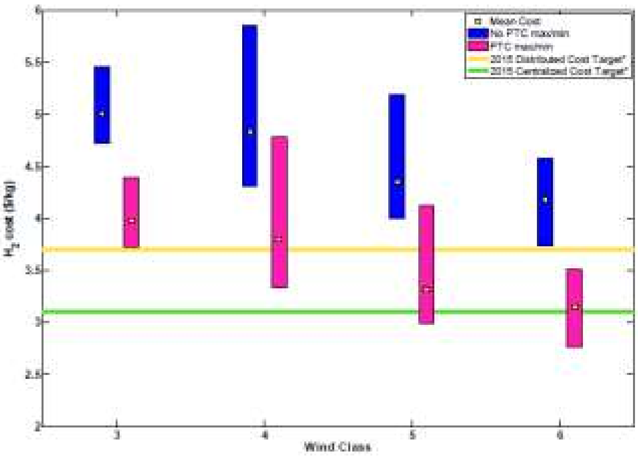


Figure 2.17 Range of Hydrogen Costs by Wind Class, the green and yellow line are centralized and distributed US DOE cost target,

Hydrogen costs ranged from \$3.74kg to \$5.86/kg. The base results show no wind sites that meet the centralized or distributed U.S. Department of Energy 2015 targets of \$3.10/kg and \$3.70/kg, respectively.
However, when considering the effects of the Production Tax Credit (PTC) and Investment Tax Credits (ITC) (reduction of \$0.02/kWh), almost half the sites analysed meet the distributed target and a few of the sites can meet the central target (fig 21).

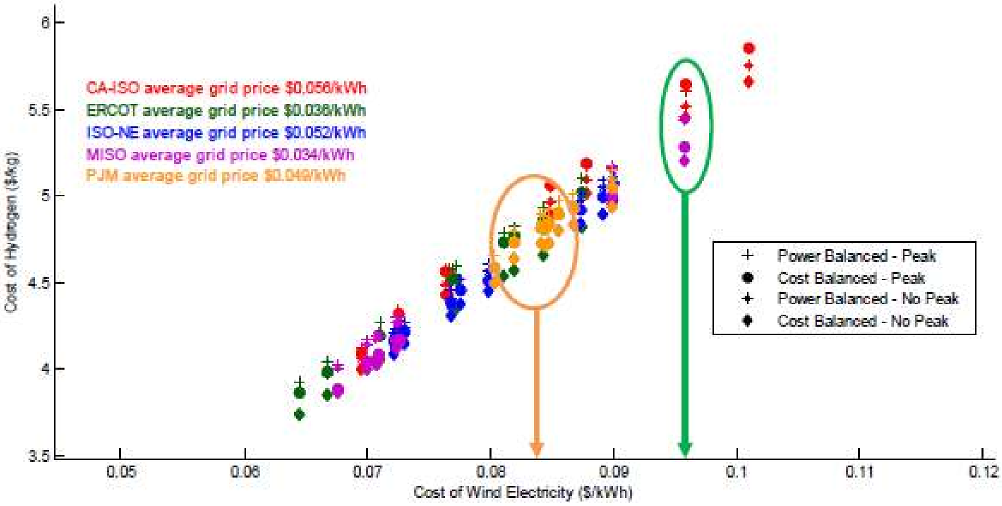


Figure 2.18 Hydrogen cost vs Wind electricity cost, the colors indicate different electricity grid prices

The cost of renewable wind-based hydrogen production is very sensitive to the cost of the wind electricity (fig 22). Using differently priced grid electricity to supplement the system had only a small effect on the cost of hydrogen; because wind electricity was always used either directly or indirectly to fully generate the hydrogen.
Sensitivity shows that the electricity price, based upon the wind turbine capital cost, can affect the cost of hydrogen more than even the electrolyser capital cost and performance.

All wind electricity is not equivalent, but even a range of wind class sites can provide renewable, green hydrogen at a cost close to current DOE targets.

2.2.4 Hydrogen space assessment for medium and heavy-duty trucks

The fuel cell application for medium and heavy-duty truck is particularly appropriate, guaranteeing high range and fast charging time which are two of the most important parameters for freight transportation efficiency, as far as for buses.
Below it has been presented a computer modelling of a heavy-duty truck, which underline the available space for the components (hydrogen tank especially) of the fuel cell system.

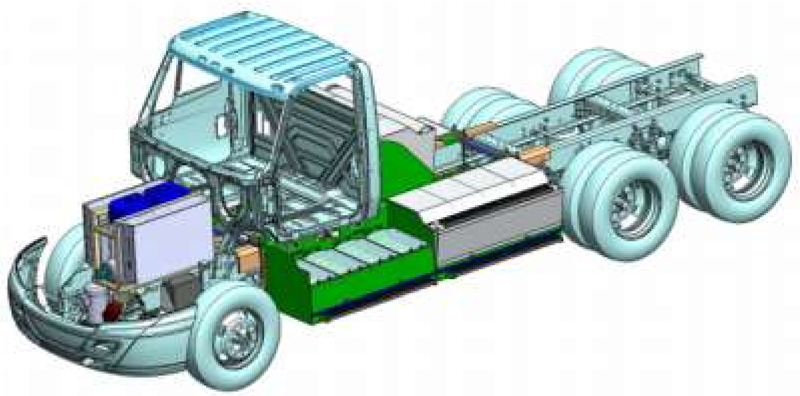


Figure 2.19: CAD modelling of a heavy-duty truck for emphasizing the amount of space available for FCET components

The large amount of space, especially on the lateral side of the cab, can allow the storage of multiple hydrogen tank as underlined also by Marcinkoski in several articles e.g. [9], [10], [11].

In [10] the design of hydrogen storage on medium and heavy-duty truck has been detailed widely and different storage scenarios have been proposed considering the vehicle type and its application and funcionality.

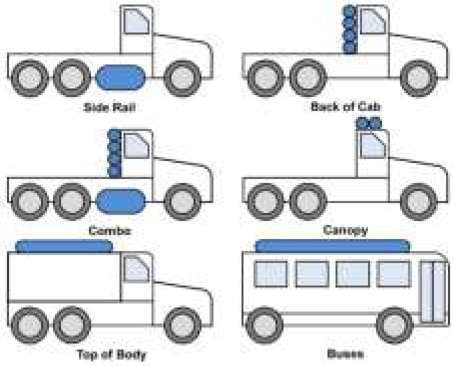


Figure 2.20: Design of storage space for medium and heavy-duty vehicles [10]

In the same paper the analysis of component sizing has been performed, considering 12 different truck types and 7 different classes. The results are summarized in the following chart, where other than fuel cell power and hydrogen requirement for each truck type also the electric motor dimension can be visualized: it is proportional to the bubble dimension

Figure 2.21: Fuel cell and hydrogen tank sizing for FCETs for guaranteeing the same performance as the baseline trucks [10]

The detailed analysis is then reported in the tables 1.3 and 1.4, they will be of cardinal importance for the techno-economic analysis developed in the following chapters
An example of drive cycle is in fig 2.7 where the fuel economy, the distance and amount of hydrogen have been analyzed; in this graph each bar represents one truck’s daily drive cycle.

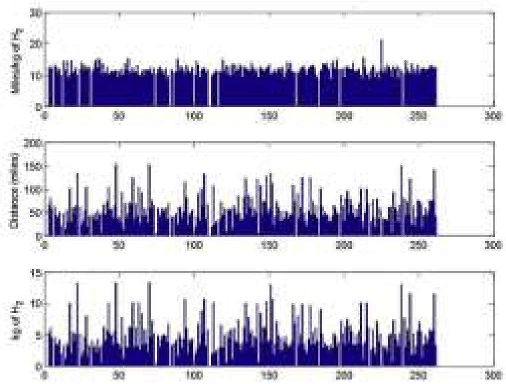


Figure 2.22: Summary of drive cycle characteristics for class 4 delivery vans [10]

2.3 Comparison between BE Trucks and FC Trucks

In the former paragraphs the most important technical aspects of battery electric vehicles and fuel cell electric vehicles have been analyzed. It is then of cardinal importance to be aware of the technical boundaries and limits for both the technologies and understand which the best fit for medium and heavy-duty trucks application could be.
The most important aspects for characterizing a medium and heavy-duty trucks are:

- Miles range
- Volume and mass occupied by fuel/battery
- Cost of ownership and life-cycle cost

This section will deal with the first two topics, on the other hand the third one will be analyzed in the chapter 4.

2.3.1 Weight variation with miles range

Regarding the miles range an important distinction has to be outlined between fuel cell and battery electric vehicles: in the first case the energy of the system, which is responsible for the range, is decoupled from the power of it; in the second case both the energy and the power are in the battery.

Table 2.5: Weight of battery and fuel cell system compared increasing range

Range [miles]	BEV weight [kg]	FCEV weight 700 bar [kg]	FCEV weight 350bar [kg]
300	5586	653	703
600	10836	875	925
1000	17836	1205	1255
1500	26586	1542	1592

For the computation of the weight for BEV the battery and the electric motor have been considered, for a class 8 truck size [17]. Regarding the FCEV the fuel cell system, electric motor, storage tank and hydrogen, and auxiliary battery have been considered, for the sizing of these components [9] has been taken into consideration.

It has to be noticed that the weight of the chassis and the structure of the vehicle has not be considered, being supposed to be the same for the two technologies.

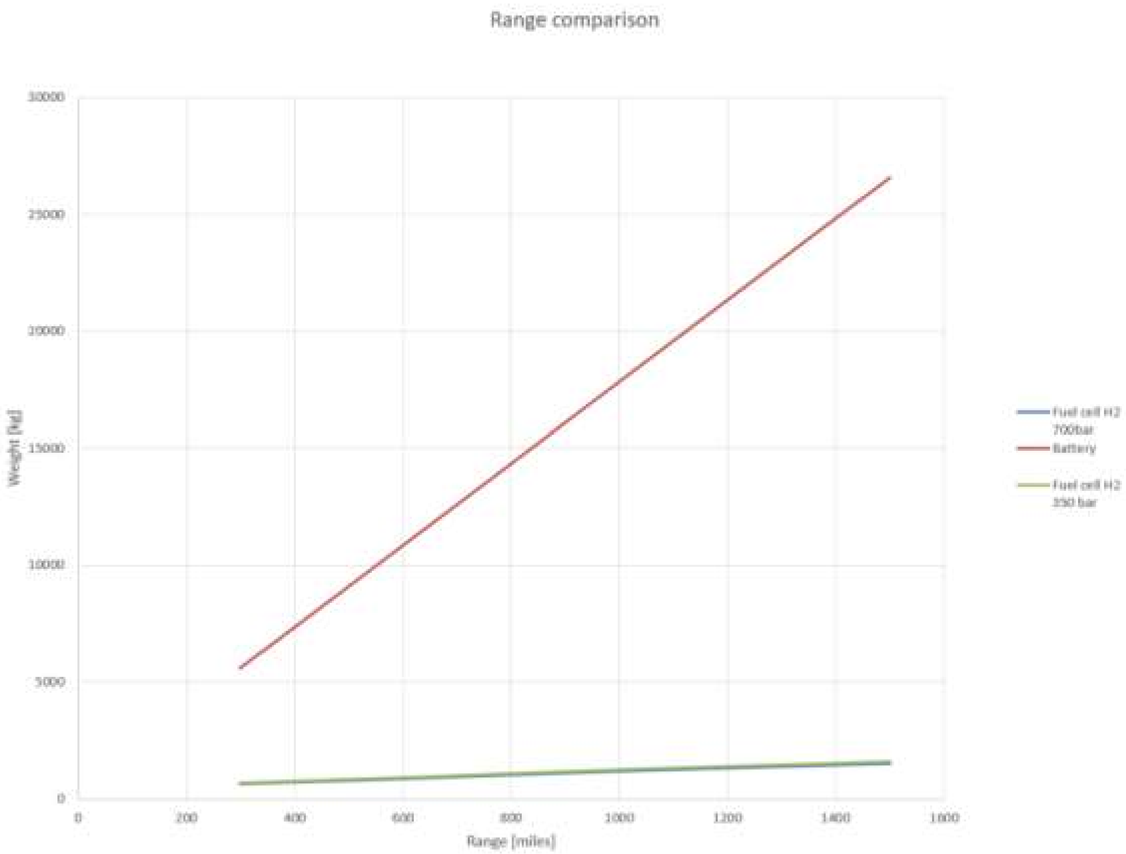


Figure 2.23: Weight of battery and fuel cell system compared increasing range

It is possible to notice from this graph that the increase in weight for the battery system is much more sensitive than fuel cell system one. The weight of the battery system will reach values higher than 20,000 lb for high range application, which is more than one-fourth of the total weight of a long-haul truck trailer.

2.3.2 Volume variation with miles range

Another important aspect for clan technology application is the volume occupied by the battery or the fuel cell system increasing the miles range of application

Table 2.6 Volume of battery and hydrogen tank compared increasing range

Range [miles]	Battery volume [l]	Hydrogen tank volume 700 bar [l]	Hydrogen tank volume 350 bar [l]
300	2100	585	988
600	4200	1171	1977
1000	7000	1951	3295
1500	10500	2927	4942

The hydrogen properties for the computation of hydrogen tank volume have been taken from [10], whereas the volumetric density of the battery is 0.4kWh/l.

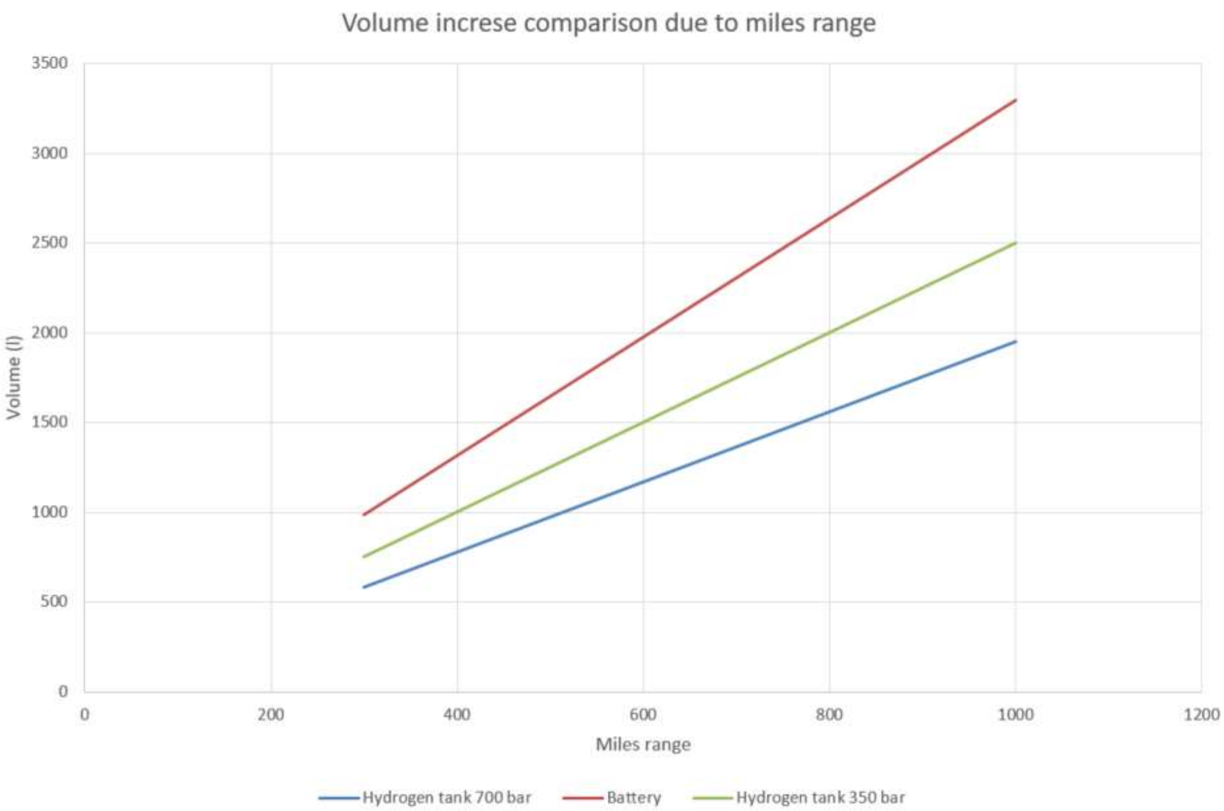


Figure 2.24: Volume of battery and hydrogen tank compared increasing range

It is possible to notice from this graph that at high values of hydrogen pressure, even the volume occupied by the hydrogen storage tank is less than the one occupied by the battery.

In [10], as described before, a design space assessment of hydrogen storage on medium and heavy-duty vehicles have been performed. For these types of trucks the volume for hydrogen tank storage it is not a huge constraint, having for trailers and buses at least $5m^3$ of space for store it [10], supposing a cylindrical shape of the storage tanks.

2.4 Health and environmental impact of new technologies

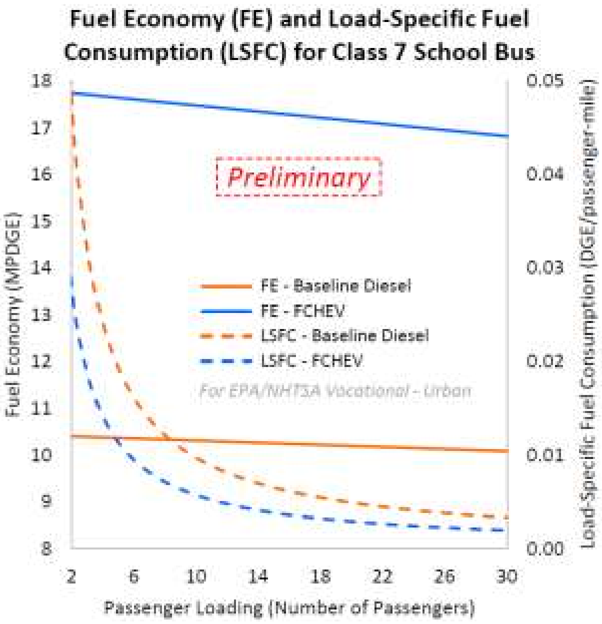
As descripted in the chapter 1.2 the freight transportation has a great impact for the overall emissions in terms of greenhouse gases (GHG) and air pollutants (NOx, SOx..).
In this chapter the emission impact and then the possible health improvements from new decarbonized technologies, like fuel cell trucks, will be analysed.

2.4.1 Life cycle benefits for fuel cell technology

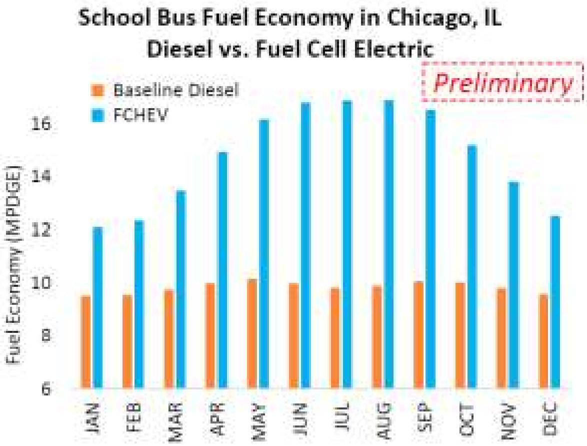
The growing interest in hydrogen fuel cell electric vehicles (FCEV) medium and heavy-duty sector is driven by gaining a better understanding of overall benefits that this technology can provide to the current world of freight transportation.
Potential benefits of medium and heavy-duty hydrogen fuel cell vehicles have to be evaluated considering not only tail-pipe but also indirect GHG and criteria air pollutants on a life-cycle basis; they may vary depending on duty cycles among others.

2.4.1.1 Fuel economy

A fuel economy analysis has been developed in [28] using the model GREET, which adopts a ratio-based approach (e.g. baseline diesel vs FCHEV fuel economy ratio).
The latter varies with the operating conditions, in the following charts the passenger load and climate conditions are analysed.



(a)



(b)

Figure 2.25: Fuel economy dependence on passenger loading (a) and on climate conditions (b) [28]

From the both plots it is possible to underline that FCEV is more efficient than the Diesel counterpart; on the other hand, FCEV is more sensitive, especially to sever climate conditions

The fuel economy varies also as function of the truck vocation and duty cycle, as presented in fig 2.9. For this chart, the Autonomie simulation tool has been used.

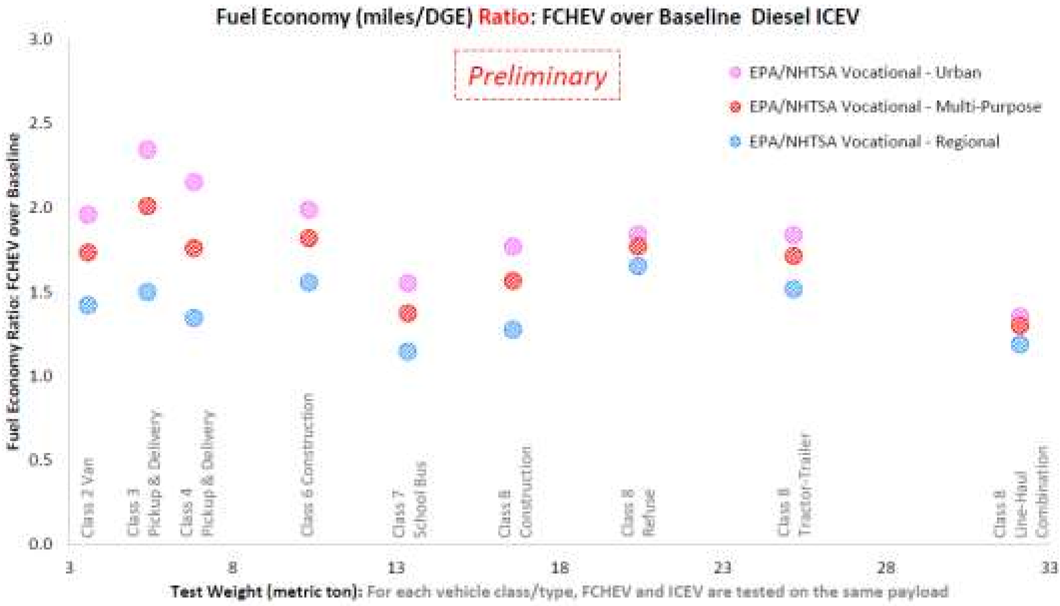


Figure 2.26: Fuel economy ratio (FCEV/Baseline) as function of class type

The ratio is varying from 1.2 to 2.3, FCEV and ICEV are tested considering the same passenger role, being it not a variable in this particular case.

2.4.1.2 Emission reduction

The adoption of fuel cell technology will eliminate completely emissions from tailpipe, shifting all the emission issue on the hydrogen production, storage and transportation.
This property will allow the reduction both in greenhouse gas emission, which highly contribute to climate change, and air pollutant (mostly SOx, NOx, PM2.5) emission which have high impact on people health, as discussed in the next section.

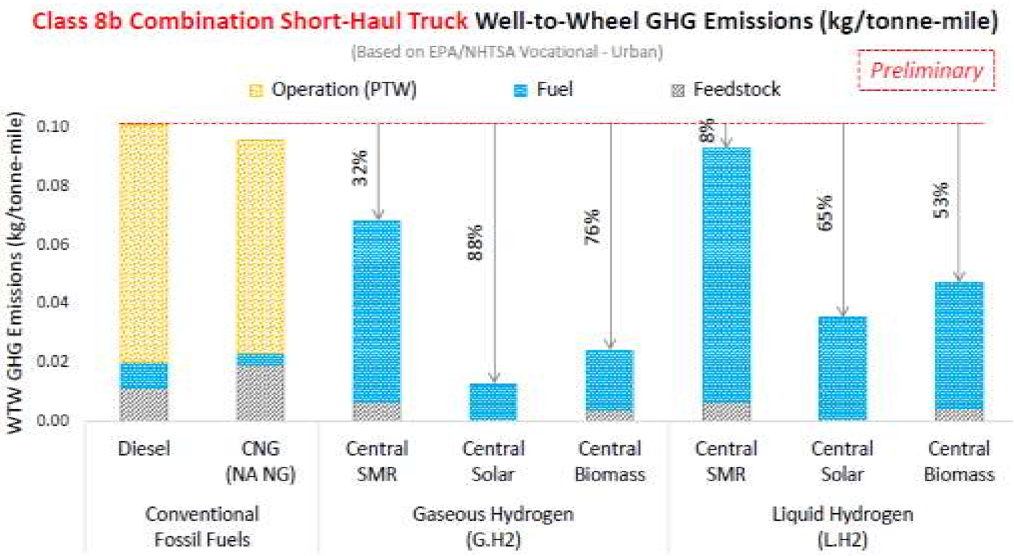


Figure 2.27: Well to wheel GHG emissions comparison between reference case (Diesel), CNG and FCEV considering different hydrogen production pathways

From the above figure can be noticed how much the hydrogen production pathway can affect the overall emissions of GHGs.
Moreover, gaseous compressed hydrogen allows to reduce emission up to 90% with respect to Diesel, more than liquified hydrogen obtain through cryogenic process.

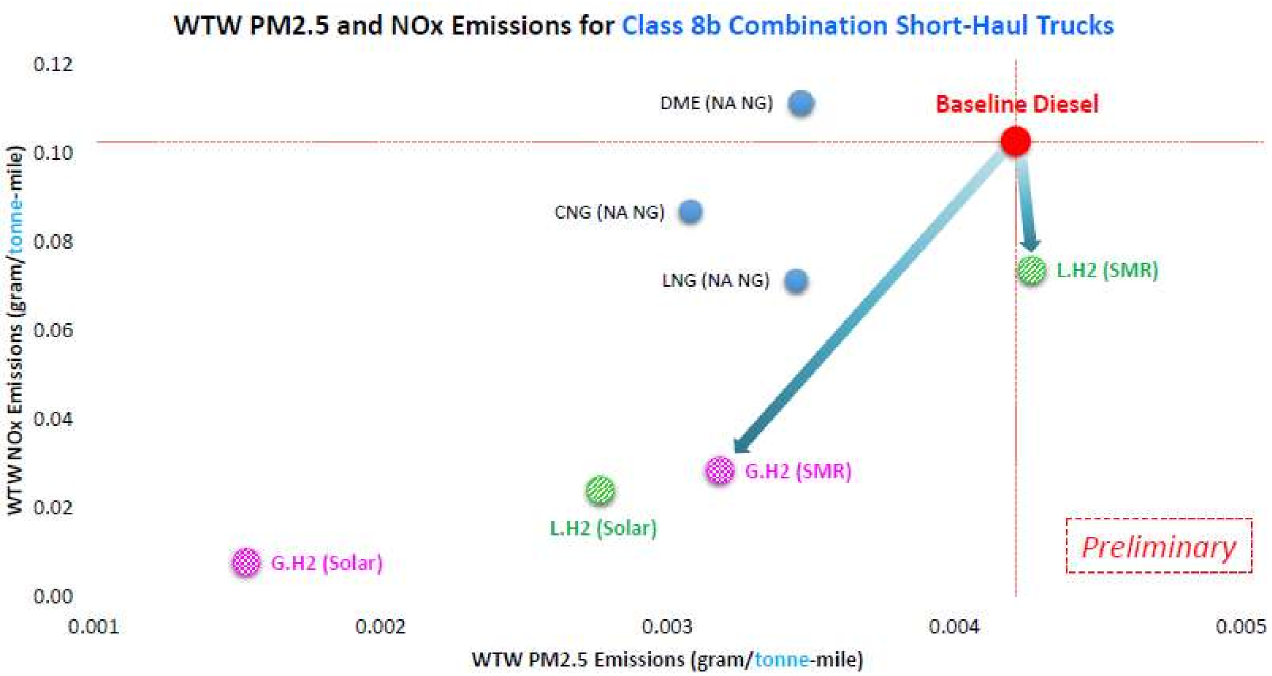


Figure 2.28: Well to wheel air pollutant (NOx and PM2.5) emissions comparison between reference case (Diesel), CNG and FCEV considering different hydrogen production pathways

Concerning the air pollutant emission, a similar overview has been shown if fig 2.11: gaseous hydrogen fuel cell electric trucks reduce overall NOx and PM2.5 emissions up to one order of magnitude.
The health impact of this important reduction will be discussed in the next section.

2.4.2 Health impact

The goal of this section is to present a quantitative tool for the estimation of social impact caused by air pollutants emissions.

2.4.2.1 Source of emissions

The most common air pollutants are SOx, NOx, PM2.5 and they have three different global sources: stationary, mobile and areawide
Table 2.1 presents the values of SOx, NOx and PM2.5 emissions from the three different emission sources.
Mobile sources contribute for the majority of NOx emissions by an order of magnitude or more, on the other hand SOx and PM2.5 are mostly emitted by stationary plants or areawide devices

Table 2.7: California Statewide emissions

	SOx (Tons/day)	NOx (Tons/day)	PM2.5 (Tons/day)
Stationary	56.6	262.6	72.8
Mobile	16.6	1,402	62.8
Areawide	4.0	62.7	236.7

Source: Data from CARB, 2017B

2.4.2.2 Modelling health damages with EASIUR model

The EASIUR model, which stands for Estimating Air pollution Social Impact Using Regression, uses emissions data to estimate social and public heath costs. EASIUR's social costs are only based on the impact of PM2.5 on mortality and three pieces of information are taken as inputs: (i) the amount of emissions, (ii) the location of emissions (longitude and latitude of emissions), and (iii) the season of the emissions.
Large changes in SOx and NOx may change the chemical environment in the atmosphere that affect PM2.5 formation, and then will have a considerable health impact.
To be noticed that EASIUR model reports damages by emission location rather than health damage location, so actual health damage incurred may occur outside California area or in general outside the considered country.

Table 2.8: Statewide average annual cost of health damages per ton of pollutants

	SOx Dam ($/ton)	NOx Dam ($/ton)	PM 2.5 Dam ($/ton)
Stationary	22,080	8,725	79,820
Mobile	22,650	10,100	186,900
Area Wide	19,000	12,100	133,910

Table 2.8 underlines the average cost at the state level for each of the pollutants per metric ton by emission category.

3 Medium heavy-duty trucks stock model

The aim of this section is to provide a vehicle stock model, referred to medium-heavy duty vehicles (so with a Gross Weight Value higher than 10,000 lb) in order to build solid base for future scenarios in terms of different truck's technologies and emissions.
For the U.S. stock it has been considered the analysis which has been done in [8], where the U.S. software VIUS has been used to estimate the vehicle fleet in 2014, as presented in fig 8.
For California instead, the software EMFAC2017 has been used for extracting data which have been then elaborated using mainly Excel.
EMFAC2017 allows to know the different trucks classes stock in the recent years and to have prediction for 2030, 2040 and 2050. This information would be very useful in order to build different future scenarios based on the vehicle stock prediction.

3.1 Vehicle categorization

The classification of vehicles used in [8] is defined in the table below:

Table 3.1: Overview of weight classes and vocations of freight vehicles

Vehicle Class	Vocation/ Description
class 2b, 6000 – 10000 lbs	Small Van
class 3, 10001 – 14000 lbs	Enclosed Van
class 3, 10001 – 14000 lbs	School Bus
class 3, 10001 – 14000 lbs	Service, Utility Truck
class 4, 14001 – 16000 lbs	Walk In, Multi Stop, Step Van
class 5, 16001 – 19500 lbs	Utility, Tow Truck
class 6, 19501 – 26000 lbs	Construction, Dump Truck
class 7, 26001 – 33000 lbs	School Bus
class 8, 33001 lbs or heavier	Construction, Dump Truck
class 8, 33001 lbs or heavier	Line haul
class 8, 33001 lbs or heavier	Refuse, Garbage Pickup, Cab over
class 8, 33001 lbs or heavier	Tractor Trailer

Regarding the vehicle classes definition, after a comparison between table 3.1, fig. 1.10 and EMFAC vehicle categories spreadsheet, it has been possible to define weight classes as outlined below in table 3.2

Table 3.2: EMFAC Vehicle classes and categories, according to fig.8 and table 3.2

EMFAC2011 Veh & Tech	EMFAC2011 Vehicle	Description	Class	Weight	Source
LHD1 - DSL	LHD1	Light-Heavy-Duty Trucks (GVWR 8501-10000 lbs)	2b	8500-10000 lb	EMFAC2011-LDV
MDV - DSL	MDV	Medium-Duty Trucks (GVWR 6000-8500 lbs)	2b	8500-10000 lb	EMFAC2011-LDV
LHD2 - DSL	LHD2	Light-Heavy-Duty Trucks (GVWR 10001-14000 lbs)	3	10000-14000 lb	EMFAC2011-LDV
T6 Ag - DSL	T6 Ag	Medium-Heavy Duty Diesel Agriculture Truck	4	14000-16000 lb	EMFAC2011-HD
T6 Public - DSL	T6 Public	Medium-Heavy Duty Diesel Public Fleet Truck	5	16000-19500 lb	EMFAC2011-HD
T6 utility - DSL	T6 utility	Medium-Heavy Duty Diesel Utility Fleet Truck	5	16000-19500 lb	EMFAC2011-HD
T6 CAIRP small - DSL	T6 CAIRP small	Medium-Heavy Duty Diesel CA International Registration Plan Truck with GVWR<=26000 lbs	6	19500-26000 lb	EMFAC2011-HD
T6 instate construction small - DSL	T6 instate construction small	Medium-Heavy Duty Diesel instate construction Truck with GVWR<=26000 lbs	6	19500-26000 lb	EMFAC2011-HD
T6 instate small - DSL	T6 instate small	Medium-Heavy Duty Diesel instate Truck with GVWR<=26000 lbs	6	19500-26000 lb	EMFAC2011-HD
T6 OOS small - DSL	T6 OOS small	Medium-Heavy Duty Diesel Out-of-state Truck with GVWR<=26000 lbs	6	19500-26000 lb	EMFAC2011-HD
T6TS - GAS	T6TS	Medium-Heavy Duty Gasoline Truck	6	16000-19500 lb	EMFAC2011-LDV
T6 CAIRP heavy - DSL	T6 CAIRP heavy	Medium-Heavy Duty Diesel CA International Registration Plan Truck with GVWR>26000 lbs	7	26000-33000 lb	EMFAC2011-HD
T6 instate construction heavy - DSL	T6 instate construction heavy	Medium-Heavy Duty Diesel instate construction Truck with GVWR>26000 lbs	7	26000-33000 lb	EMFAC2011-HD
T6 instate heavy - DSL	T6 instate heavy	Medium-Heavy Duty Diesel instate Truck with GVWR>26000 lbs	7	26000-33000 lb	EMFAC2011-HD
T6 OOS heavy - DSL	T6 OOS heavy	Medium-Heavy Duty Diesel Out-of-state Truck with GVWR>26000 lbs	7	26000-33000 lb	EMFAC2011-HD
SBUS - DSL	SBUS	School Buses	7	[illegible]	EMFAC2011-HD
UBUS - DSL	UBUS	Urban Buses	7	[illegible]	EMFAC2011-LDV
T7 Ag - DSL	T7 Ag	Heavy-Heavy Duty Diesel Agriculture Truck	8	>33000 lb	EMFAC2011-HD
T7 CAIRP - DSL	T7 CAIRP	Heavy-Heavy Duty Diesel CA International Registration Plan Truck	8	>33000 lb	EMFAC2011-HD
T7 CAIRP construction - DSL	T7 CAIRP construction	Heavy-Heavy Duty Diesel CA International Registration Plan Construction Truck	8	>33000 lb	EMFAC2011-HD
T7 NNOOS - DSL	T7 NNOOS	Heavy-Heavy Duty Diesel Non-Neighboring Out-of-state Truck	8	>33000 lb	EMFAC2011-HD
T7 NOOS - DSL	T7 NOOS	Heavy-Heavy Duty Diesel Neighboring Out-of-state Truck	8	>33000 lb	EMFAC2011-HD
T7 other port - DSL	T7 other port	Heavy-Heavy Duty Diesel Drayage Truck at Other Facilities	8	>33000 lb	EMFAC2011-HD
T7 POAK - DSL	T7 POAK	Heavy-Heavy Duty Diesel Drayage Truck in Bay Area	8	>33000 lb	EMFAC2011-HD
T7 POLA - DSL	T7 POLA	Heavy-Heavy Duty Diesel Drayage Truck near South Coast	8	>33000 lb	EMFAC2011-HD
T7 Public - DSL	T7 Public	Heavy-Heavy Duty Diesel Public Fleet Truck	8	>33000 lb	EMFAC2011-HD
T7 Single - DSL	T7 Single	Heavy-Heavy Duty Diesel Single Unit Truck	8	>33000 lb	EMFAC2011-HD
T7 single construction - DSL	T7 single construction	Heavy-Heavy Duty Diesel Single Unit Construction Truck	8	>33000 lb	EMFAC2011-HD
T7 SWCV - DSL	T7 SWCV	Heavy-Heavy Duty Diesel Solid Waste Collection Truck	8	>33000 lb	EMFAC2011-HD
T7 tractor - DSL	T7 tractor	Heavy-Heavy Duty Diesel Tractor Truck	8	>33000 lb	EMFAC2011-HD
T7 tractor construction - DSL	T7 tractor construction	Heavy-Heavy Duty Diesel Tractor Construction Truck	8	>33000 lb	EMFAC2011-HD
T7 utility - DSL	T7 utility	Heavy-Heavy Duty Diesel Utility Fleet Truck	8	>33000 lb	EMFAC2011-HD
T7IS - GAS	T7IS	Heavy-Heavy Duty Gasoline Truck	8	[illegible]	EMFAC2011-LDV
PTO - DSL	PTO	Power Take Off	8	>33000 lb	EMFAC2011-HD

There can be outlined 7 different weight classes, with the 8th class which have the highest range in terms of weight (from 30,000 lb up to 90,000 lb or even more).

3.1.1 Stock model inputs

In this section will be depicted all the inputs which are necessary for building a stock model, using a software called LEAP.

Using EMFAC has been possible to extract data of vehicle population, emissions, vehicle miles travelled (VMT).
From these data have been possible to compute and define all the parameters which have to be inserted for the stock modelization in LEAP:

- Lifetime and survival rate
- Stock and sale in the current year
- Sales in the reference scenario
- Stock vintage
- Vehicle miles travelled (VMT)
- Fuel economy (MPG)
- Sales share by classes and by drive train
- Annual sales increase

For computing the fuel economy, the following equation has been used:

$$\mathrm{MPG}\left[\frac{\mathrm{miles}}{\mathrm{gallon}}\right] = \frac{\mathrm{VMT[miles]}}{\mathrm{CO_{2\,em}}[ton]} \cdot \frac{\mathrm{x}\,[\frac{\mathrm{pound}}{\mathrm{gallon}}]}{2000[\frac{\mathrm{pound}}{\mathrm{ton}}]}$$

Two corrective factors have been introduced:

- x = 22.4 for Diesel, 1 gallon of Diesel emits 22.4 pounds of CO_2

- x = 17.6 for E10 Gasoline (90% Gasoline and 10% fuel ethanol), 1 gallon of E1 Gasoline emits 17.6 pounds of CO_2
- 1 ton of CO_2 is equal to 2000 pounds

All the constant coefficient has been taken from [31].
All the data from EMFAC has been extracted and analysed in terms of vintage, starting from 1972. This is of cardinal importance especially for the population, it allows to determine the population behaviour varying the truck's year.
The data extracted from EMFAC have been compared with that one extracted from VISION, another software developed by ARB. The error of the data is slightly higher than 10%, so it has been considered acceptable.
To sum up on the whole, in the following table below has been presented all the input parameters which have been found in the analysis.

Table 3.3: Input parameters extracted from EMFAC

	Class 2b		*Class 3*		*Class 4*		*Class 5*		*Class 6*		*Class 7*			*Class 8*		
Fuel type	*D*	*G*	*D*	*G*	*D*	*G*	*D*	*G*	*D*	*G*	*D*	*G*	*NG*	*D*	*G*	*NG*
Population	4.9m		180k		1.2k		30k		230k		100k			300k		
VMT (daily) [miles]	183m		7.2m				453k		11.4m		8.9m			36.9m		
VMT/vehicle (daily) [miles]	37		40				15		50		89			123		
VMT/vehicle (yearly) [miles]	13,505		14,600				5,475		18,250		32,485			44,895		
VMT/new vehicle (yearly) [miles]	13,903	13,981	22,249	22,251			6,683		25,064	32,266	58,251	20,241	6,858	77,268		14,882
Lifetime (years)	16		18				16		12*		11*			15		
Fuel economy (MPG)	18	9.5	16	8			9		7	10	6.5	10	10	4.5	7	7

*the survival plot and then the lifetime is not reliable

The population of the 4th class is one order lower than the smallest value of population of the other classes, for this reason it has not been considered in the analysis.

3.1.2 Stock model input validation

In order to evaluate the input parameters extracted from EMFAC a comparison with the literature [30] has been made:

Table 3.4: Fuel Economy for each category [30]

Typical Operating Weight	MPG	Average Operating Speed (MPH)
Less than 20,000 lbs	6.3	46
20,001 - 40,000 lbs	6.7	53
40,001 - 60,000 lbs	6.8	51
60,001 - 80,000 lbs	6.0	55
Greater than 80,000 lbs	5.4	51

It is possible to notice that for Classes 6-7-8, that one regarding vehicles with a mass higher than 20,000 lbs the values of fuel economy founded after the elaboration of EMFAC data are consistent with that one proposed by the literature.

The average lifetime of drayage truck is 8 years and 500,000 miles, as reported in [29]. Another estimation of lifetime in terms of years and miles driven has been done in [30], as reported in the table below

Table 3.5: Lifetime of medium heavy-duty trucks [30]

Equipment Type	Average Number of Years Until Replacement	Average Miles Driven Until Replacement
Straight Trucks	10.0	350,000
Truck-Tractors	6.3	754,000
Trailers	12.7	

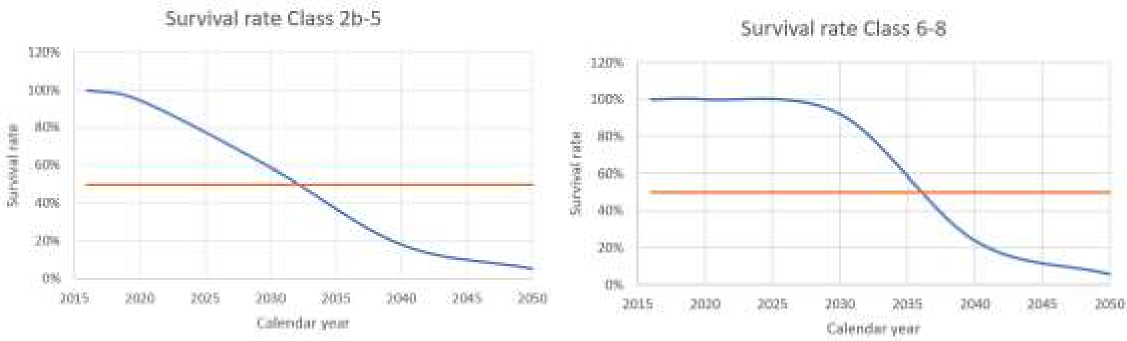
The values which have been founded analysing the data from EMFAC generally overestimate the lifetime of trucks with respect to [30] by a factor which oscillates from 1.5 and 2 varying on the vehicle classes.

3.2 Stock model lifecycle profiles

The lifecycle properties represent the vehicle properties which will be valid for all the scenarios that will be presented in chapter 5. In order to compute and plot them, data have been pulled from EMFAC and then analysed.

3.2.1 Survival rate

The survival rate is the fraction of vehicles surviving after a given number of years, and it is shown in the plots below.



(a) (b)

Figure 3.1: Survival rate's plot, (a) represents light duty trucks, (b) the heavy-duty ones; the orange line represents 50% of the vehicle life

The survival rate plots evidence an important difference between medium and heavy-duty trucks, the latter have a much longer 100% survival and then after around 10-15 years the number of trucks fall rapidly.

This characteristic is reasonable, being the Fig 3.1(a) close to the one representing light duty vehicle(LDV) profile and considering also the vocation of heavy-duty trucks which are more inclined to survive as much as possible and not be replaced for small defects.

3.2.2 Vintage stock profiles

The stock is the number of vehicles existing in calendar year, which for our case is 2016. The model year of the vehicle is also called “vintage” and the vehicle which has vintage=0 are the new one, so are part of the new sales.

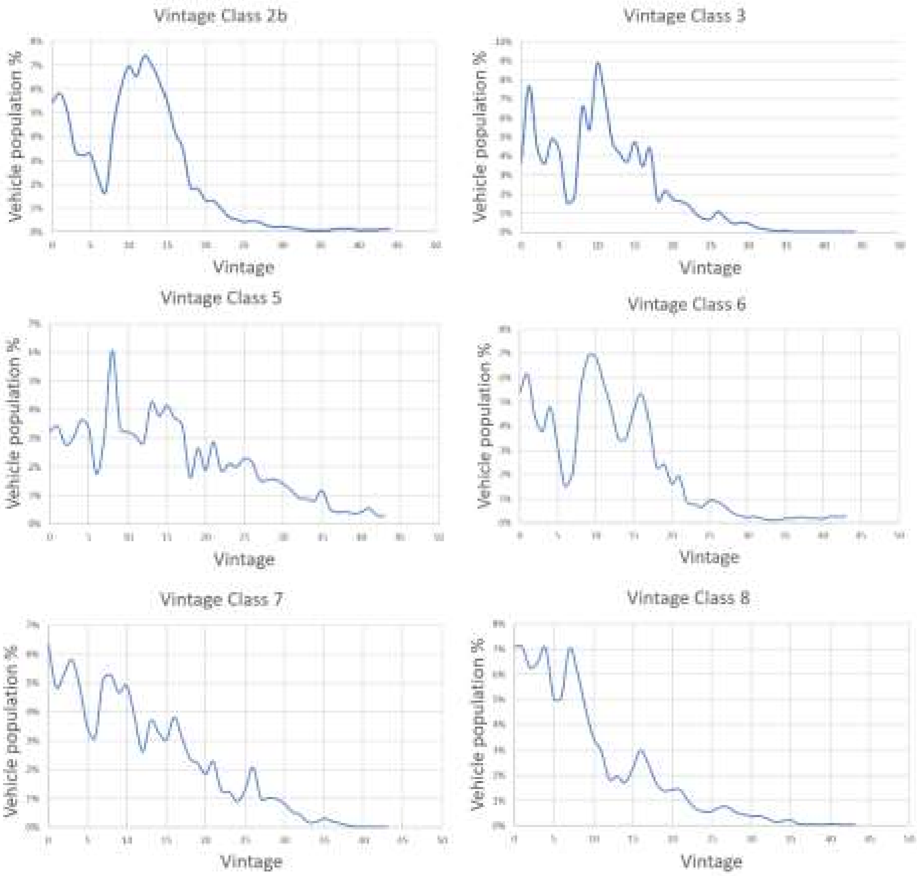


Figure 3.2: Vintage plots for all the classes which have been considered, the year considered is 2016 (base year)

The behaviour suggested by the vehicle survval plot find similarities with that one proposed by vehcile vintage in Fig 3.2.
In particular it is possible to notice that Class 8 vehicles has really high population percentge (around 7%) in the first 6-7 years of vintage and then there is a sudden drop.
Another interesting aspect is that in almost all the vintage profile evidence a drop at around 8 years of vintage and then a sudden increase.
This is mostly due to the financial crisis occurred in 2008 which determine a drop in the vehicle’s sell during that year.

3.2.3 Vehicle miles tralelled (vmt) profiles

The vehicle miles travelled in this case are the miles that one vehicle travels in one year. This number is decreasing over years and the trends are outlined in the plots below

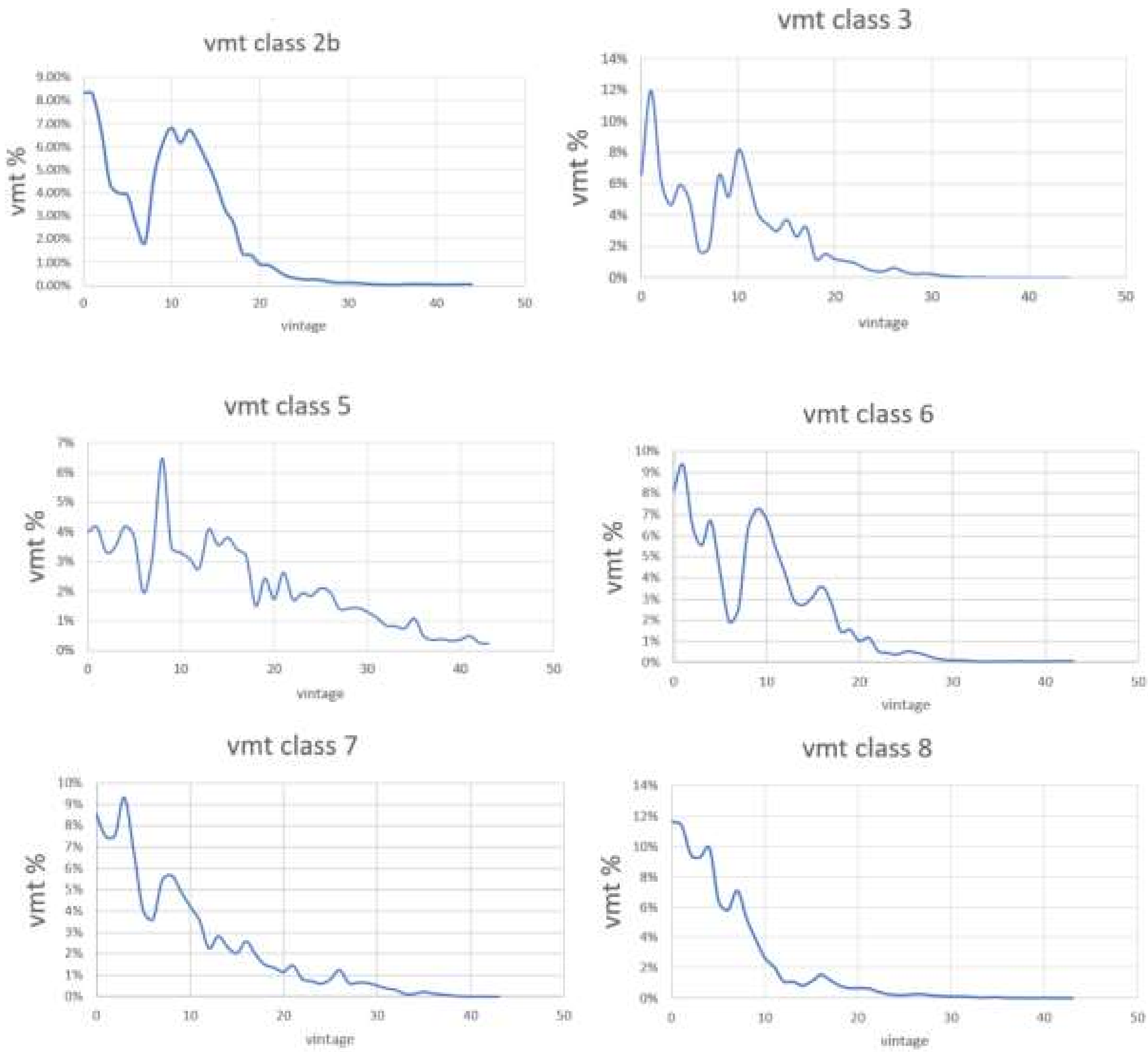


Figure 3.3: Vmt plots for all the considered classes, the reference year is 2016

The behavior suggested by the vmt profiles reflects that one of the stock vintage, with the heaviest classes which have a higher and more steady mileage for the first five years, followed by a sudden drop. On the other hand, the lighter classes' plots presents various spikes and the behavior is more irregular.

3.3 Stock model reference trends

The fuel share, the class share and sales trends and have been pulled from EMFAC and imported in LEAP for building the reference scenario.

3.3.1 Fuel shares

The fuel shares represent the percentage of a given fuel type for each class. They usually change over time, having a great impact on emissions of both air pollutants and GHG.

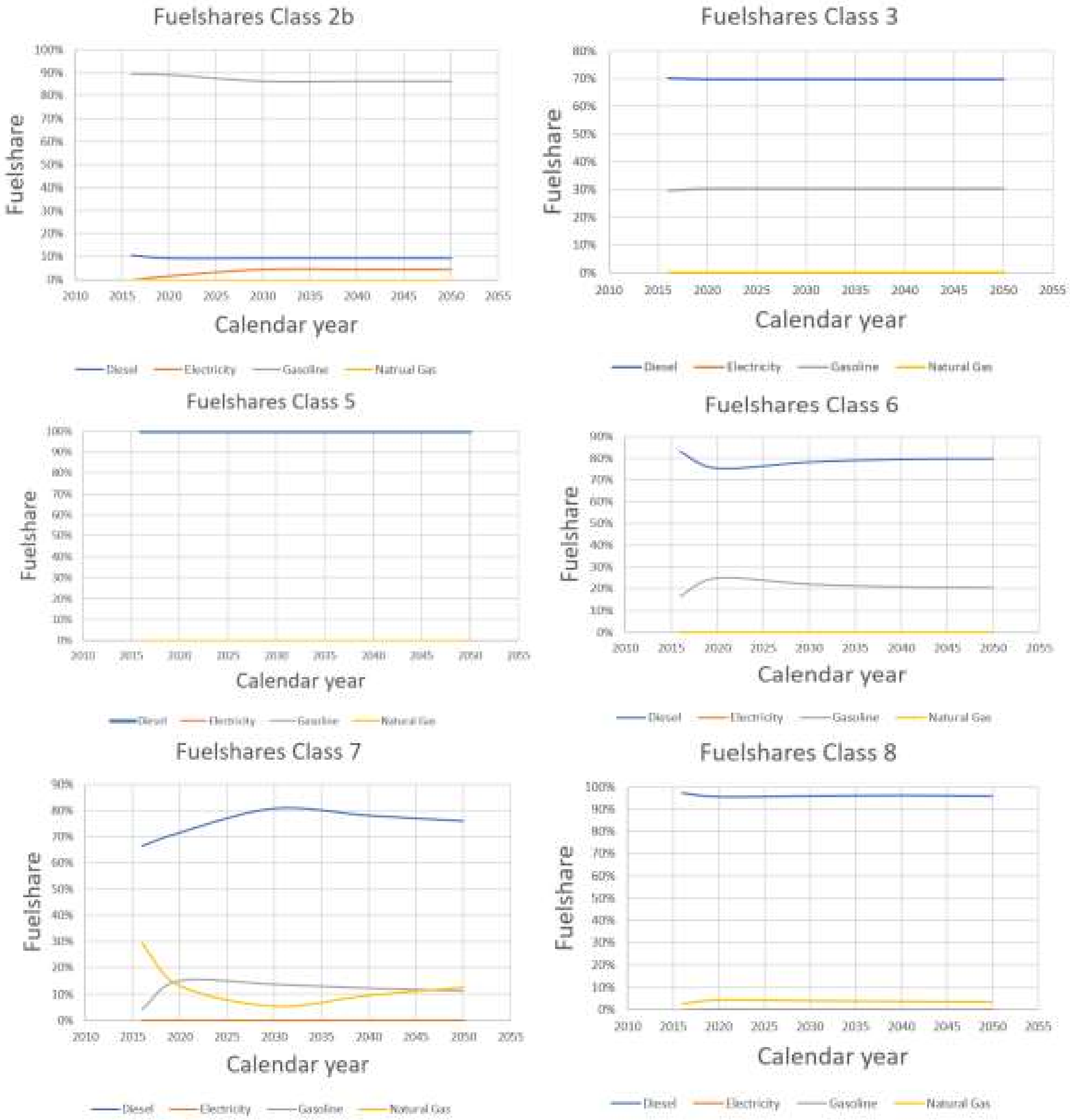


Figure 3.4: Fuel share plots on the base year (2016)

All the classes evidence a higher Diesel percentage with respect to the other technologies, except for Class 2b which has a higher Gasoline percentage. This is a clear sign that identifies Class 2b as lighter trucks or pick-up and not properly part of medium and heavy-duty trucks.
Moreover, for class 7 and class 8 there is the presence of Natural Gas vehicles, which represent a particularly high percentage in class 7.

3.3.2 Sales share trend

The last reference trend input from EMFAC are the new sales trend and then the class shares. Having these information it is possible to have a baseline regarding the new vehicle adoption the future years, based on the actual policies for California.

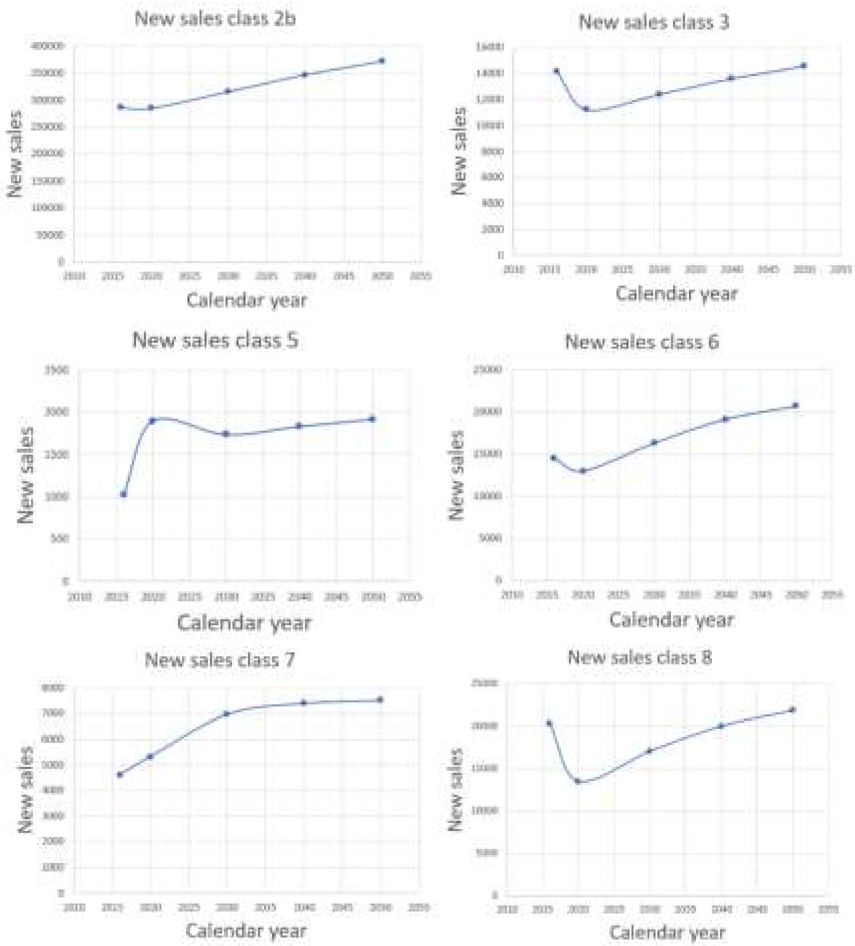


Figure 3.5: New sales trend for all the classes, from the current year to 2050

From figure 3.5 an increasing trend from 2020 on is outlined. In most of the cases from 2016 to 2020 a sharp decrease in new sales is outlined.

4 Cost model for battery and fuel cell electric truck

4.1 State of the art

4.1.1 Component cost analysis

In order to evaluate the total cost of a fuel cell truck, the total cost of ownership (TCO) and the upstream process of hydrogen production and distribution must be considered.
This process has been widely explained in the project done by the U.S. Department of Energy in [28] and it is summarized in the figure posted below.

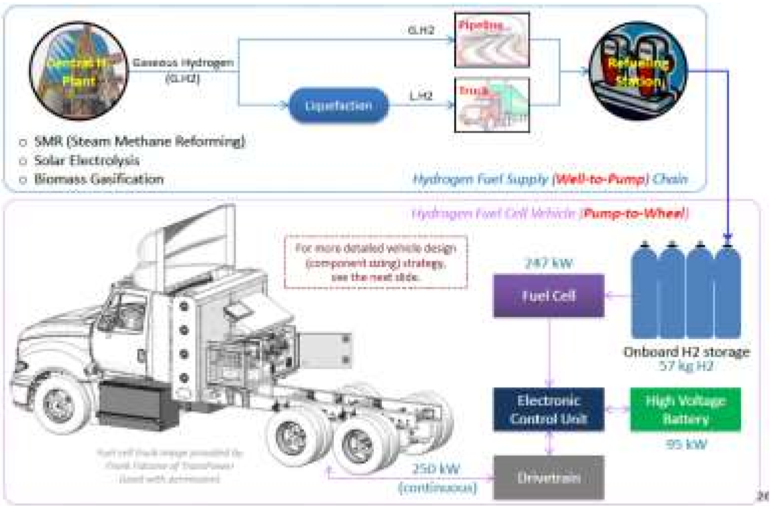


Figure 4.1: Medium and heavy-duty hydrogen fuel cell truck system configuration [28]

Component cost modelling has been studied more deeply in [24] - [25] - [26], instead the infrastructure cost has been studied in [19].
As far as component cost modelling has concerned, in [24] has been presented a cost comparison between Fuel Cell Electric Vehicle and Battery Electric Vehicle, considering light duty ones.

Table 4.1: Estimated weight, on-board space, and mass-production cost requirements of the FCV propulsion system for light duty vehicles [24]

Component	Weight	Volume	Cost	Reference
Fuel-Cell	617 kg	1182 liters	$23,033	ADL(2001)
3.2 kg storage tank	51 kg	215 liters	$2,288	Padro and Putsch(1999)
Drivetrain	53 kg	68 liters	$3,826	AC Propulsion, Inc.(2001), Solectria Corp (2001)
Total	**721 kg**	**1465 liters**	**$29,147**	

The cost of the fuel cell stack has been then deeply analysed by Brian James in [25], where both the automobile case and the bus case have been considered.
Buses are part of the medium and heavy-duty vehicles analysed in this report, being a big part of Class 7, so they will be considered in the cost data reported here.

The results of the cost analysis of the 2016 bus technology system at 200, 400, 800 and 1,000 systems per annual production rate are presented in the tables below.

Table 4.2: Stack components cost for 2016 bus system varying the annual production rate

			2016 Bus System			
Annual Production Rate		**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)		**kWnet**	160	160	160	160
System Gross Electric Power (Output)		**kWgross**	194.71	194.71	194.71	194.71
Stack Components						
	Bipolar Plates (Stamped)	**$/stack**	$1,873	$1,632	$1,422	$1,876
	MEAs					
	Membranes	**$/stack**	$9,563	$6,475	$4,467	$3,980
	Catalyst Ink & Application (dispersed	**$/stack**	$6,759	$6,167	$5,669	$5,504
	GDLs	**$/stack**	$6,641	$5,340	$3,406	$2,952
	M & E Hot Pressing	**$/stack**	$121	$100	$97	$81
	M & E Cutting & Slitting	**$/stack**	$14	$14	$13	$13
	MEA Gaskets (Frame or Sub-Gasket)	**$/stack**	$621	$503	$481	$432
	Coolant Gaskets (Laser Welding)	**$/stack**	$482	$383	$423	$340
	End Gaskets (Screen Printing)	**$/stack**	$2	$1	$1	$1
	End Plates	**$/stack**	$168	$156	$145	$142
	Current Collectors	**$/stack**	$13	$13	$12	$12
	Compression Bands	**$/stack**	$17	$16	$15	$14
	Stack Insulation Housing	**$/stack**	$275	$146	$83	$70
	Stack Assembly	**$/stack**	$158	$142	$132	$130
	Stack Conditioning	**$/stack**	$290	$151	$146	$120
Total Stack Cost		**$/stack**	$26,995	$21,239	$16,516	$15,669
Total Cost for all 2 Stacks		**$/2 stacks**	$53,989	$42,478	$33,032	$31,338
Total Stacks Cost (Net)		**$/kWnet**	$337.43	$265.49	$206.45	$195.86
Total Stacks Cost (Gross)		**$/kWgross**	$277.28	$218.16	$169.65	$160.95

Table 4.3: Balance of plant components cost for 2016 bus system varying the annual production rate

			2016 Bus System			
Annual Production Rate		**Sys/yr**	200	400	800	1,000
System Net Electric Power (Output)		**kWnet**	160	160	160	160
System Gross Electric Power (Output)		**kWgross**	194.71	194.71	194.71	194.71
BOP Components						
	Air Loop	**$/system**	$8,863	$7,421	$6,445	$6,193
	Humidifier & Water Recovery Loop	**$/system**	$1,278	$1,043	$896	$859
	High-Temperature Coolant Loop	**$/system**	$1,935	$1,873	$1,813	$1,794
	Low-Temperature Coolant Loop	**$/system**	$222	$216	$209	$207
	Fuel Loop	**$/system**	$997	$950	$905	$891
	System Controller	**$/system**	$283	$275	$268	$266
	Sensors	**$/system**	$1,087	$992	$905	$879
	Miscellaneous	**$/system**	$1,118	$909	$792	$766
Total BOP Cost		**$/system**	$15,784	$13,679	$12,234	$11,856
Total BOP Cost		**$/kW (Net)**	$98.65	$85.49	$76.46	$74.10
Total BOP Cost		**$/kW (Gross)**	$81.06	$70.25	$62.83	$60.89

Table 4.2 details the stack's components cost, whereas table 4.2 details the cost of the balance of plants components.
The stack and the balance of plant together build the fuel cell system, which is the core of each fuel cell vehicle, independently on light, medium or heavy-duty vehicle and on their vocations.
The fuel cell system scheme for the bus technology case has been reported in fig. 4.2, where all the main system components are linked in a flow diagram.

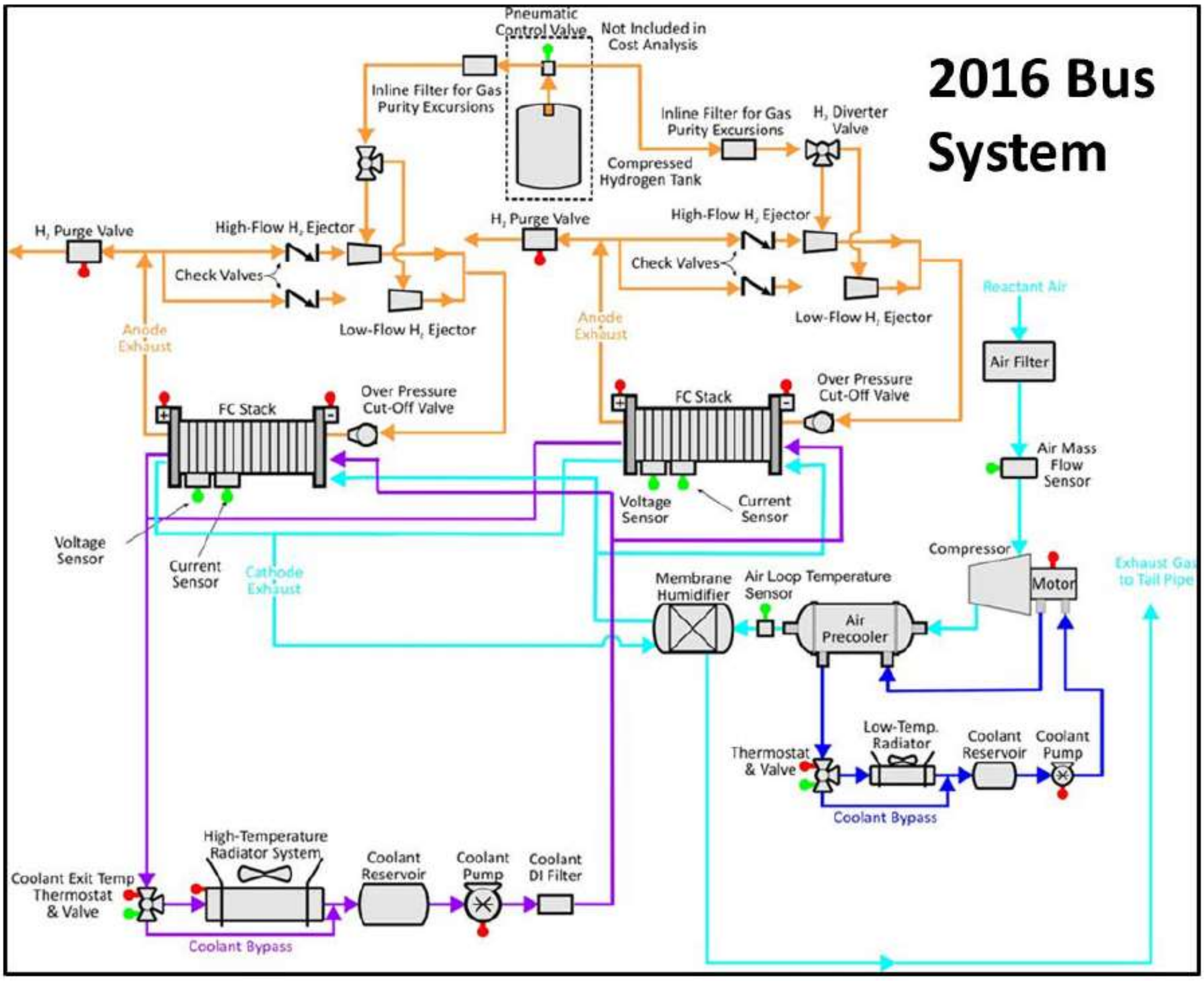


Figure 4.2 Flow schematic for the bus fuel cell system

The last challenge for fuel cell vehicle is the hydrogen storage, storage tank costs have been analysed by NREL and Argonne National Laboratory in [26], which have been synthesized in the following table

Table 4.4: Single tank and two-tank system based on Toyota design [26]

	Available H_2 (kg)	L/D	Cost/tank ($/kWh)	CF Reduction (%)	BOP & Assembly ($/kWh)*	Total ($/kWh)
SA Baseline (single tank)	5.6	3	11.05	--	3.54	14.59
SA Two-Tank Configuration	5.6	3	11.28	--	4.66	15.94
SA Two-Tank w/Toyota winding pattern	5.6	2.8	10.53	-7.2%	4.66	15.19

It is important to notice that for the cost reported above also the error has been analysed in [26], being $3\sigma=14.0\%$ for the baseline single tank case.
Finally, both a low voltage and high voltage battery have to be present in a fuel cell electric vehicle as reported in figure 2.1 and 4.1.
The cost of the battery has been analysed by the U.S. Department of Energy, which have provided a broad overview of the current technology cost and the future predictions, as presented in section 1.2.2.
Finally, in [25] a single variable analysis considering the bus case has been performed. It allows to understand the impact of each component's value on the overall system cost, as it is possible to see in fig. 4.3.

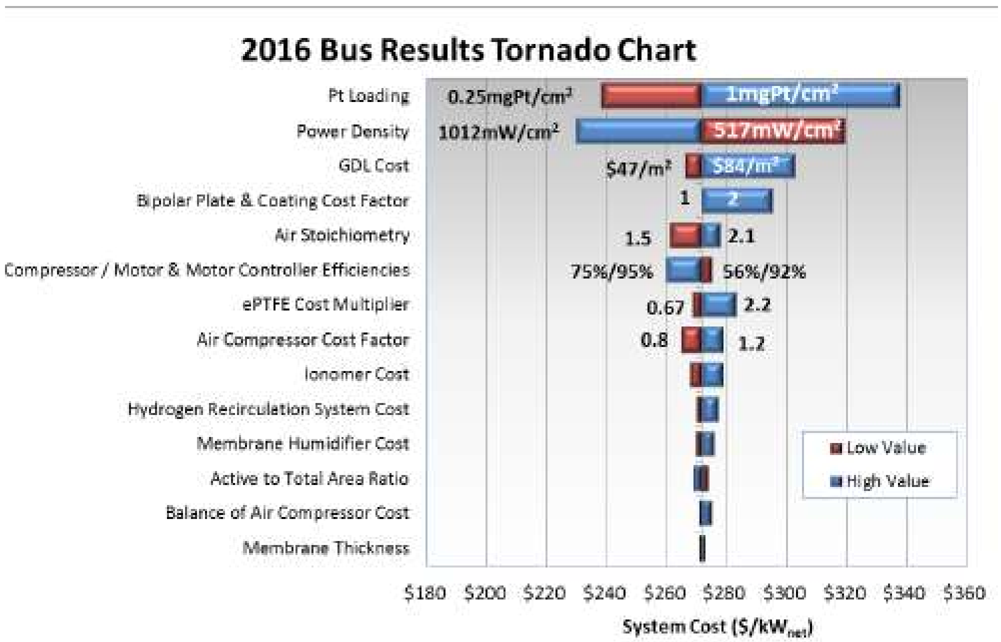


Figure 4.3 Bus tornado chart

In the literature has not been found a complete detailed cost analysis on medium-heavy duty trucks, and this will be part of the aim of this work.

An important study is being conducted in collaboration between Ricardo Strategic Consulting and California Fuel Cell Partnership [23] to provide economic modelling tools that will enable the assessment of Total Cost of Ownership (TCO) of fuel cell powered trucks

4.1.2 Hydrogen infrastructure cost

Beside the cost of ownership, to understand the feasibility of fuel cell trucks deployment hydrogen production and infrastructure costs are of cardinal importance.
The deployment of the hydrogen infrastructures has been studied by the Department of Energy in collaboration with Clean Energy Manufacturing Analysis Center in [38]. Hydrogen infrastructure networks continue to be developed in areas where vehicle manufacturers, hydrogen providers and government share an interest and through active policies incentive the fuel cell vehicle adoption and spread.
In figure 4.2 the two hydrogen delivery hydrogen configurations have been shown:

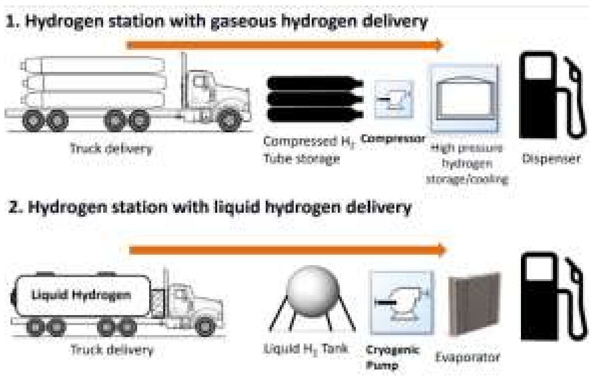


Figure 4.4: Hydrogen delivery: Station Configuration [38]

Based on the analysis conducted in [38], by the end of 2015 at least 250 Hydrogen Refuelling Stations (HRS) had been build or founded across the world as can be visualised in fig. 4.3.

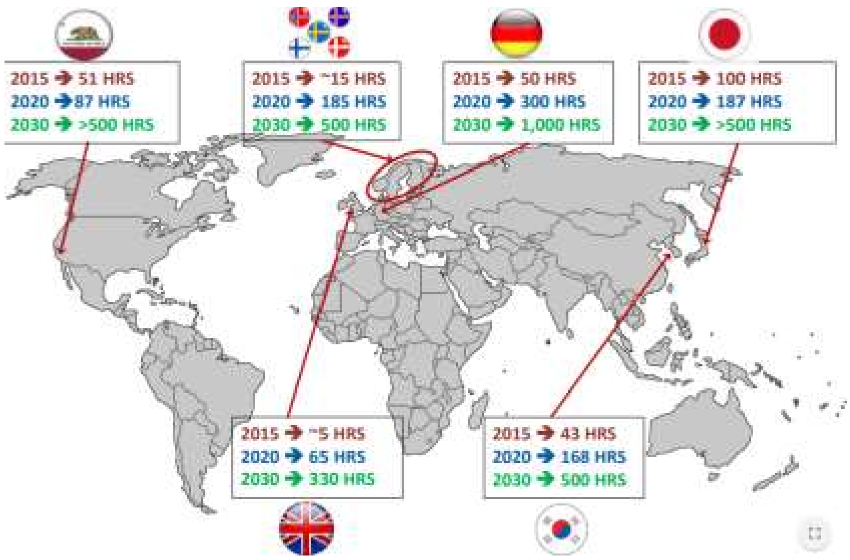


Figure 4.5: International Hydrogen Refueling Stations rollout [38]

As indicated above, more than 2000 stations are planned to be built all over the world for 2030, which would be a step forward for HRS deployment.
The cost of hydrogen infrastructures has been studied in [19] where a cost analysis varying the hydrogen daily volume has been provided and the results are shown in the following graph.

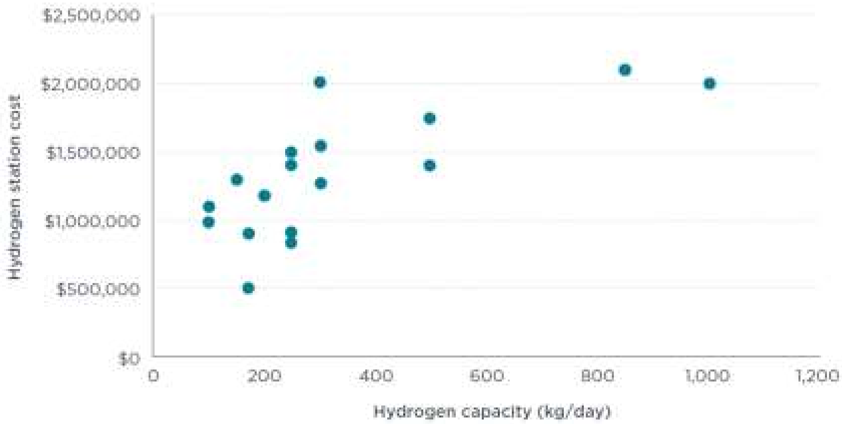


Figure 4.6: Modeled hydrogen station cost varying hydrogen daily volume [19]

It is worth to notice that cost reduction with respect to the one proposed in fig. 4.4 can be expected as demand for hydrogen increases and economy of scale will possibly take place.

4.1.3 Hydrogen production, delivery and dispensing cost

In order to estimate the cost related to the hydrogen the H2A model has been considered in [37], which analysed the hydrogen production through central steam methane reforming (SMR) and on-site electrolysis.
The graph presented below summarizes the final results of [37], where for the central SMR case the gaseous hydrogen distribution has been considered by truck trailer.

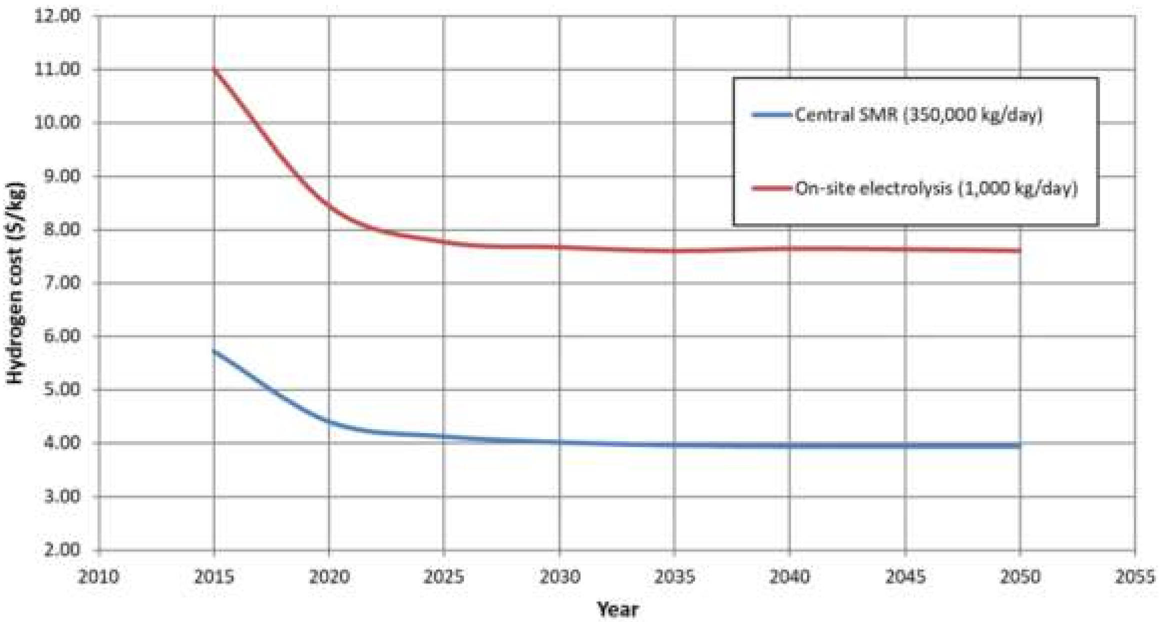


Figure 4.7 Hydrogen cost projections for central SMR and on-site electrolysis

The cost of electricity considered in [37] are referred to California, so the price of hydrogen production through on-site electrolysis can be higher with respect to other regions in the US

4.1.4 Cost variation: annual production rate and system size

The fuel cell vehicle components cost, so mainly the fuel cell system, is subjected to variation mainly considering two parameters:

- Annual production rate
- System electric power

4.1.4.1 Annual production rate

The first variable is taken into consideration in table 4.2 and 4.3 where the component details for fuel cell stack and balance of plant is considered.
In table 4.5 the whole bus fuel cell system is considered, putting together the fuel stack cost and the balance of plant one for the bus technology case.

Table 4.5: System cost for 2016 bus system varying the annual production rate

		2016 Bus System			
Annual Production Rate	Sys/yr	200	400	600	1,000
System Net Electric Power (Output)	kWnet	160	160	160	160
System Gross Electric Power (Output)	kWgross	194.71	194.71	194.71	194.71
Component Costs/System					
Fuel Cell Stacks (High Value)	$/system	$69,339	$55,009	$45,471	$42,610
Fuel Cell Stacks (Nominal Value)	$/system	$53,989	$42,478	$33,032	$31,338
Fuel Cell Stacks (Low Value)	$/system	$45,405	$35,209	$27,662	$26,296
Balance of Plant (High Value)	$/system	$17,267	$14,955	$13,374	$12,961
Balance of Plant (Nominal Value)	$/system	$15,784	$13,679	$12,234	$11,856
Balance of Plant (Low Value)	$/system	$14,260	$12,370	$11,083	$10,748
System Assembly & Testing	$/system	$464	$339	$275	$262
Cost/System (High Value)	$/system	$85,688	$69,105	$58,073	$54,982
Cost/System (Nominal Value)	$/system	$70,237	$56,495	$45,541	$43,456
Cost/System (Low Value)	$/system	$61,447	$49,088	$40,029	$38,293
Total System Cost	$/kWnet	$438.98	$353.10	$284.63	$271.60
Cost/kWgross	$/kWgross	$360.72	$290.15	$233.89	$223.18

It is possible to notice how cost change, changing the annual production rate, due to serveral factors: (i) economy of scale, (ii) technological learning and (iii) competiton throuh different companies which dirives prices down.
The third aspect has not been analyzed by Strategic Analysis Inc. in [25], where for the cost model one company has been considered driving the market.

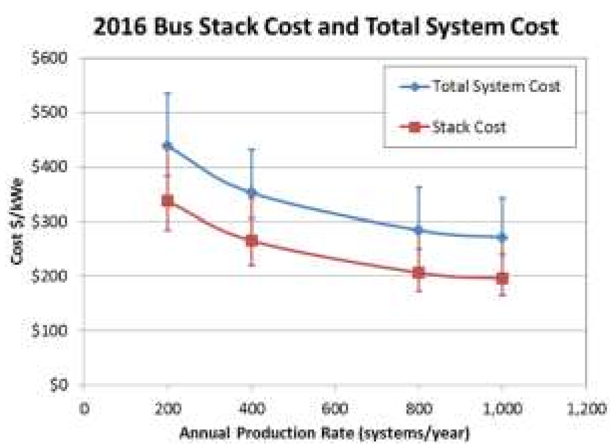


Figure 4.8: Bus stack and system cost at various manufacturing rates. Error bars are based on Monte Carlo sensitivity analysis and denote the middle 90% confidence range of results

Each error bar which can be visualised in fig 4.6 is based on Monte Carlo sensitivity analysis and represents the middle 90% of confidence range of results, as it is shown in the plot below.

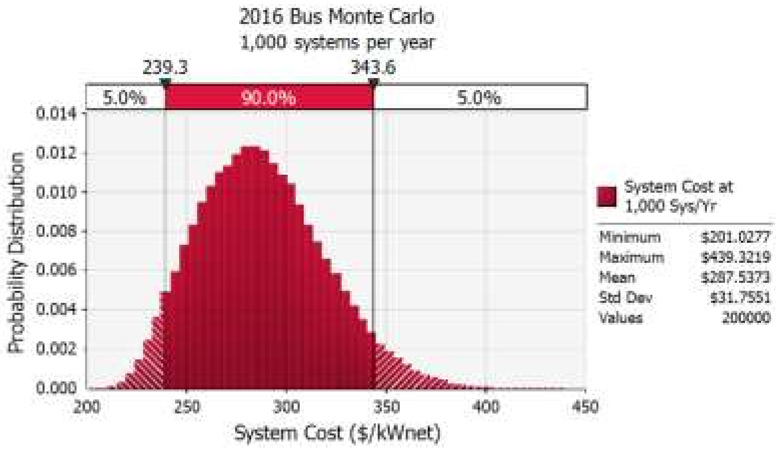


Figure 4.9: Bus technology system Monte Carlo analysis results

The Monte Carlo analysis examines the probability of various model outcomes based on assumed probability distribution functions (PDFs) for the selected inputs.
In this case a triangular distribution for each input of the system has been chosen, a maximum, a minimum and the most likely value; the production rate of 1,000 systems has been considered in this example but the same treatment has been done for the other manufacturing rates.

2016 Bus Technology Monte Carlo Sensitivity Analysis				
Parameter	Unit	Minimum Value	Likeliest Value	Maximum Value
Power Density	mW/cm2	517	719	1012
Pt Loading	mgPt/cm2	0.35	0.5	1
Ionomer Cost Multiplier		0.22	1.00	2.45
Ionomer Cost (@ 1ksys/yr)	$/kg	$48.38	$219.85	$538.08
GDL Cost Multiplier		0.73	1.00	1.30
GDL Cost (@ 1ksys/yr)	$/m2	$47.27	$64.76	$84.18
Bipolar Plate & Coating Cost Multiplier		1	1	2
Bipolar Plate Cost (1k sys/yr)	$/kWnet	$23.08	$25.88	$46.08
Membrane Humidifier Cost Multiplier		0.5	1.00	2
Membrane Humidifier Cost (@ 1ksys/yr)	$/system	$324.92	$649.83	$1,299.66
Compressor Effic. Multiplier		0.97	1.00	1.29
Compressor Effic.	%	56%	58%	75%
Motor/Controller Effic. Multiplier		0.97	1.00	1.00
Motor/Controller Effic.	%	92%	95%	95%
Air Compressor Cost Multiplier		0.8	1.00	1.2
Air Compressor Cost	$/system	$5,344	$6,681	$8,017
Balance of Air Compressor Cost Multiplier		0.6667	1.00	2
Balance of Air Compressor Cost (@ 1ksys/yr)	$/system	$441.48	$612.79	$1,225.58
Hydrogen Recirculation System Cost Multiplier		0.6667	1.00	2
Hydrogen Recirculation System Cost (@ 1ksys/yr)	$/system	$594.20	$891.26	$1,782.52
ePTFE Cost Multiplier		0.687	1.00	2.20
ePTFE Cost (@ 1ksys/yr)	$/m2	$9.67	$14.49	$31.89
Membrane Thickness	µm	15	18.0	25.4
Active to Total Area Ratio		0.55	0.625	0.80

Figure 4.10: Monte Carlo analysis for bus technology systems. The cost multipliers were applied also to the other annual manufacturing rates, the individual costs are related to 1,000 systems per year

4.1.4.2 System electric power

The other variable which is of cardinal importance for a cost analysis of fuel cell vehicle is the system electric power variation.
In the literature this type of analysis has not been found for mobile sources but only for stationary applications in [35].

Table 4.6: Fuel cell stack (a) and balance of plant (b) cost varying system size and annual production rate

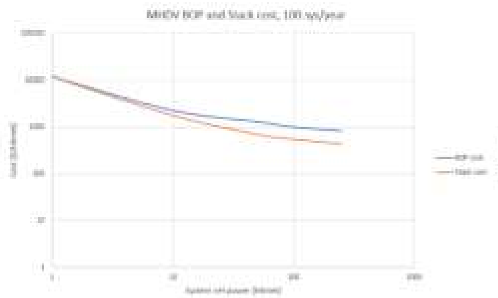
System Size[kW]	100 Systems/ yr	1000 Systems/ yr	10000 Systems/ yr	50000 Systems/ yr	100 to 1000 Systems/ yr	1000 to 10000 Systems/ yr	10000 to 50000 Systems/ yr	100 to 50000 Systems/ yr
1	$11,973	$ 2,041	$ 779	$ 540	83%	62%	31%	95%
10	$ 1,790	$ 590	$ 370	$ 311	67%	37%	16%	83%
50	$ 705	$ 396	$ 297	$ 260	44%	25%	12%	63%
100	$ 556	$ 346	$ 273	$ 238	38%	21%	13%	57%
250	$ 438	$ 307	$ 252	$ 220	30%	18%	13%	50%

(a)

System Size(kW)	100 Systems/ yr	1000 Systems/ yr	10000 Systems/ yr	50000 Systems/ yr	100 to 1000 Systems/ yr	1000 to 10000 Systems/ yr	10000 to 50000 Systems/ yr	100 to 50000 Systems/ yr
1	$11,871	$ 9,489	$ 8,079	$ 7,125	20%	15%	12%	40%
10	$ 2,254	$ 1,873	$ 1,582	$ 1,413	17%	16%	11%	37%
50	$ 1,307	$ 1,118	$ 962	$ 853	14%	14%	11%	35%
100	$ 998	$ 855	$ 739	$ 665	14%	14%	10%	33%
250	$ 827	$ 724	$ 640	$ 573	13%	12%	10%	31%

(b)

From table 4.6 two different trend are outlined, the fuel cell stack costs scale more rapidly than balance op plant costs increasing volume and increasing system size.
Considering the system size dependence, a huge drop is present passing from 1kW system to 10kW one, so in order to visualize better the trend a log-log scale has been used in the graphs below



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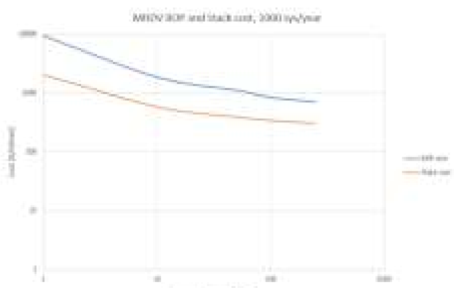

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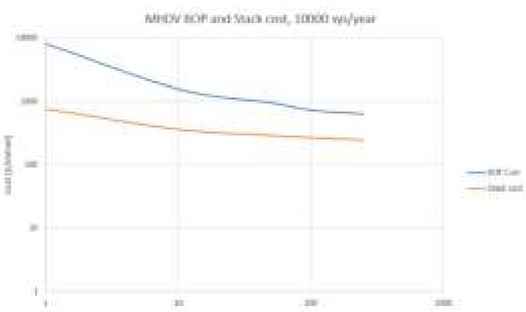

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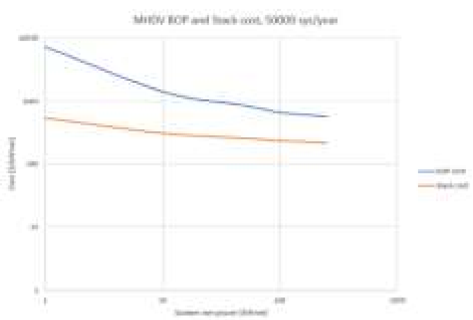


(d)

Figure 4.11: Cost dependence on system power, varying the manufacturing rate

4.1.5 Literature review results

All the cost analysis presented in the previous paragraphs has been summarized in the following table, highlighting the gaps and limitation that are present nowadays in the literature

Table 4.7: Fuel cell electric trucks total cost of ownership (TCO): gaps and limitation in the literature

Component	Cost Data	Reference	Gaps / limitations
Fuel cell system	$/kWnet [450-280] from low to high production rate Component sizing	[25] [28]	
Hydrogen storage tank	$/kWh 14.59 single tank $/kWh 15.94 two tanks	[26]	
Electric Motor / Drivetrain	$11.6/kWh Component sizing	[36] [28]	
Battery pack	$/kW 495 nowadays Component sizing	[13] [28]	
Chassis + Body	$79,000 medium heavy-duty truck (Drayage truck) Medium and heavy duty price	[17] [39] [40]	Chassis price it is not present in [39] [40]

Table 4.8: Infrastructure and hydrogen production costs

Component	Data	Reference	Gaps / limitations
Hydrogen production	- Water Electrolysis - Methane reforming	[37]	Only truck trailer dispensing is considered
Refuelling infrastructure	-Initially: 2-3 million $ / station -Future scenarios reduction to 1 or even 0.5 million $ for small stations	[19]	

4.2 Cost modelling development

In order to estimate the cost of a fuel cell truck for the classes which have been analysed in this report, all the data reported in the previous sections have been used.
The estimated cost of a fuel cell truck will be compared to the reference diesel case and to a battery electric truck application. The process of hydrogen production, dispensing and infrastructure is then considered for the payback period computation. Both hydrogen production by electrolysis and steam methane reforming process are considered in the analysis

4.2.1 Miles range sensitivity analysis

Four values of miles range (300, 600, 1000 and 1500 miles) have been considered for a sensitivity analysis in the cost model for both battery electric and fuel cell electric costs.
For the cost analysis class 8 heavy-duty trucks have been considering with a lifetime of 10 years and a mileage of 70,000 miles yearly. The Diesel price is assumed constant during 10 years of vehicle lifetime, its price has been calculated with a net present value approach imposing 7% discount rate.
The new technologies have been compared with the reference case (Diesel), its cost have been calculated as shown in the table before, considering data from [17].

Table 4.9 Input parameters for current Diesel truck cost

Fuel efficiency [miles/gallon]	6.5	6.5	6.5	6.5	
Range [miles]	300	600	1000	1500	
Yearly miles [miles]	70,000	70,000	70,000	70,000	
Diesel price [$/gallon]	3	3	3	3	
Engine + Transmission [$]	25,000	25,000	25,000	25,000	[17]

As a result, from the input in the previous table the final price for a Class 8 Diesel tuck after 10 years in $251,915. This price will be taken as a reference for the new technologies, even if it is worth it to underline that nowadays the miles range for a Class 8 Diesel truck is up to 400 miles.

4.2.1.1 Battery electric trucks cost analysis

The main component which affects battery electric cost is the battery itself. The cost, expressed in [$/kWh], varies over time as descripted in fig 1.13b and different values have been considered in this analysis. The fuel efficiency assumed for battery electric trucks analysed in this section is 2.8 kWh/mile [17], even if Tesla has recently announced that the efficiency of the new semi-truck (a Class 8 truck) will be 2 kWh/miles.

Table 4.10: Input parameters for battery electric vehicle cost analysis

Fuel efficiency [kWh/miles]	2.8	2.8	2.8	2.8	[17]
Range [miles]	300	600	1000	1500	
Yearly miles [miles]	70,000	70,000	70,000	70,000	[17]
Electricity price [$/kWh]	0.12	0.12	0.12	0.12	[31]
Battery size [kWh]	840	1680	2800	4200	
Electric motor power [kW]	350	350	350	350	[17]

The electricity price considered is 0.12 $/kWh and the cost of electricity for charging the battery during the 10 years has been analysed with a net present value approach, considering a discount rate of 7%.

Below are presented four different plots and tables, varying the miles range of the vehicles and battery prices.

Table 4.11 BEV lifecycle cost analysis for 300 miles range

Range [miles]	300	300	300	300	300	300	300	
Battery price [$/kWh]	75	150	200	300	400	450	500	[13]
Battery cost [$]	63,000	126,000	168,000	252,000	336,000	378,000	420,000	
Total electricity cost [$]	165,194	165,194	165,194	165,194	165,194	165,194	165,194	
Electric motor cost [$]	8,000	8,000	8,000	8,000	8,000	8,000	8,000	[17]
Payback years	3.4	9	12.8	20.3	27.8	31.6	35.4	
Lifetime savings [$]	73,711	10,721	-31,278	-115,278	-199,278	-241,278	-283,278	

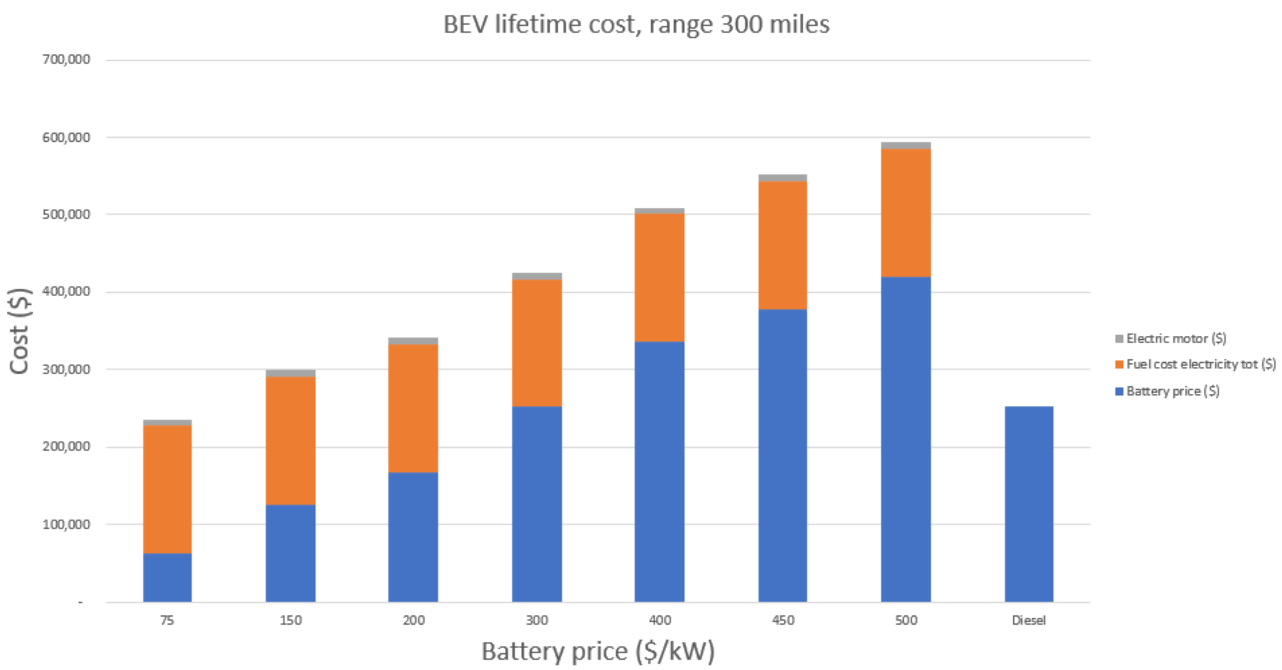


Figure 4.12: BEV cost comparison with baseline Diesel varying the battery price, for 300 miles range

Table 4.12: BEV lifecycle cost analysis for 600 miles range

Range [miles]	600	600	600	600	600	600	600	
Battery price [$/kWh]	75	150	200	300	400	450	500	[17]
Battery cost [$]	126,000	252,000	336,000	504,000	672,000	756,000	840,000	
Total electricity cost [$]	165,194	165,194	165,194	165,194	165,194	165,194	165,194	
Electric motor cost [$]	8,000	8,000	8,000	8,000	8,000	8,000	8,000	[17]
Payback years	9.0	20.3	27.8	42.9	57.9	65.4	72.9	
Lifetime savings [$]	10,711	-115,278	-199,278	-367,278	-535,278	-619,278	-703,278	

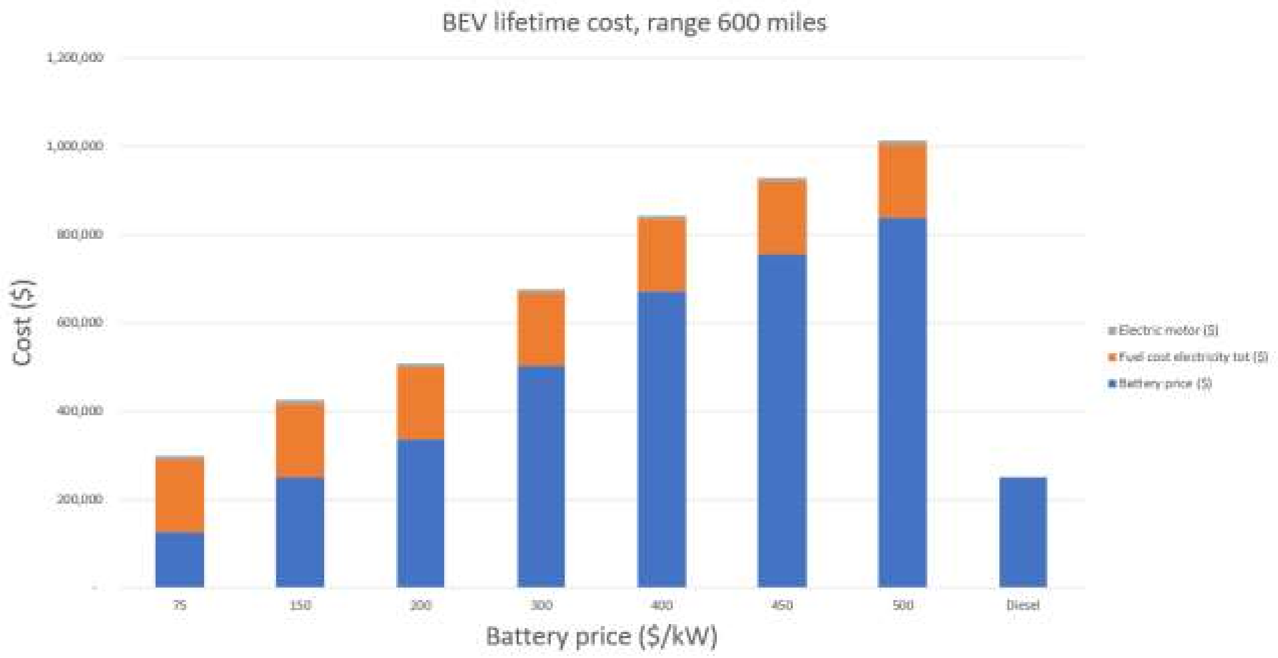


Figure 4.13 BEV cost comparison with baseline Diesel varying the battery price, for 600 miles range

Table 4.13: BEV lifecycle cost analysis for 1000 miles range

Range [miles]	1000	1000	1000	1000	1000	1000	1000	
Battery price [$/kWh]	75	150	200	300	400	450	500	[13]
Battery cost [$]	210,000	420,000	560,000	840,000	1,120,000	1,260,000	1,400,000	
Total electricity cost [$]	165,194	165,194	165,194	165,194	165,194	165,194	165,194	
Electric motor cost [$]	8,000	8,000	8,000	8,000	8,000	8,000	8,000	[17]
Payback years	16.6	35.4	47.9	72.9	98.0	110.5	123.1	
Lifetime savings [$]	-73,233	-283,278	-423,278	-703,278	-983,278	- 1,123,278	- 1,263,278	

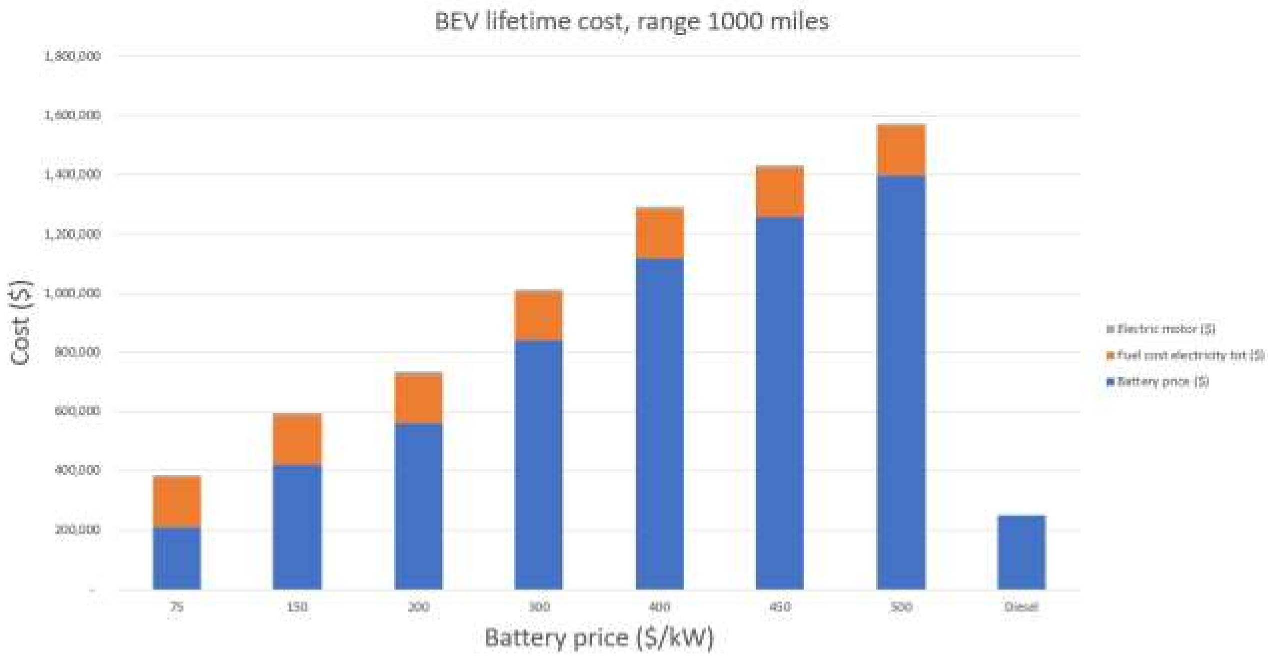


Figure 4.14 BEV cost comparison with baseline Diesel varying the battery price, for 1000 miles range

Table 4.14: BEV lifecycle cost analysis for 1500 miles range

Range [miles]	1500	1500	1500	1500	1500	1500	1500	
Battery price [$/kWh]	75	150	200	300	400	450	500	[13]
Battery cost [$]	315,000	630,000	840,000	1,260,0 00	1,680,0 00	1,890,0 00	2,100,0 00	
Total electricity cost [$]	165,194	165,194	165,194	165,194	165,194	165,194	165,194	
Electric motor cost [$]	8,000	8,000	8,000	8,000	8,000	8,000	8,000	[17]
Payback years	26.0	54.2	72.9	110.5	148.1	166.9	185.7	
Lifetime savings [$]	- 178,288	- 493,278	- 703,278	- 1,123,2 78	- 1,543,2 78	- 1,753,2 78	- 1,963,2 78	

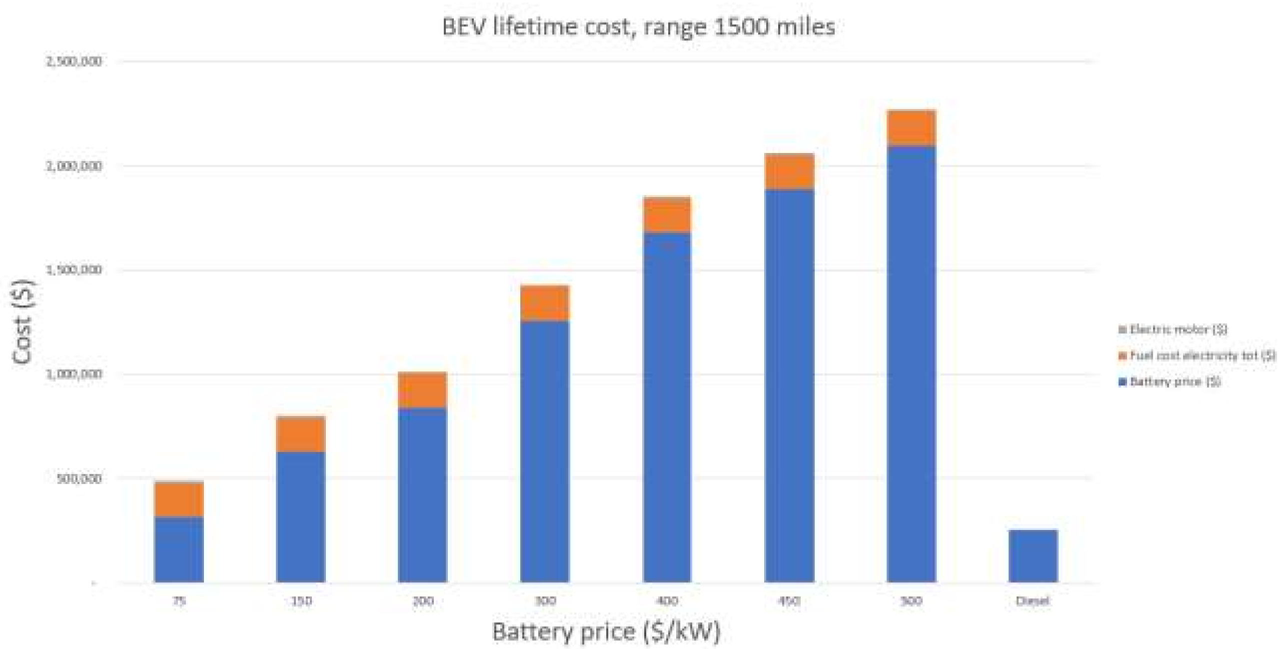


Figure 4.15 BEV cost comparison with baseline Diesel varying the battery price, for 1500 miles range

The price of the battery as predicted before is the driving price for the cost analysis in battery electric vehicles especially for medium and heavy duty classes where high miles range is considered.
Considering a high miles range means to store lot of energy in the vehicle, which results in a heavy, big and expensive battery pack. For 300 miles range, the price of the electricity needed for run 70,000 per year the truck are comparable to the battery price, for higher values of the miles range the value of
The yearly miles did not change with the change in miles range, so the price of the electricity for refuelling the battery did not change.
The total electricity price has been considered as net present value at the current year, considered a fixed price for the electricity for the life of the vehicle (10 years).

4.2.1.2 Fuel cell electric truck cost analysis

Opposite from battery electric application, in the fuel cell electric vehicles two are the main components which affect the final cost of the vehicle during its lifetime. The first one is the fuel cell system, and in particular the fuel cell stack, the second is the hydrogen price which is affected by its production, dispensing and infrastructures.
The cost of hydrogen is not treated in deeply on this report and it is out of the scope of this project, but reference data has been taken from [37] as shown in figure 4.7 where on site electrolysis and central steam methane reforming has been considering as production pathways.
In the table presented below are expressed the main input parameters for the fuel cell hydrogen electric truck (Class 8) cost analysis.

Table 4.15: Input parameters for fuel cell electric trucks cost analysis

Fuel efficiency [kWh/miles]	1.72	1.72	1.72	1.72	Nikola Truck
Fuel cell (PEM) efficiency	40%	40%	40%	40%	[9]
Range [miles]	300	600	1000	1500	
Yearly miles [miles]	70,000	70,000	70,000	70,000	[17]
Hydrogen on board [kg]	38.83	77.66	129.44	194.16	
Fuel cell power [kW]	400	400	400	400	[11]
Electric motor power [kW]	100	100	100	100	[11]

The hydrogen price could not be inserted in the table above because it is varying over time, as shown in figure 4.7.

4.2.2 Hydrogen production through on-site electrolysis

Here below are presented the four mileage cases (300, 600, 1000, 1500 miles) considering on-site electrolysis as the hydrogen production process:

Table 4.16: FCEV lifecycle cost analysis for 300 miles range

Range [miles]	300	300	300	300	300	300	300	
Storage cost [$/kWh]	15	15	15	15	15	15	15	[8]
Fuel cell system cost [$/kWh]	100	150	280	290	300	400	450	[25]
Storage tank cost [$]	7,758	7,758	7,758	7,758	7,758	7,758	7,758	
Fuel cell system cost [$]	40,000	60,000	112,000	116,000	120,000	160,000	180,000	
Total hydrogen cost [$]	232,324	232,324	232,324	232,324	232,324	232,324	232,324	[37]
Electric motor [$]	2,285	2,285	2,285	2,285	2,285	2,285	2,285	
Payback years	5.6	10.1	21.8	22.7	23.6	32.5	37..0	
Lifetime savings [$]	19,527	-462	-52,452	-56,452	-60,452	-100,452	-120,452	

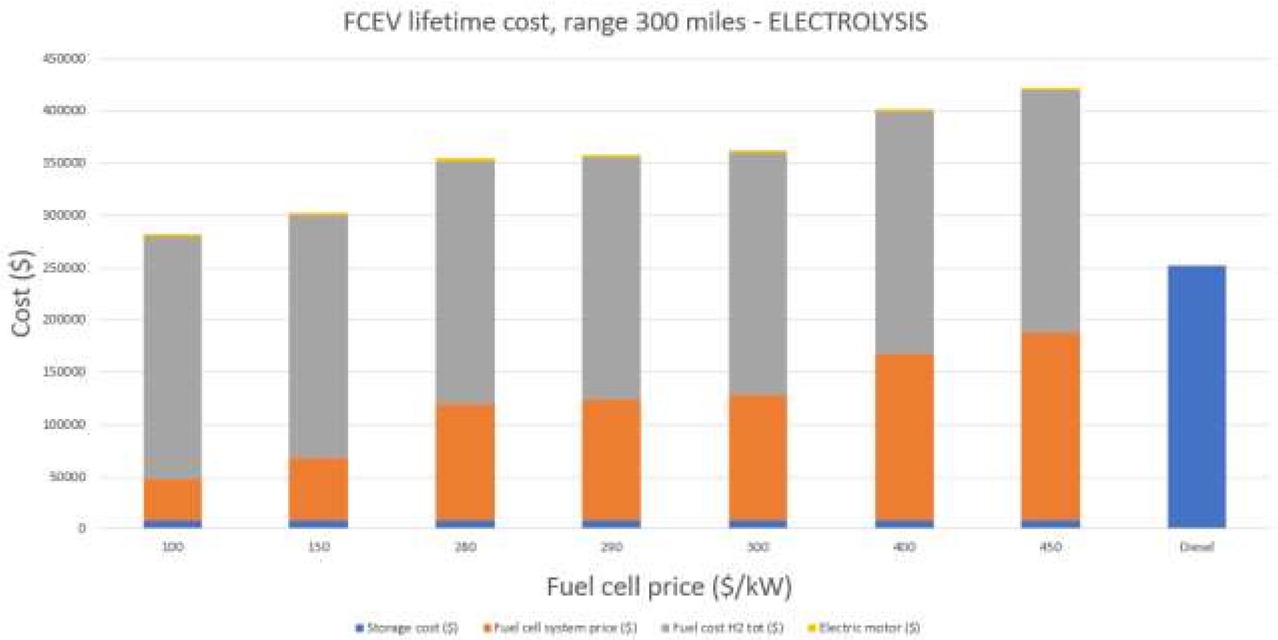


Figure 4.16 FCEV cost comparison with baseline Diesel varying the fuel cell system price, for 300 miles range

Table 4.17: FCEV lifecycle cost analysis for 600 miles range

Range [miles]	600	600	600	600	600	600	600	
Storage cost [$/kWh]	15	15	15	15	15	15	15	[8]
Fuel cell system cost [$/kWh]	100	150	280	290	300	400	450	[25]
Storage tank cost [$]	15,517	15,517	15,517	15,517	15,517	15,517	15,517	
Fuel cell system cost [$]	40,000	60,000	112,000	116,000	120,000	160,000	180,000	
Total hydrogen cost [$]	232,324	232,324	232,324	232,324	232,324	232,324	232,324	[37]
Electric motor [$]	2,285	2,285	2,285	2,285	2,285	2,285	2,285	
Payback years	7,4	11.8	23.5	24.4	25.3	34.3	38.8	
Lifetime savings [$]	11,768	-8,211	-60,211	-64,211	-68,211	-108,211	-128,211	

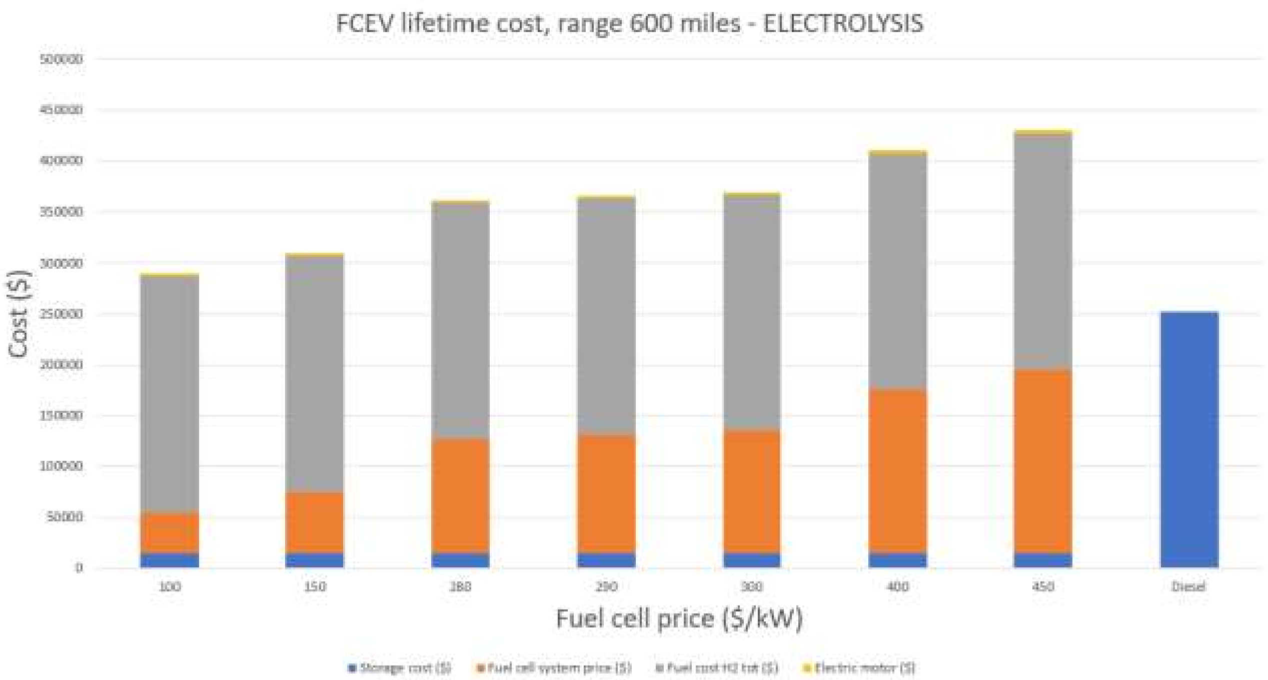


Figure 4.17: FCEV cost comparison with baseline Diesel varying the fuel cell system price, for 600 miles range

Table 4.18: FCEV lifecycle cost analysis for 1000 miles range

Range [miles]	1000	1000	1000	1000	1000	1000	1000	
Storage cost [$/kWh]	15	15	15	15	15	15	15	[8]
Fuel cell system cost [$/kWh]	100	150	280	290	300	400	450	[25]
Storage tank cost [$]	25,862	25,862	25,862	25,862	25,862	25,862	25,862	
Fuel cell system cost [$]	40,000	60,000	112,000	116,000	120,000	160,000	180,000	
Total hydrogen cost [$]	232,324	232,324	232,324	232,324	232,324	232,324	232,324	[37]
Electric motor [$]	2,285	2,285	2,285	2,285	2,285	2,285	2,285	
Payback years	9.7	14.2	25.8	26.7	27.6	36.6	41.1	
Lifetime savings [$]	1,423	-18,566	-70,556	-74,566	-78,566	- 118,566	- 138,566	

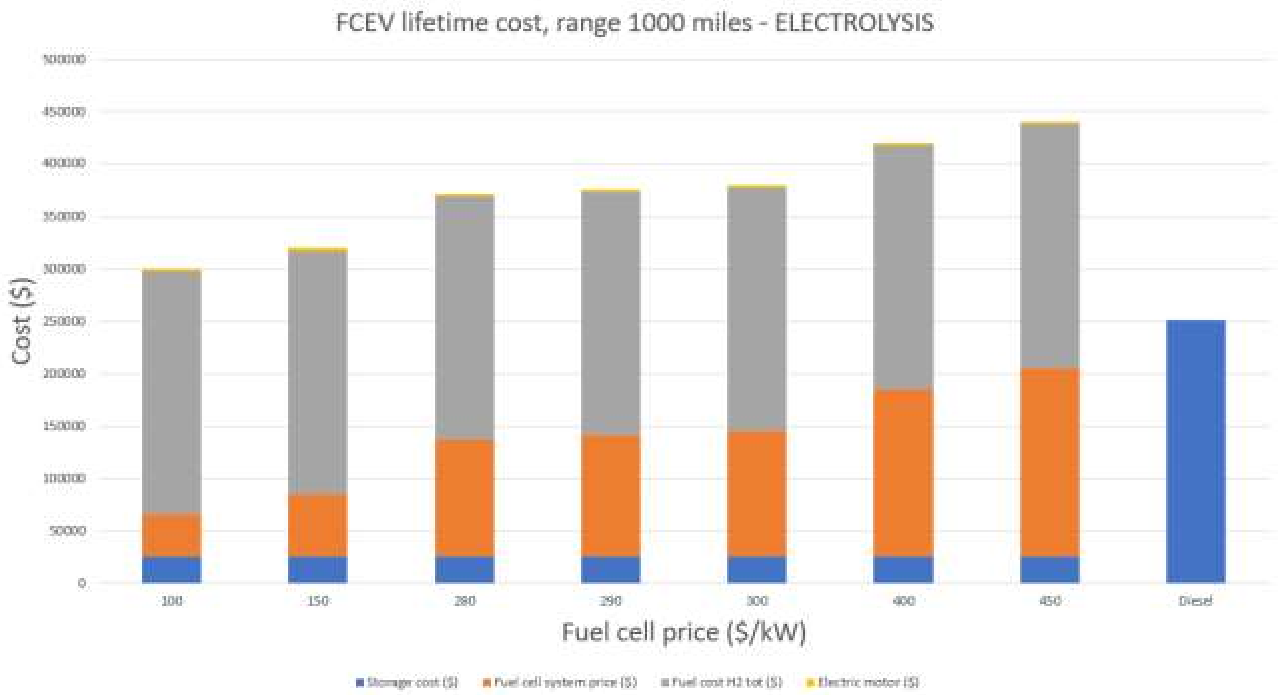


Figure 4.18: FCEV cost comparison with baseline Diesel varying the fuel cell system price, for 1000 miles range

Table 4.19: FCEV lifecycle cost analysis for 1500 miles range

Range [miles]	1500	1500	1500	1500	1500	1500	1500	
Storage cost [$/kWh]	15	15	15	15	15	15	15	[8]
Fuel cell system cost [$/kWh]	100	150	280	290	300	400	450	[25]
Storage tank cost [$]	38,793	38,793	38,793	38,793	38,793	38,793	38,793	
Fuel cell system cost [$]	40,000	60,000	112,000	116,000	120,000	160,000	180,000	
Total hydrogen cost [$]	232,324	232,324	232,324	232,324	232,324	232,324	232,324	[37]
Electric motor [$]	2,285	2,285	2,285	2,285	2,285	2,285	2,285	
Payback years	12.6	17.1	28.7	29.6	30.5	39.5	44.0	
Lifetime savings [$]	-11,507	-31,497	-83,487	-87,487	-91,487	-131,487	-151,487	

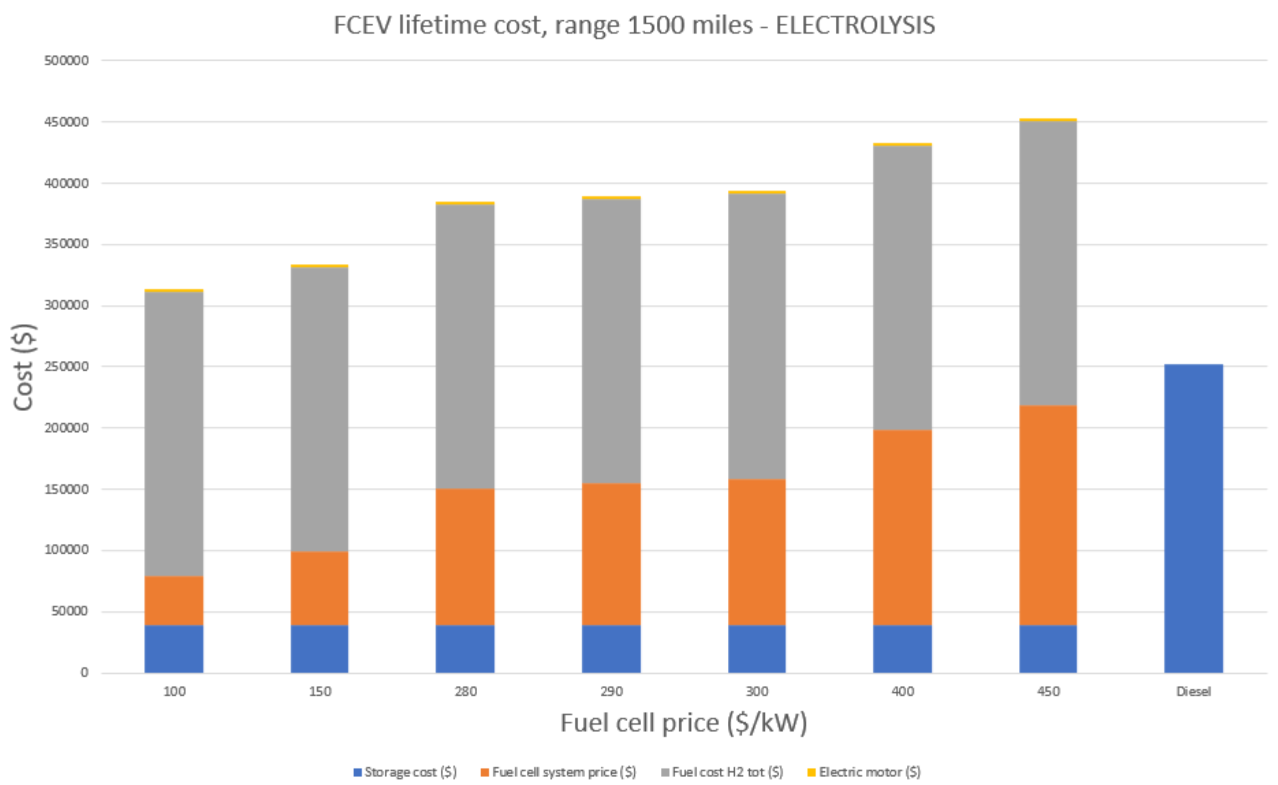


Figure 4.19: FCEV cost comparison with baseline Diesel varying the fuel cell system price, for 1500 miles range

4.2.2.1.1 Hydrogen production through central steam methane reforming

Here below are presented the four mileage cases (300, 600, 1000, 1500 miles) considering central steam methane reforming as the hydrogen production process:

Table 4.20 FCEV lifecycle cost analysis for 300 miles range

Range [miles]	300	300	300	300	300	300	300	
Storage cost [$/kWh]	15	15	15	15	15	15	15	[8]
Fuel cell system cost [$/kWh]	100	150	280	290	300	400	450	[25]
Storage tank cost [$]	7758	7758	7758	7758	7758	7758	7758	
Fuel cell system cost [$]	40,000	60,000	112,000	116,000	120,000	160,000	180,000	
Total hydrogen cost [$]	120,410	120,410	120,410	120,410	120,410	120,410	120,410	[37]
Electric motor [$]	2,285	2,285	2,285	2,285	2,285	2,285	2,285	
Payback years	1.6	2.9	6.2	6.5	6.7	9.3	10.5	
Lifetime savings [$]	131,440	111,450	59,460	55,460	51,460	11,460	-8,539	

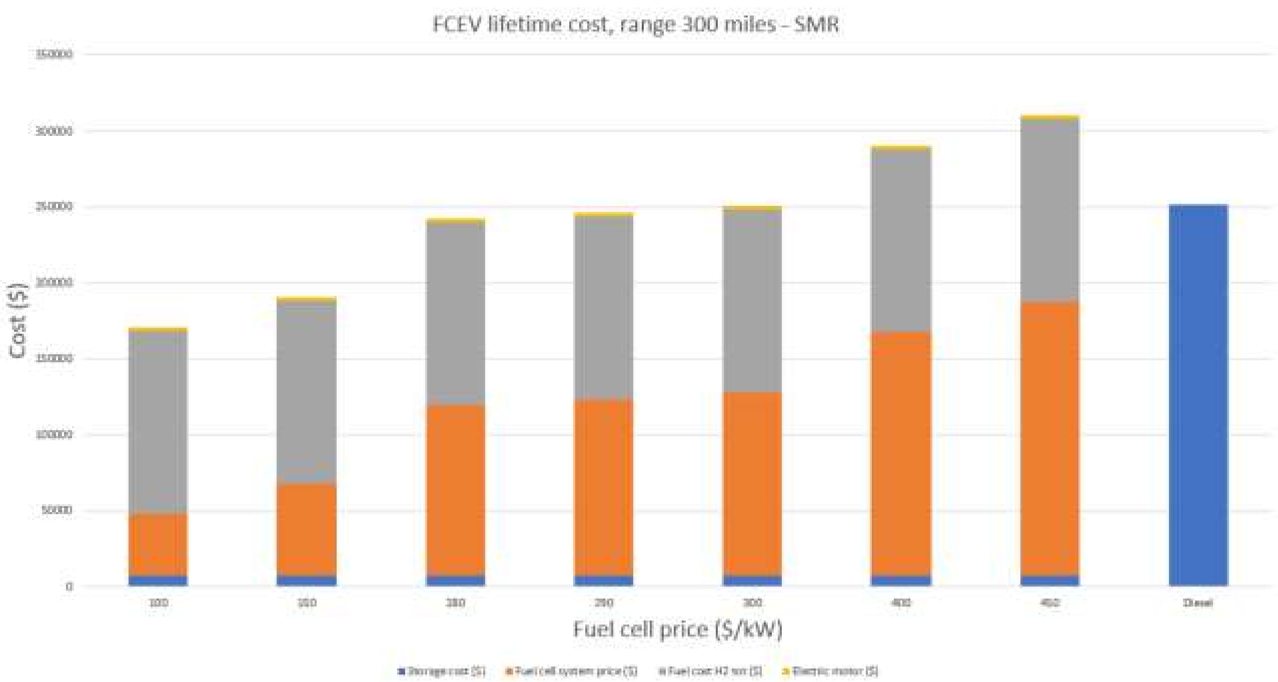


Figure 4.20: FCEV cost comparison with baseline Diesel varying the fuel cell system price, for 300 miles range

Table 4.21: FCEV lifecycle cost analysis for 600 miles range

Range [miles]	600	600	600	600	600	600	600	
Storage cost [$/kWh]	15	15	15	15	15	15	15	[8]
Fuel cell system cost [$/kWh]	100	150	280	290	300	400	450	[25]
Storage tank cost [$]	15,517	15,517	15,517	15,517	15,517	15,517	15,517	
Fuel cell system cost [$]	40,000	60,000	112,000	116,000	120,000	160,000	180,000	
Total hydrogen cost [$]	120,410	120,410	120,410	120,410	120,410	120,410	120,410	[37]
Electric motor [$]	2,285	2,285	2,285	2,285	2,285	2,285	2,285	
Payback years	2.1	3.4	6.7	7.0	7.2	9.8	11.0	
Lifetime savings [$]	123,682	103,692	51,702	47,702	43,702	3,702	-16,297	

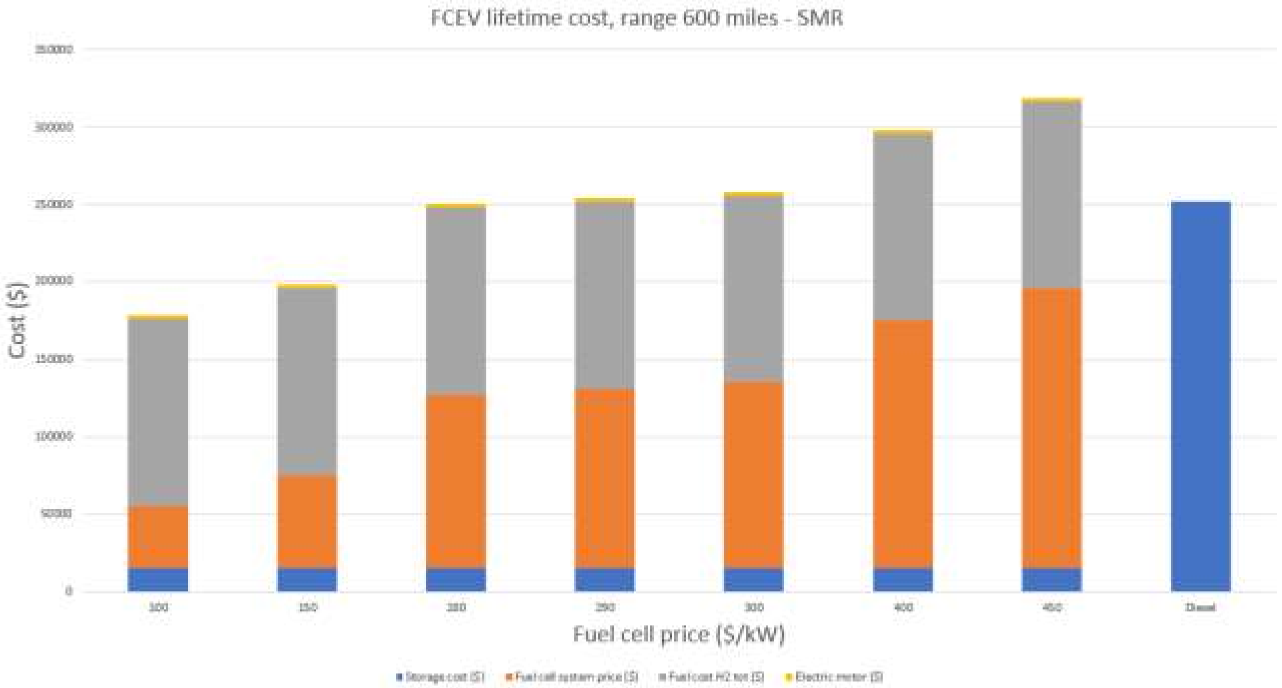


Figure 4.21: FCEV cost comparison with baseline Diesel varying the fuel cell system price, for 600 miles range

Table 4.22: FCEV lifecycle cost analysis for 1000 miles range

Range [miles]	1000	1000	1000	1000	1000	1000	1000	
Storage cost [$/kWh]	15	15	15	15	15	15	15	[8]
Fuel cell system cost [$/kWh]	100	150	280	290	300	400	450	[25]
Storage tank cost [$]	25,862	25,862	25,862	25,862	25,862	25,862	25,862	
Fuel cell system cost [$]	40,000	60,000	112,000	116,000	120,000	160,000	180,000	
Total hydrogen cost [$]	120,410	120,410	120,410	120,410	120,410	120,410	120,410	[37]
Electric motor [$]	2,285	2,285	2,285	2,285	2,285	2,285	2,285	
Payback years	2.8	40	7.4	7.6	7.9	10.4	11.7	
Lifetime savings [$]	113,337	93,347	41,357	37,357	33,357	-6,642	-26,642	

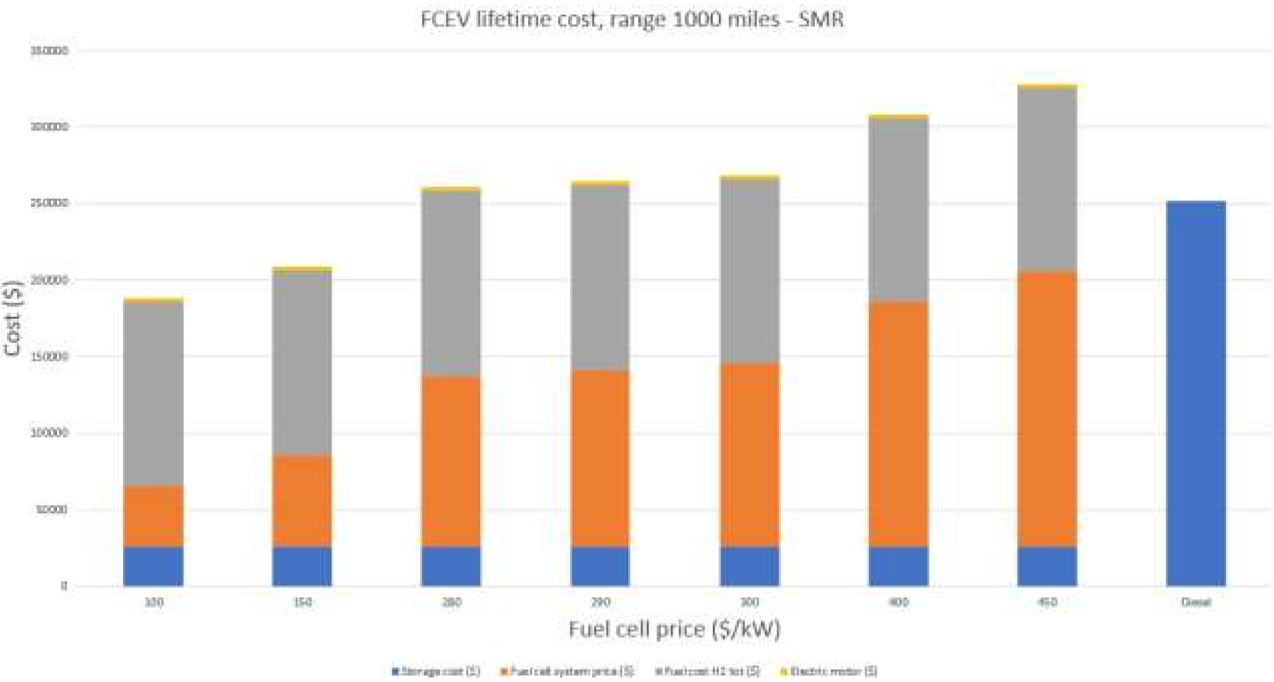


Figure 4.22: FCEV cost comparison with baseline Diesel varying the fuel cell system price, for 1000 miles range

Table 4.23: FCEV lifecycle cost analysis for 1500 miles range

Range [miles]	1500	1500	1500	1500	1500	1500	1500	
Storage cost [$/kWh]	15	15	15	15	15	15	15	[8]
Fuel cell system cost [$/kWh]	100	150	280	290	300	400	450	[25]
Storage tank cost [$]	38,793	38,793	38,793	38,793	38,793	38,793	38,793	
Fuel cell system cost [$]	40,000	60,000	112,000	116,000	120,000	160,000	180,000	
Total hydrogen cost [$]	120,410	120,410	120,410	120,410	120,410	120,410	120,410	[37]
Electric motor [$]	2,285	2,285	2,285	2,285	2,285	2,285	2,285	
Payback years	3.6	4.9	8.2	8.4	8.7	11.3	12.5	
Lifetime savings [$]	100,406	80,416	28,426	24,426	20,426	-19,573	-39,573	

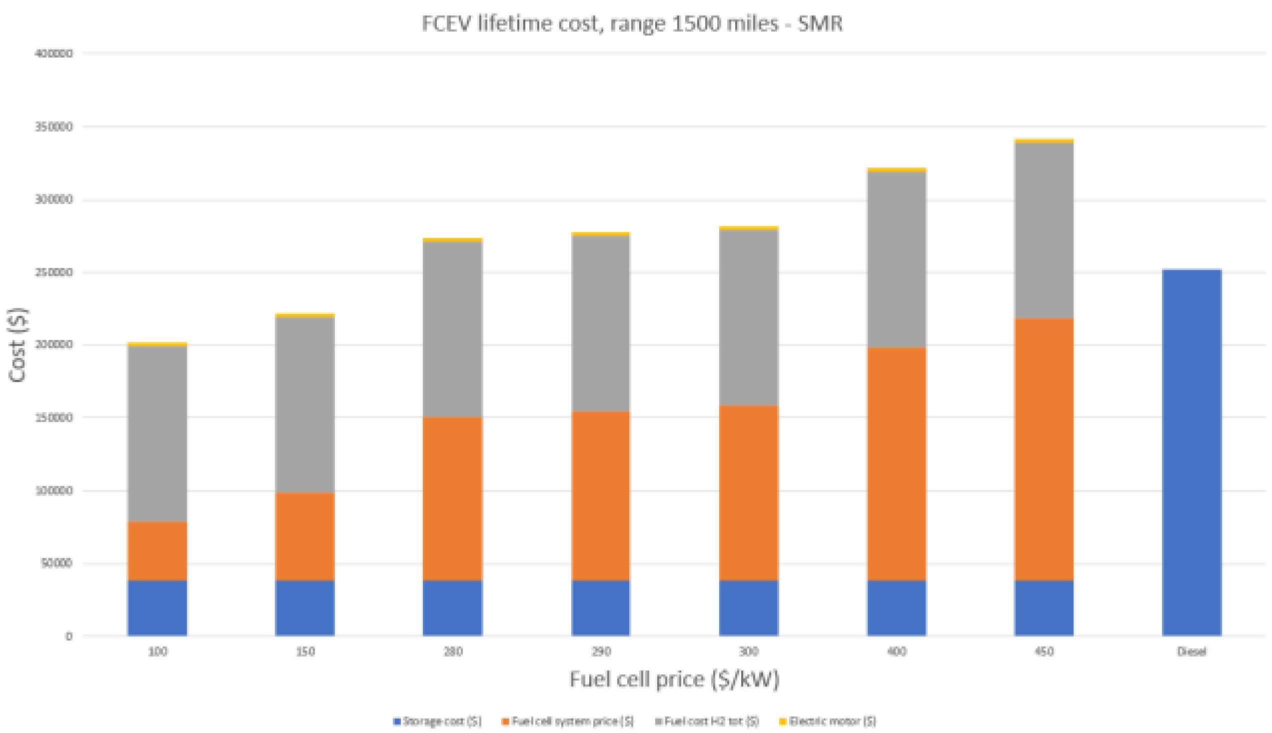


Figure 4.23: FCEV cost comparison with baseline Diesel varying the fuel cell system price, for 1500 miles range

From this cost analysis performed considering fuel cell electric technology, it is possible to have an overview on the different components' contribution for the lifecycle cost of the technology, compared to the baseline (Diesel).

Firstly, over ten years of truck's lifetime the hydrogen price obtained using on-site electrolysis is almost double than the hydrogen price from central steam methane reforming. This leads to the conclusion that the hydrogen production plays a key role in the overall cost of the vehicle, more than on the lifecycle emission of that. Implementing a central electrolysis plant and introducing high range applications as early adopters for this technology can lead to a rapid cost cut-down. Moreover, the hydrogen price does not change with the range of the vehicle, having imposed a constant annual mileage of 70,000 miles, neither the fuel cell stack and system, being responsible only for the power of the vehicle and to of its energy and mileage.
What actually changes with increasing the vehicle range is the price of the storage tank which has to be of course bigger. As it can be noticed from all the plots presented in this section, the cost of the storage tank is a marginal cost with respect to the fuel cell system or the hydrogen.

4.2.2.2 Battery electric and fuel cell electric technology comparison

In order to visualize in a proper way the differences between lifecycle cost for the new technologies considered in this report, a comparative study has been developed considering three different scenarios: (i) high rate of adoption of the new technologies (>100,000sys/year), (ii) medium rate of adoption (1,000< system/year<100,000), (iii) low rate of adoption (<1,000 sys/year).
Note the these numbers are referred to fuel cell and not to batteries, the prices taken in consideration have been analysed by Brian James in [25].
For the price of the batteries, a prediction from [13] taken from The Economist have been considered (fig. 1.13b) and the high adoption price is lower than the 2030 value for battery cost.

The cost of fuel cell system for the different rate of adoption are:

- 100 $/kW – high rate of adoption
- 280 $/kW – medium rate of adoption
- 400$/kW – low rate of adoption, current technology price

The cost of batteries for different rates of adoption are

- 75 $/kWh – high rate of adoption
- 200 $/kWh – medium rate of adoption
- 450$/kWh – low rate of adoption, actual prices for the technology

Table 4.24: High rate of adoption technology comparison

Range [miles]	300	600	1000	1500
BEV cost [$]	236,194	299,194	383,194	488,194
FCEV ELC cost [$]	282,368	290,127	300,472	313,403
FCEV SMR cost [$]	170,454	178,213	188,558	201,489
Diesel cost [$]	251,915	251,915	251,915	251,915

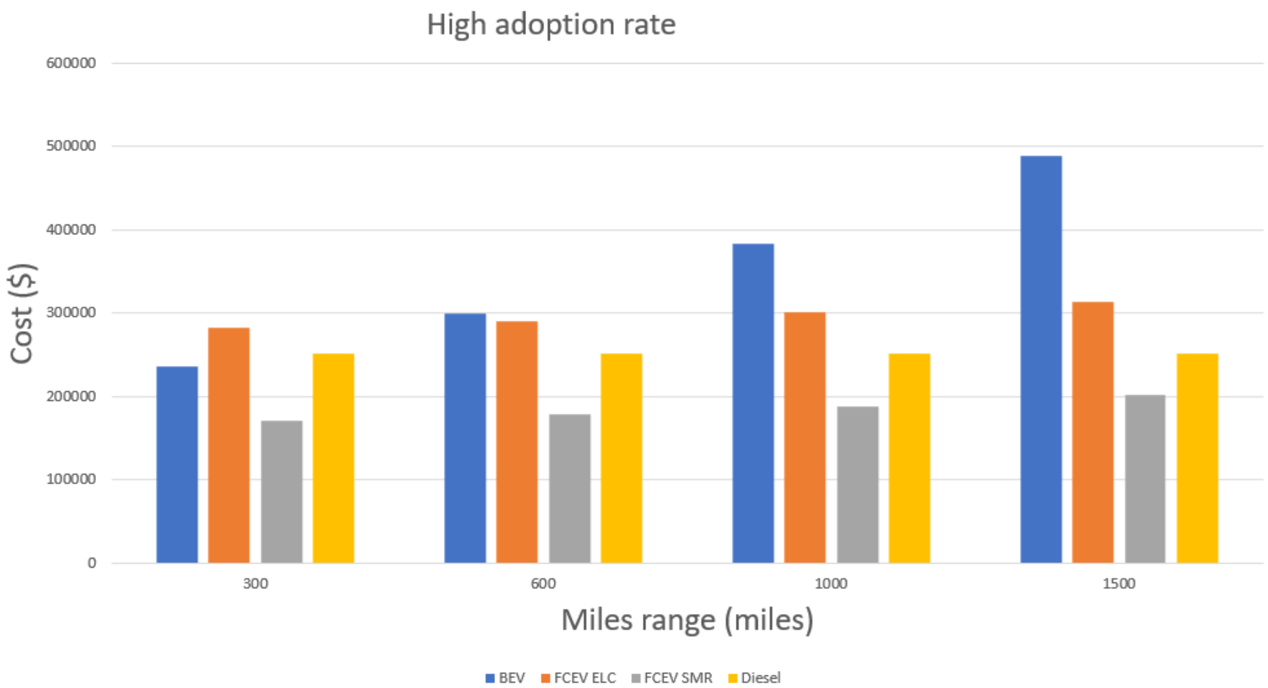


Figure 4.24: High rate of adoption technology comparison

Table 4.25: Medium rate of adoption technology comparison

Range [miles]	300	600	1000	1500
BEV cost [$]	341,194	677,194	1,013,194	1,433,194
FCEV ELC cost [$]	354,368	362,127	274,472	385,403
FCEV SMR cost [$]	242,454	250,213	260,558	273,489
Diesel cost [$]	251,915	251,915	251,915	251,915

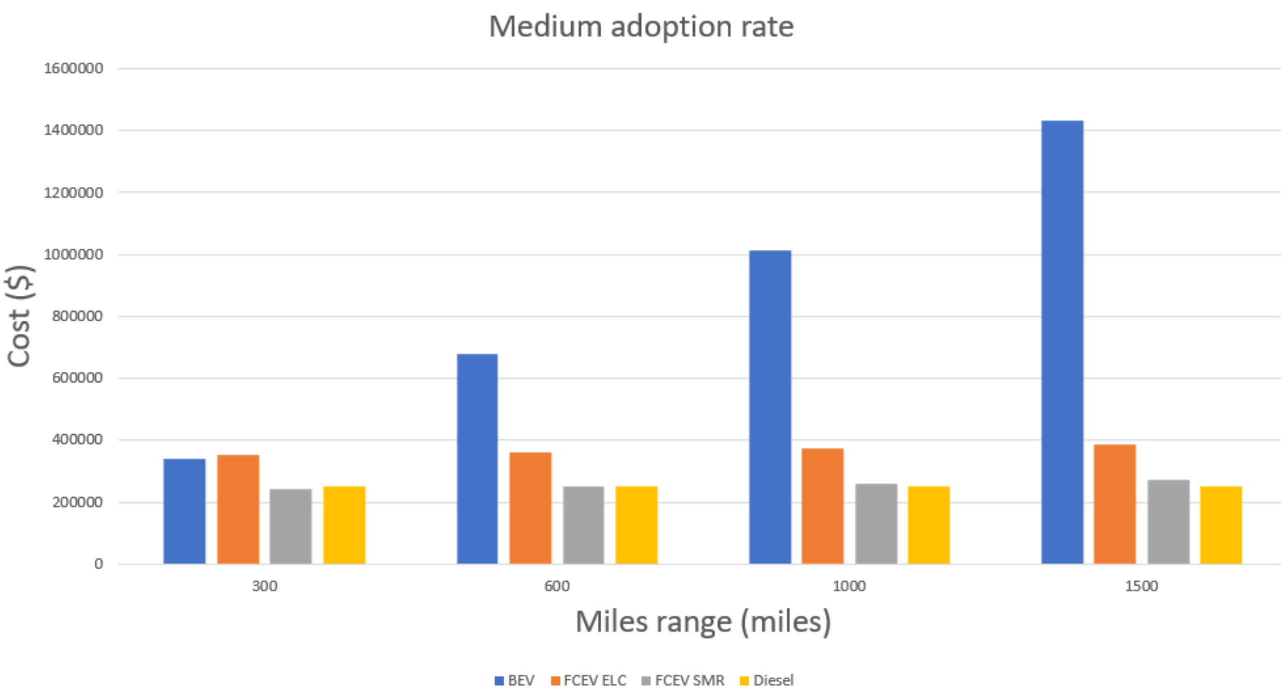


Figure 4.25: Medium rate of adoption technology comparison

Table 4.26: Low rate of adoption technology comparison

Range [miles]	300	600	1000	1500
BEV cost [$]	551,194	929,194	1,433,1 94	2,063,1 94
FCEV ELC cost [$]	402,368	410,127	420,472	433,403
FCEV SMR cost [$]	290,454	298,213	308,558	321,489
Diesel cost [$]	251,915	251,915	251,915	251,915

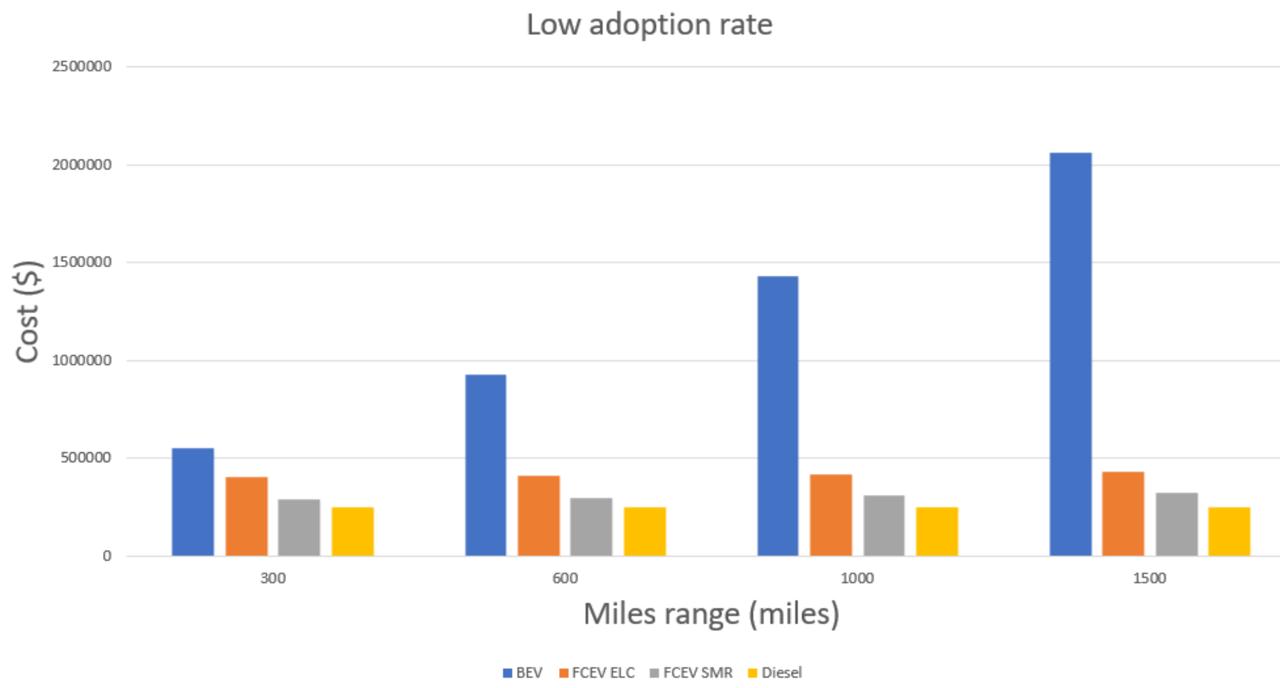


Figure 4.26: Low rate of adoption technology comparison

These three comparison plots evidences hoe the battery electric system is much more sensitive to the increase of mileage and to the adoption rate proposed with respect to the fuel cell hydrogen electric one. This difference is due to the nature of the two technologies, where the former is

completely dominated by the battery in all his features, the latter has different components which are responsible for the various characteristics of the vehicle itself.
Moreover, cutting down the price of the battery is much more challenging than reducing that one of the fuel cell (PEM) stack or the hydrogen production. This because the battery technology nowadays is much more spread and used all over the world with respect to the fuel cell technology.

4.2.3 Other parameters sensitivity discussion

The sensitivity analysis performed for the various possible miles range of a Class 8 truck can be expanded using the same approach for other important parameters of the system.
First of all, the lifetime of the vehicle considered in this analysis is ten years, which is a conservative number for this application. In the future will be possible to arrive at 15-20 years of lifetime for medium and heavy-duty trucks and thus will be a great advantage for payback of the new technologies.
The second aspect is concerned to the battery electric truck application, where the battery performance is continuously enhancing nowadays both in terms of technology (increasing the gravimetric and volumetric energy density) and in terms of capital costs. One critical issue is the lifespan of the battery due to the capacity degradation of it, which can be lower than the lifetime of the truck, especially if the lifetime will increase in the future up to the values cited before.
Third aspect is the fuel efficiency of the vehicle, which can be enhanced working both on the new technologies (fuel cell and battery efficiency) both on the aerodynamic of the system. On this side Tesla is one of the first company which is investing on enhancing as much as possible the fuel efficiency, even if this could have important cost impact, especially in terms of capital cost.
Finally, will be important performing a sensitivity analysis on fuel cost variation, both for electricity and hydrogen, considering different ways for producing it.

5 Scenarios modelling

5.1 Vehicle classes considered

In the stock model section, six different vehicle classes were taken into consideration (class 2b, class 3, class 5, class 6, class 7, class 8).
Considering the GWV (gross weight value) of these classes, class2b<10,000 lb which is the minimum value for medium or heavy-duty vehicles.
Moreover, comparing from EMFAC the emission impact of class 2b and the other classes, it is possible to notice that the overall emissions from class 2b are quite high due to the high population number (class 2b is around 5 million, from class 3 to class 8 less than 1 million) but the emission per vehicle is almost one order of magnitude less

$$GHGem/vehicle_{Class2b} = \frac{28\ mton/year}{5\ m} = 5.6\ ton/year$$
$$GHGem/vehicle_{Class3-8} = \frac{31\ mton/year}{0.84\ m} = 37\ ton/year$$

This is the reason why Class 2b has not anymore been considered in the analysis.

5.2 Reference scenario

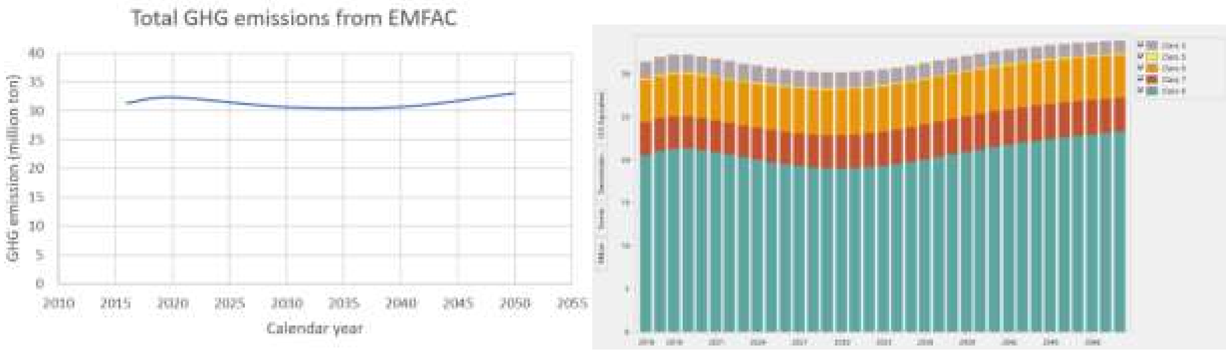
5.2.1 Actual policies for California

The first scenario which will be analysed is the reference scenario, where the actual policies have been considered. In the last twenty-five years, California has made enormous strides in improving air quality and reducing the greenhouse gases emission. The former has the goal of promoting public health benefits as descripted in section 2.2.2.2, the latter is mostly related to climate change and ozone levels.
California Air Resource Board (ARB) mobile source strategy has the goal of minimizing health risk from the exposure to toxic air contaminants. The goals include:

- Attaining federal health-based air quality standards for ozone in 2023 and 2031 in the South Coast and San Joaquin Valley, and fine particulate matter (PM 2.5) standards in the next decade.
- 80% reduction in smog forming emissions by 2030/2031 from 2016 levels
- 45% in GHG emissions by 2030/2031 from 2016 levels
- 50% reduction in petroleum usage by 2030/2031 from 2016 levels
- 45% diesel PM emissions by 2030/2031 from 2016 levels
- Overall NOx emissions 50% drop by 2030/2031 from 2016 levels

5.2.2 LEAP model calibration with EMFAC

These policies have been considered in the EMFAC2017 data, which are directly inserted in the system by the California Air Resource Board. This is the reason why the model which has been built using the software LEAP has been calibrated using the results data taken from EMFAC2017. The input lifecycle profiles have been presented in section 3.2 and will be the same for all the scenarios which will be run, the input trends for the reference scenario have been descripted in section 3.3.
The GHG emission and air pollutant emissions have been checked in order to calibrate the model built on LEAP. The parameter which has been modified in order to meet the reference from EMFAC is the fuel efficiency, both in 2016 and in the future trend.
Regarding the fuel emitters trend, a linear trend has been considered and the value for 2050 has been guessed applying an iteration process for having an error lower than 5% in GHG emissions.



(a) (b)

Figure 5.1: GHG emission comparison between (a) EMFAC2017 and (b) LEAP reference scenario

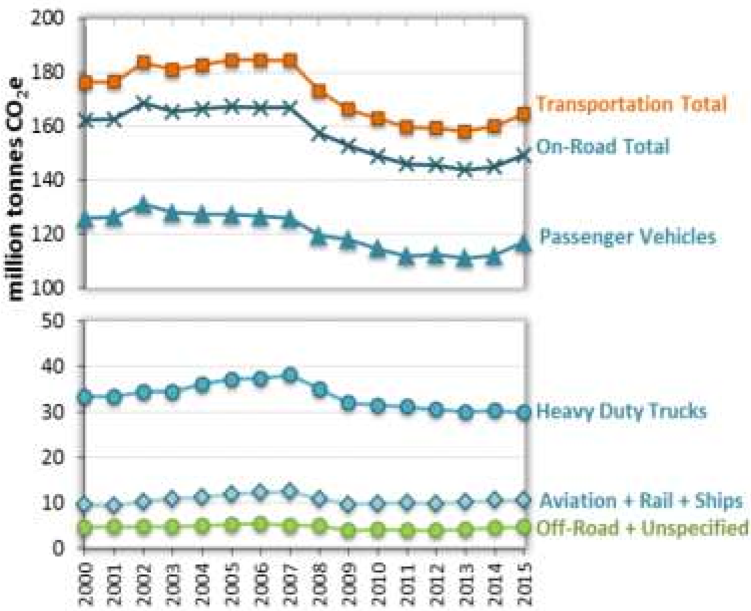
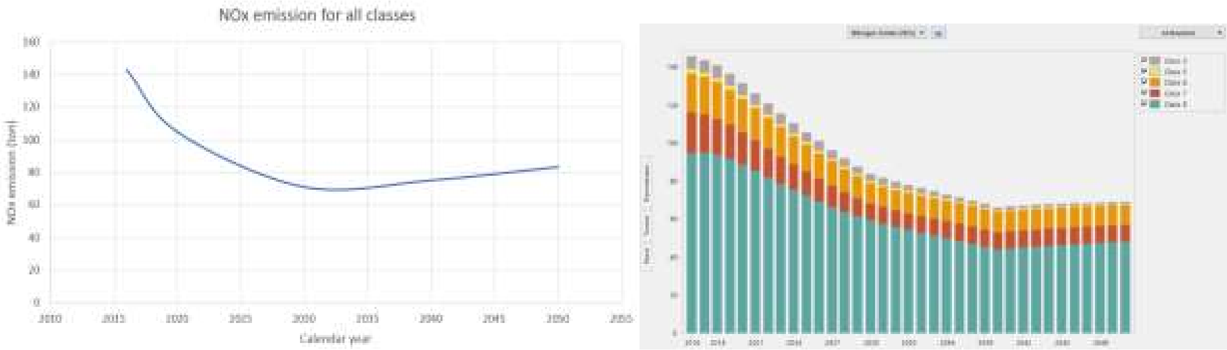


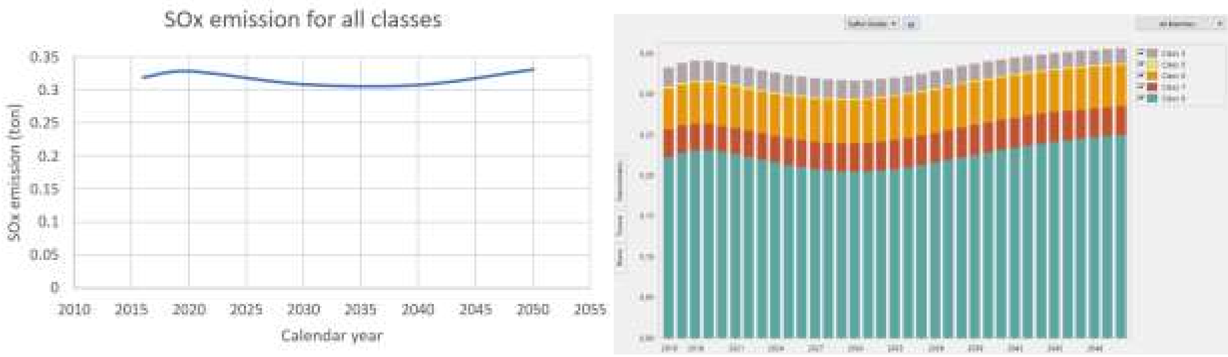
Figure 5.2: CARB GHG emission in transportation sector

As it is possible to notice there is a perfect match between the reference case propose by EMFAC2017, LEAP and the forecast proposed by the California Air Resource Board.
The same approach considered for greenhouse gases has been applied for the air pollutants NOx, Sox and PM2.5. The trends of this emitters will be shown in the following plots, comparing the EMFAC2017 trends to the LEAP ones



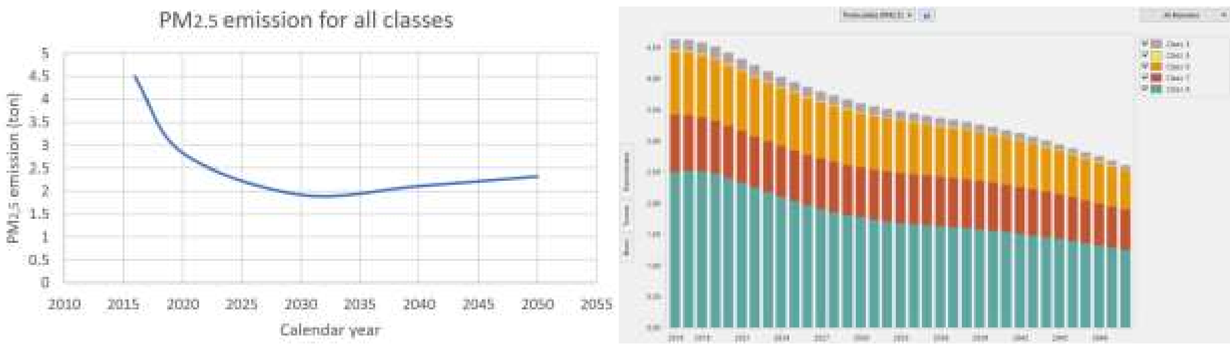
(a) (b)

Figure 5.3: NOx emission profile, (a) EMFAC2017 reference case, (b) LEAP reference case



(a) (b)

Figure 5.4: SOx emission profile, (a) EMFAC2017 reference case, (b) LEAP reference case



(a) (b)

Figure 5.5: PM2.5 emission profile, (a) EMFAC2017 reference case, (b) LEAP reference case

From these comparative plots it is possible to notice that there is not a perfect match in the EMFAC2017 reference case for air pollutant emission and LEAP. This is mainly due to the fact that only a linear shape has been introduced in the emitters for each fuel and each class.
Even if it is not visible form the figures showed in this section, the best match has been guaranteed for each class and each fuel considered.

5.3 Future scenarios

After the calibration of LEAP model, three future scenarios have been created in order to understand the impact on new technologies under an emission point of view.

5.3.1 Fuel cell hydrogen electric truck adoption

In section 2 and 4 have been developed the technical and economic analysis and comparison between the two technologies of interest for this report: (i) battery electric vehicles and (ii) fuel cell hydrogen electric vehicles.
From both the technical and economic analysis fuel cell hydrogen electric trucks demonstrates to be more adaptable at higher ranges and varying the capital cost of the vehicle in terms of cost of the fuel cell stack. For this reason this technology has been preferred with respect to the battery electric and will be adopted in the future scenarios.

5.3.2 Description of the three future scenarios

The three future scenarios will be characterized by a different adoption percentage in 2050:

- Low rate of adoption scenario, 10% of fuel cell electric trucks population in 2050
- Medium rate of adoption scenario, 50% of fuel cell electric trucks population in 2050
- High rate of adoption scenario, 80% of fuel cell electric trucks population in 2050

The new technology vehicles will enter in the market with a logistic curve shape, descripted by the equation below

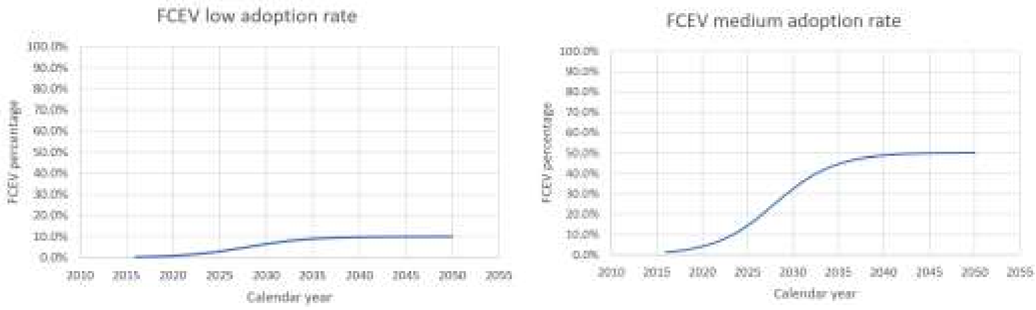
$$\%FCEVcurr\_year = \%FCEVi + \frac{\%FCEVf}{1 + e^{-s\cdot(curr\_year - \frac{1}{2}year)}}$$

where $\%FCEVcurr\_year$ is the percentage of fuel cell electric vehicle in the considered current year, $= \%FCEVi$ is the initial value of the fuel cell vehicle market share (in this case it is 0), $\%FCEVf$ is the final value of the fuel cell vehicle market share, which will vary in the three different scenarios, s is the shape factor, $curr\_year$ is the considered current year and $\frac{1}{2}year$ is the ear in which the FCEV share will reach the half of the final market share.
The parameter considered for the three scenarios are:

Table 5.1: input parameters for logistic curves

Scenario	Low rate	Medium rate	High rate
%FCEVf	10%	50%	80%
s	0.3	0.3	0.3
$\frac{1}{2}year$	2028	2028	2028

Below the three logistic curves used in the future scenarios have been reported.



(a) (b)

Figure 5.6 (a) FCEV low rate of adoption and (b) FCEV medium rate of adoption

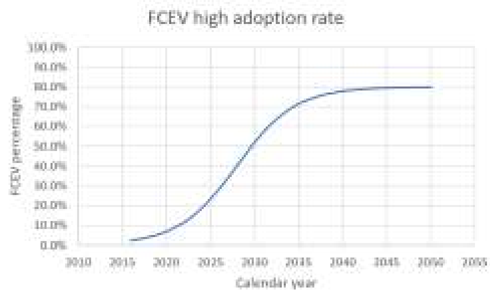


Figure 5.7 FCEV high rate of adoption

5.3.3 Low rate of adoption scenario

5.3.3.1 New fuel share for each class

With the adoption of the new technology the fuel share will be modified over time following the logistic curve of adoption for fuel cell electric vehicles.

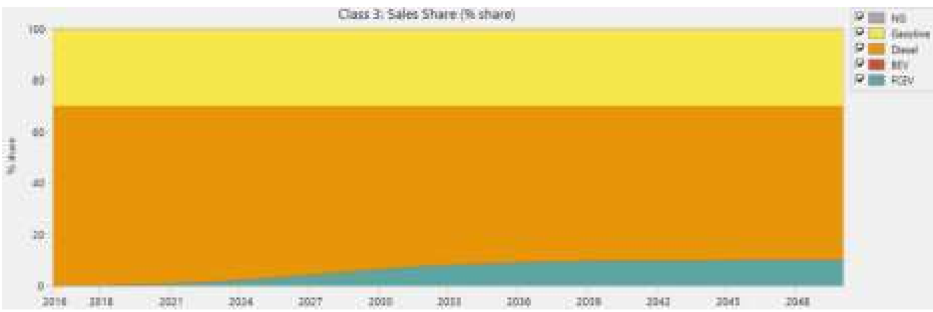


Figure 5.8: Class 3 fuel shares for low rate of FCEV adoption

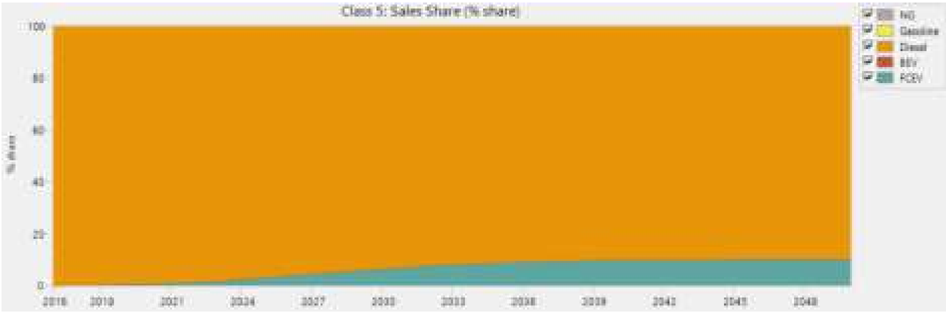


Figure 5.9: Class 5 fuel shares for low rate of FCEV adoption

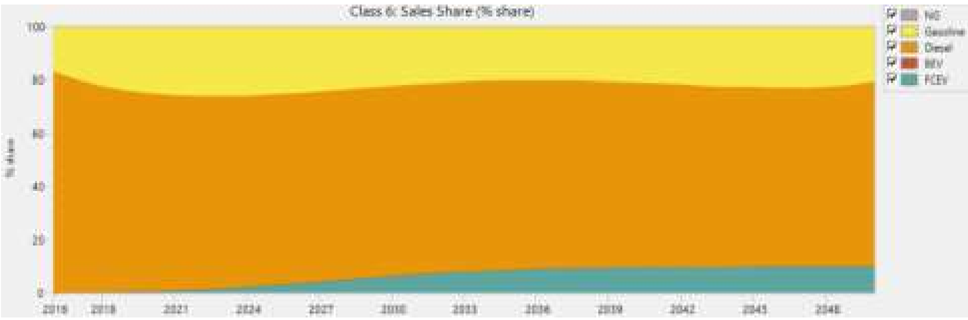


Figure 5.10: Class 6 fuel shares for low rate of FCEV adoption

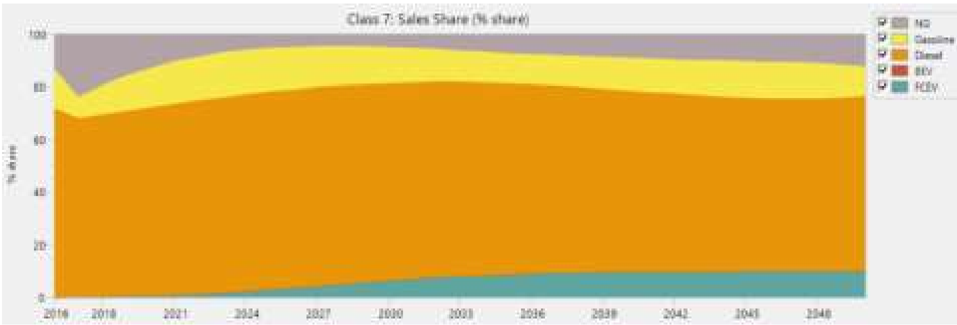


Figure 5.11: Class 7 fuel shares for low rate of FCEV adoption

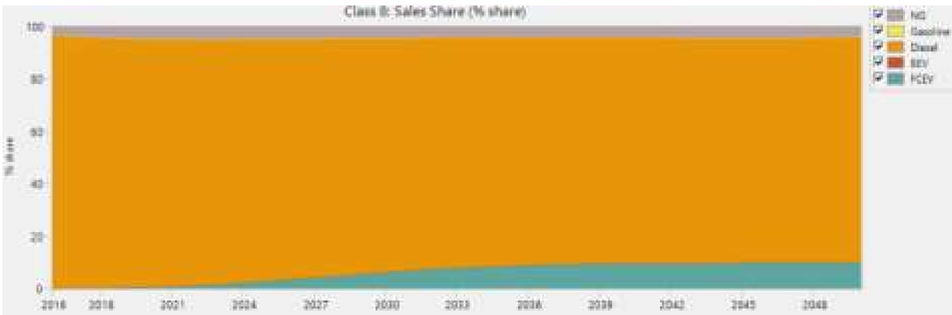
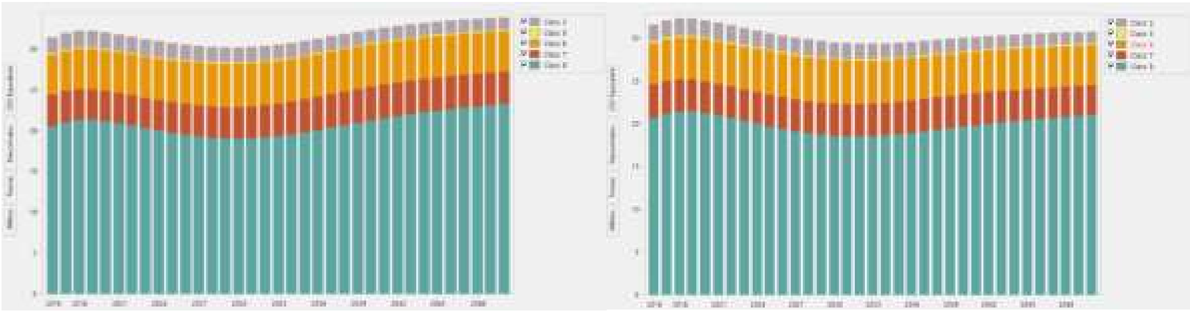


Figure 5.12: Class 8 fuel shares for low rate of FCEV adoption

In this scenario Diesel trucks have been suppressed over time to allow the adoption of fuel cell electric vehicles.

5.3.3.2 Emission results compared with reference scenario

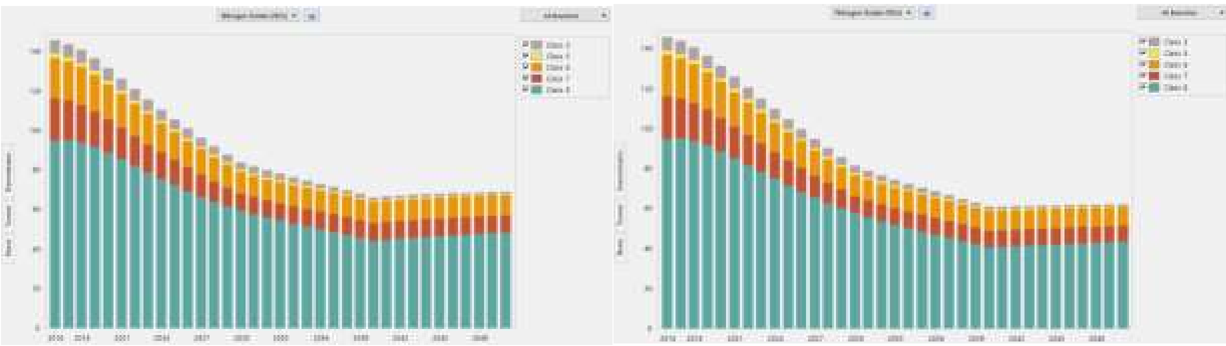
In this section the emission reduction after a low rate of fuel cell electric vehicle adoption will be reported, in order to evaluate then which will be a scenario that allows to meet the state emission reduction target.



(a) (b)

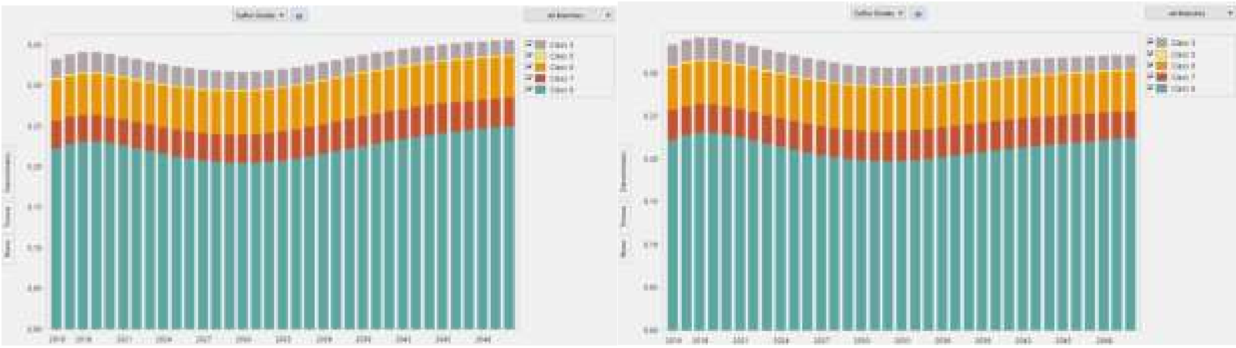
Figure 5.13: GHG emission comparison between (a) reference scenario and (b) low rate of adoption scenario

The reduction in GHG emission is less than 10% and it is not sufficient to meet the state targets, so a higher rate of adoption is necessary for mitigate the greenhouse gas emission.



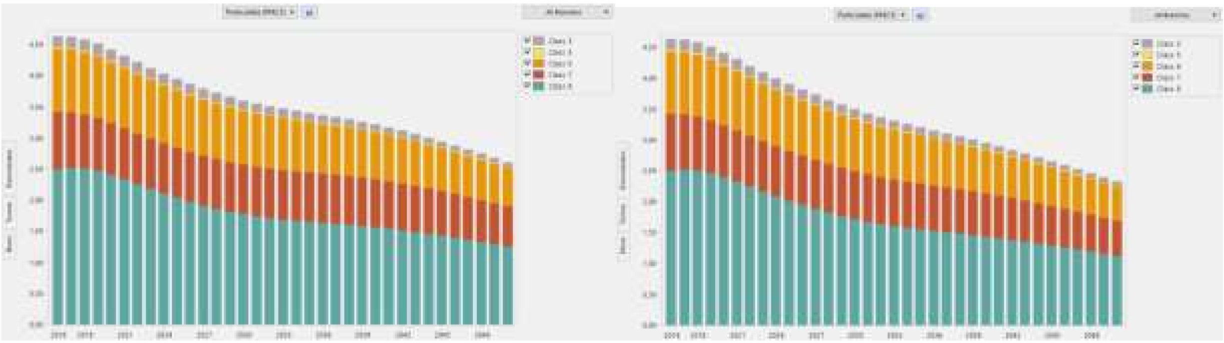
(a) (b)

Figure 5.14: NOx emission comparison between (a) reference scenario and (b) low rate of adoption scenario



(a) (b)

Figure 5.15: SOx emission comparison between (a) reference scenario and (b) low rate of adoption scenario



(a) (b)

Figure 5.16 $PM_{2.5}$ emission comparison between (a) reference scenario and (b) low rate of adoption scenario

As for the greenhouse gases, also the air pollutants do not present a reduction higher than 10% introducing fuel cell electric vehicle with a low rate of adoption

5.3.4 Medium rate of adoption scenario

5.3.4.1 New fuel share for each class

With the adoption of the new technology the fuel share will be modified over time following the logistic curve of adoption for fuel cell electric vehicles.

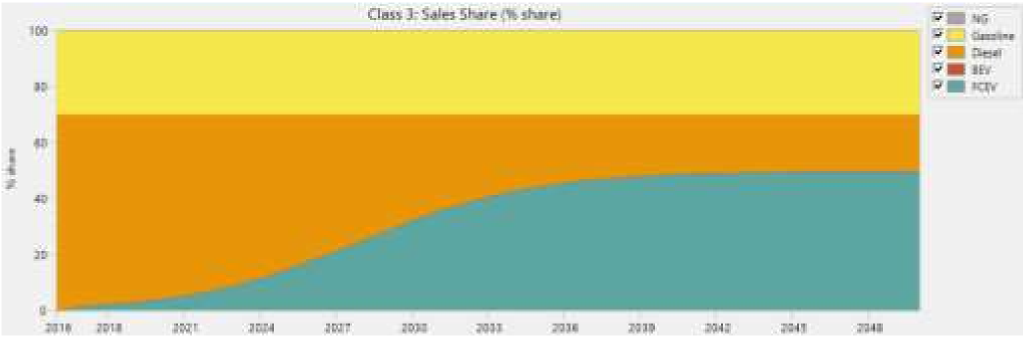


Figure 5.17: Class 3 fuel shares for medium rate of FCEV adoption

Figure 5.18: Class 5 fuel shares for medium rate of FCEV adoption

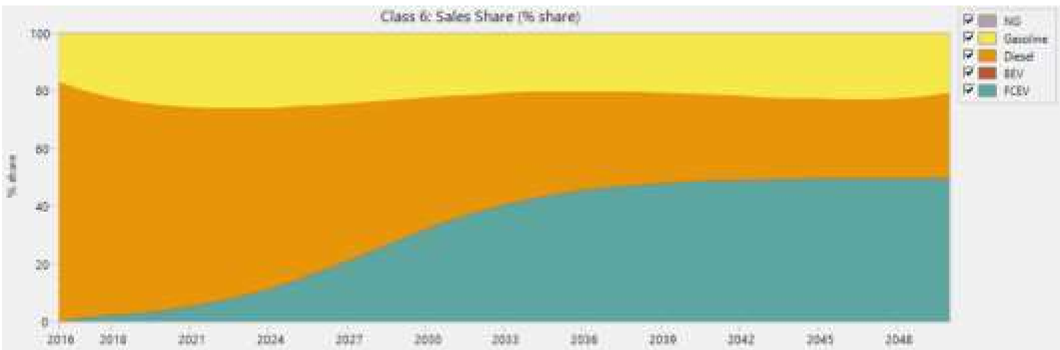


Figure 5.19: Class 6 fuel shares for medium rate of FCEV adoption

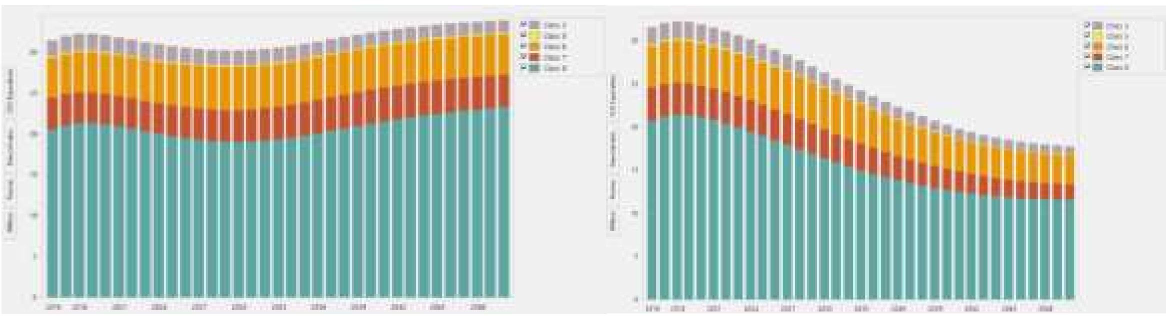
Figure 5.20: Class 7 fuel shares for medium rate of FCEV adoption

Figure 5.21: Class 8 fuel shares for medium rate of FCEV adoption

In this scenario Diesel trucks have been suppressed over time to allow the adoption of fuel cell electric vehicles.

5.3.4.2 Emission results compared with reference scenario

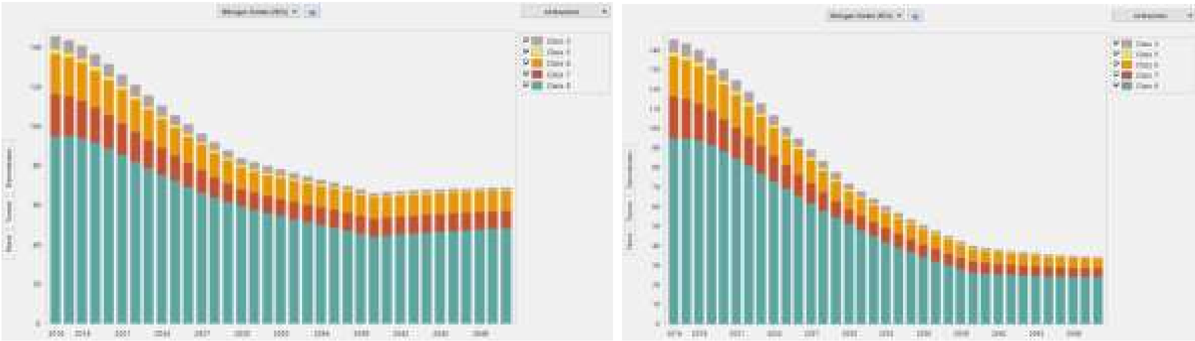
In this section the emission reduction after a medium rate of fuel cell electric vehicle adoption will be reported, in order to evaluate then which will be a scenario that allows to meet the state emission reduction target.



(a) (b)

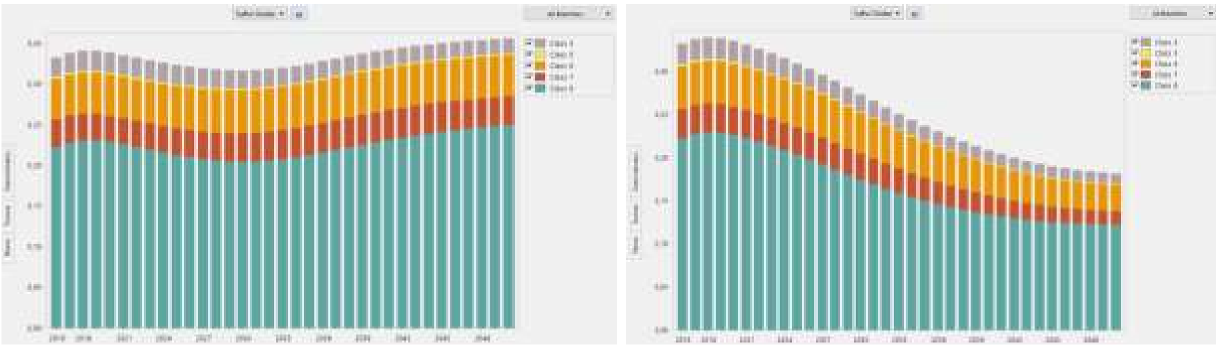
Figure 5.22: GHG emission comparison between (a) reference scenario and (b) medium rate of adoption scenario

The reduction in GHG emission reaches 30% in 2030 and up to 40% in 2050, this emission reduction can have a great impact in order to achieve the state target and reducing the greenhouse gas emission from the transportation sector.



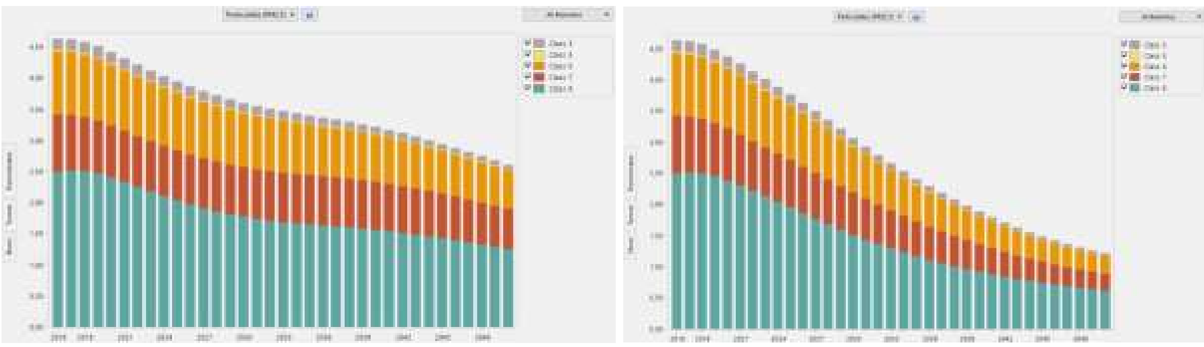
(a) (b)

Figure 5.23: NOx emission comparison between (a) reference scenario and (b) medium rate of adoption scenario



(a) (b)

Figure 5.24: SOx emission comparison between (a) reference scenario and (b) medium rate of adoption scenario



(a) (b)

Figure 5.25: $PM_{2.5}$ emission comparison between (a) reference scenario and (b) medium rate of adoption scenario

For the air pollutants, the percentage in reduction with respect to the reference case is lower than the GHG reduction, being the shape of the air pollutants (except SOx) a decreasing shape also in the reference scenario.
To sum up on the whole, for NOx there is a reduction of 80% in 2050 with respect to 2016 values, when in the reference scenario it was not more than 60%.
A reduction of 30% can be visualized in SOx, where in the reference scenario the shape was roughly constant over time.
Finally, for $PM_{2.5}$ the final emission reduction is 60%, comparing to the 30% reduction in the reference case in 2050 with respect to 2016 value.

5.3.5 High rate of adoption scenario

5.3.5.1 New fuel share for each class

With the adoption of the new technology the fuel share will be modified over time following the logistic curve of adoption for fuel cell electric vehicles.

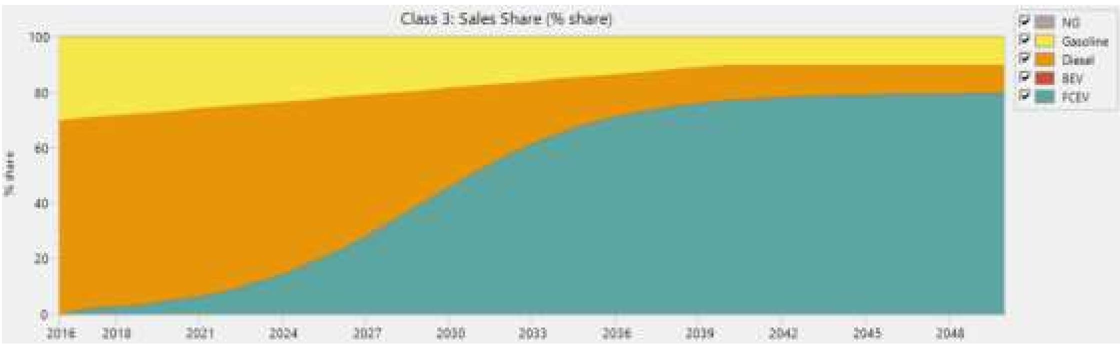


Figure 5.26: Class 3 fuel shares for high rate of FCEV adoption

Figure 5.27: Class 5 fuel shares for high rate of FCEV adoption

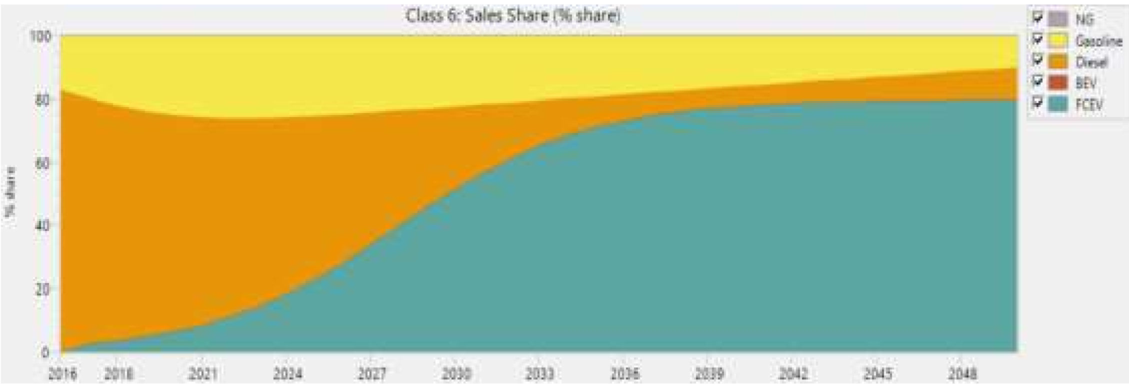


Figure 5.28: Class 6 fuel shares for high rate of FCEV adoption

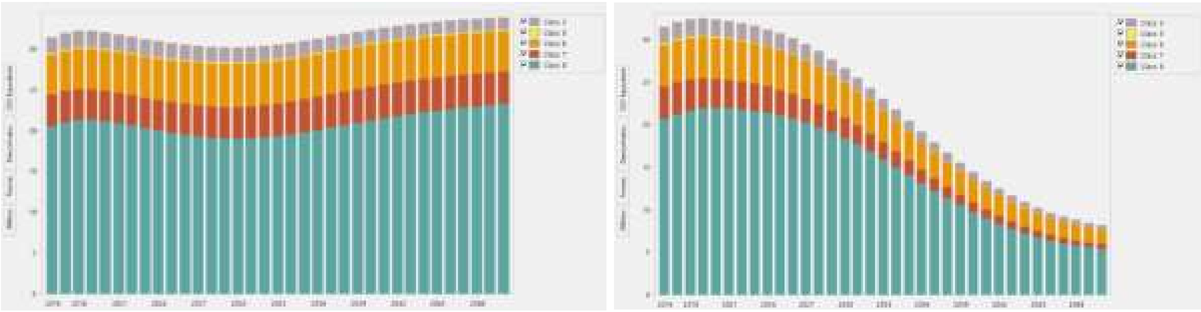
Figure 5.29: Class 7 fuel shares for high rate of FCEV adoption

Figure 5.30: Class 8 fuel shares for high rate of FCEV adoption

In this scenario not just Diesel trucks have been suppressed over time to allow the adoption of fuel cell electric vehicles, but in some cases a reduction in the other fuel types has been necessary.

5.3.5.2 Emission results compared with reference scenario

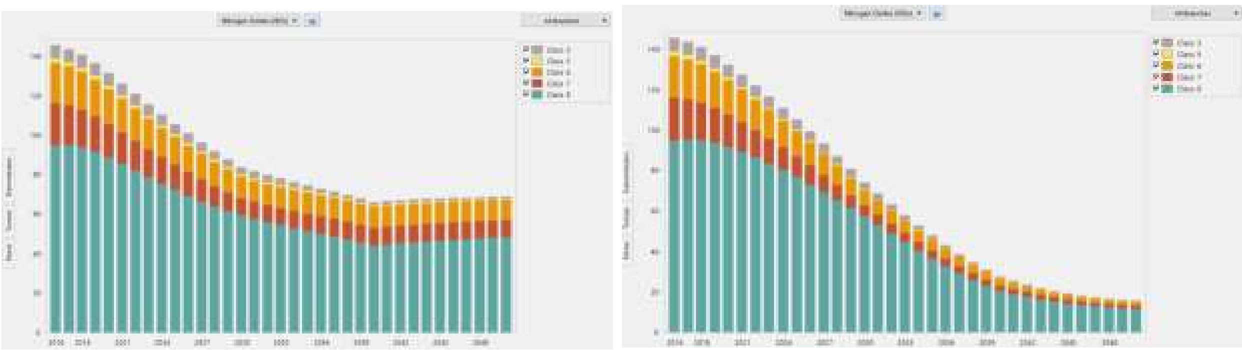
In this section the emission reduction after a high rate of fuel cell electric vehicle adoption will be reported, in order to evaluate then which will be a scenario that allows to meet the state emission reduction target.



(a) (b)

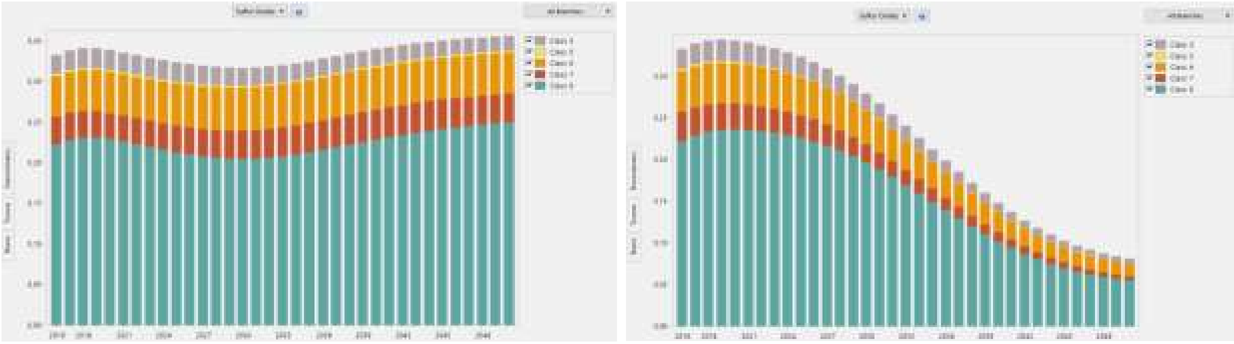
Figure 5.31: GHG emission comparison between (a) reference scenario and (b) high rate of adoption scenario

The reduction in GHG emission reach 80% in 2050 which will allow to reduce the climate change impact for medium and heavy-duty trucks in a drastic way.
On the other hand, a massive adoption as the high rate of adoption proposed in this section is highly challenging and requires high incentives from the state and massive adoption of refueling infrastructures too.



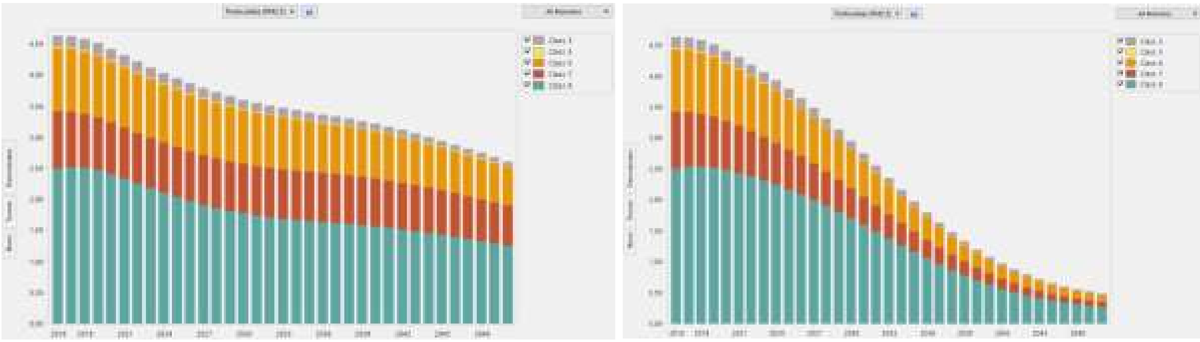
(a) (b)

Figure 5.32: NOx emission comparison between (a) reference scenario and (b) high rate of adoption scenario



(a) (b)

Figure 5.33: SOx emission comparison between (a) reference scenario and (b) high rate of adoption scenario



(a) (b)

Figure 5.34 $PM_{2.5}$ emission comparison between (a) reference scenario and (b) high rate of adoption scenario

As for the greenhouse gases, also the air pollutants evidence a massive reduction, up to 90% in 2050 from the 2016 values.

An important notice has to be added for explaining the meaning of this analysis. In this section, the emission from the fuel production has not been considered, so only the emission from the tailpipe has been considered. For fuel cell electric vehicle, the emissions from the tailpipe are zero (the emit only water), so the new vehicles' mileage has not been considered as a variable in this analysis. The reduction in percentage from the Reference case, which takes into account only Diesel and Gasoline vehicles, considering also the fuel production emission can be higher or lower depending if the Diesel or Gasoline production emits more or less than the hydrogen production process. An analysis of this type can be interesting as a future work, with the opportunity to consider different hydrogen production pathways.

6 Conclusions and future developments

The primary goal of this thesis has been to analyze under different aspects the GHG and criteria pollutants emission benefits and the techno-economic feasibility for zero emissions vehicles in the medium and heavy-duty vehicle applications.

Based on the technical and economic analysis, it was possible to notice that fuel cell electric vehicle weight and cost is much less sensitive to increasing range than batteries. This finding is mainly due to the fact that for battery electric trucks, the battery is responsible for both for the power and the energy, while for fuel cell electric trucks, the power is provided by the fuel cell system and the energy is related to the amount of on board stored hydrogen fuel. For these reasons, fuel cell electric trucks are identified as a promising technology for future trucking decarbonization scenarios.
Analysing the three future scenarios, the medium adoption rate gives a reduction of 50% in GHG emission in 2050 with respect to the 2016 value, and a 80% reduction in NOx and $PM_{2.5}$. This would represent, so it would allow an important reduction and impact in the greenhouse gases and air pollutants emissions.
Since half of the medium and heavy-duty truck population will be FCEV in the medium adoption rate scenario in 2050, the resultant high manufacturing rate is projected to give lower cost ($/kW) for the fuel cell stack.

Finally, one of the most important aspects necessary for a massive fuel cell electric truck adoption is the hydrogen production process. Nowadays the two main processes are water electrolysis and steam methane reforming, the former guarantees extremely low emission, down to null if renewable electricity is used for the electrolysis. The price of this technology is still too high and more deployment programs are needed to bring the price of this mode of production down.
Moreover, the hydrogen dispensing and infrastructure is the other key aspect for fuel cell vehicles adoption. Introducing medium and heavy-duty vehicles costumers as early adopters for this technology will allow for an easier design of locations for refuelling infrastructures, since routes for this type of vehicles are more predictable and scheduled.
The last aspect of interest to be analysed deeply will be the safety of hydrogen tank in the vehicles, ensuring a minimal volatility risk of hydrogen from the tank.

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