POLITECNICO DI TORINO

Master of Science in Energy and Nuclear Engineering

Master's Degree Thesis

TCO calculation of hydrogen light duty vehicles and forecast up to 2050

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Abstract

The key role that has been assigned to the mobility sector in the decarbonization goals in place both on a European and National level, makes crucial the introduction of no-emission technologies inside the light-duty vehicles market. In recent years we are observing an important increase in battery-powered electric cars sales but, the long recharge times and the low autonomy of these vehicles make it necessary to consider the introduction of hydrogen-powered vehicles on the market, characterized by higher performance in terms of autonomy and recharging times but, at the same time, by a cost that is still too high and that does not allow their diffusion in the automotive market.

The objective of this work is to develop a tool to calculate the Total Cost of Ownership of the main technologies with a role in the light-duty vehicles market and predict their evolution up to 2050. In this regard, a review of the state of the art of the components which form the powertrain of the reference technologies of interest for zero-emissions mobility is presented. Fuel Cell Electric Vehicles and Battery Electric Vehicles are compared with Internal Combustion Engine Vehicles, their main competitor under the economic aspect. Subsequently, the methodology to calculate the TCO of the vehicles mentioned has been selected, defining a quantitative model for all the expenses the owner must deal with, during the lifetime of the vehicle.

Defined the methodology and implemented the tool, the data from real models of different sizes and technology have been inserted to prove the reliability of the tool. It turned out to be reliable in approximating their sale price with an accuracy of 10% when the assumptions underlying the tool are respected. Subsequently, four case studies for different sizes and specifications have been defined for each technology, trying to simulate the average vehicles in common use today.

The results obtained show an important reduction in the cost of ownership of FCEVs and BEVs, respectively of 40% and 29% by 2050. On the contrary, the ownership cost of ICEVs is expected to remain the same, leading the FCEVs to potentially be the technology with the lowest cost of ownership starting from 2035, followed by the BEVs.

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Acronyms

ARR	Adjusted retention rate.
BEV	Battery electric vehicle.
BOP	Balance of plant.
CHP	Combined heat and power.
ECV	Electrically chargeable vehicle.
EM	Electric motor.
EV	Electric vehicle.
FC	Fuel cell.
FCEV	Fuel cell electric vehicle.
GHG	Green house gasses.
HEV	Hybrid electric vehicle.
ICEV	Internal combustion engine vehicle.
LCOD	Levelized cost of driving.
LDV	Light duty vehicle.
MHEV	Micro hybrid electric vehicle.
MSRT	Manufacturer suggested retail price.
MY	Manufacturing year.
OEM	Original equipment manufacturer.
PCU	Power control unit.
PHEV	Plug-in electric vehicle.
TCO	Total cost of ownership.
VAT	Value-added tax.
VTM	Vehicle total mileage.

Introduction

1.1 Context

The transport sector accounts for almost 25% of the total European emissions. For this reason, in a context in which it is essential to limit the effects of global warming throughout the world, solutions to limit the emissions from the road transport must be particularly considered. In fact, it is an uncontrollable source of carbon dioxide (CO2) but also of other pollutants such as carbon monoxide (CO), nitrogen oxides (NOx) but also fine dust (PM). The last few years have shown an increase in total emissions from the transport sector of approximately 33,5% from 1990 to 2019 but at the same time, the increasing diffusion of low-emission vehicles has made it possible to lower the specific consumption for each vehicle sold of 22,4% from 2010 to 2021. [1, 2]
This trend is mainly due to the excellent sales data of Battery electric vehicles (BEVs), Plug-in electric vehicles (PHEVs) and Hybrid electric vehicles (HEVs) that have been continuously increasing over the years. The same trend can be found for Fuel Cell Electric vehicles (FCEVs), which, however, due to their high cost and the lack of recharging infrastructures, are still diffused in numbers that are too low to consider the hydrogen passenger car market completely developed. As is well known, however, only the FCEVs, together with BEVs technology, provide zero emissions, as PHEVs and HEVs exploit the combined action of battery and internal combustion engine, reducing the emissions of the classic petrol or diesel engine without eliminating them. The new measures designed by the European Union and in particular the new package 'fit for 55' [3] aim to reduce pollutant emissions by 100% for new cars sold starting from 2035. This solution will result in a ban on the sale of ICEVs, PHEVs and HEVs in the EU starting from that year. So what are the prospects for the road transport market?
Despite the advantages of the BEVs, linked to their brilliant performance, their reduced noise pollution and their low running costs, these cars guarantee autonomy that is still too low and high charging times, which do not make them suitable for the needs of all types of consumers. In addition, the increasing diffusion of battery-powered vehicles results in an always higher demand for electricity, which in turn results in the need to adapt the network, also through the development of a bidirectional vehicle-to-grid management system.
Considering these problems, a greater diffusion of hydrogen cars is not only advantageous but also necessary. In fact, they are complementary in characteristics to the BEVs, guaranteeing short recharging times and greater autonomy, allowing the diversification of the fuel request, and lowering the stress on the electric network. This makes it important to study the evolution of their economic feasibility both in terms of the selling price and in the management and operation costs.

1.2 EIFER and EDF's motivations

EDF through EIFER, its R&D center, aims to study and predict the evolution of the hydrogen market and its applications. In particular, a correct prediction of the TCO of different hydrogen means of transport is useful to create scenarios regarding their diffusion and the barriers to be overcome. This objective is fundamental above all for the development of a network of refuelling stations, in which various manufacturers are interested. The creation of a tool for light-duty vehicles arises in this context, adding to the works already developed for buses, trucks, ships and trains.

1.3 Objectives of the thesis

The aim of this thesis is to establish a methodology for calculating the TCO of light-duty vehicles at a European level, looking for a comparison between FCEVs and BEVs and ICEVs as its main competitors.

At the beginning of the second chapter, the European policies actually in place to reduce the emissions coming from the mobility sector will be presented, after a brief introduction about the light-duty vehicle market. In the second part of the chapter, the state of the art of the FCEV technologies is presented, showing the main powertrain architectures of interest and comparing them with BEV and ICEV, deepening from a technological point of view the components which form all of them and defining their cost through a review of the bibliography, in a time window ranging from 2020 to 2050. In the third chapter, the methodology is going to be presented, assessing the quantitative model to be used and the hypotheses applied to each term which forms the vehicle's Total Cost of Ownership. Subsequently, the method obtained will be applied through a dedicated tool, developed in Excel, to hydrogen, battery and internal combustion engine vehicles. In the fourth and fifth chapters, the interface of the tool and its results will be presented and commented on, trying to establish a year for the definitive overcoming of zero-emission technologies over conventional ones. The data uncertainty will be assessed through a sensitivity analysis, in order to understand the validity limits of the study.

State of the Art

In this chapter, the European framework for light-duty vehicles is studied and discussed. In the first section, different data about the transport market are analysed in order to give a view of the necessity to favor the spread of zero-emissions technologies, and hydrogen vehicles in particular, inside the European market. Following, the road map of hydrogen vehicles is introduced, starting from the first concept presented up to the models currently on the market.
The second section is focused on the policies of the European countries and the subsidies introduced in the last years to favour the zero emissions technologies penetration, decreasing both their retail price and annual taxes.
In the third section, the reference powertrain structures for every technology considered are presented, together with the elements that compose them. In every subsection, the primary information about the components' state-of-the-art technology is given, followed by the analysis of their cost from 2020 to 2050. In this regard, 5-year intervals from 2020 to 2035 are considered, arriving then directly to 2050 due to the difficulty of finding data in the years in between.

2020
2025
2030
2035
2050

Table 2.1: Reference timeframe.

2.1 Private light duty vehicles

The Green House Gasses emissions from road transport in the European Union were 28,8% higher in 2019 than in 1990 (figure 2.1,[2]) and, despite a drop in 2020 due to the COVID-19 pandemic, it is expected that emissions will rebound. In 2019, road transport accounted for 71.7% of the EU-27 transport sector emissions, this share can be divided among passenger light-duty vehicles, light-duty commercial vehicles and heavy-duty vehicles (figure 2.2,[2]), with the first one that causes the largest part of the GHG emissions (60,6% in 2019).[2]

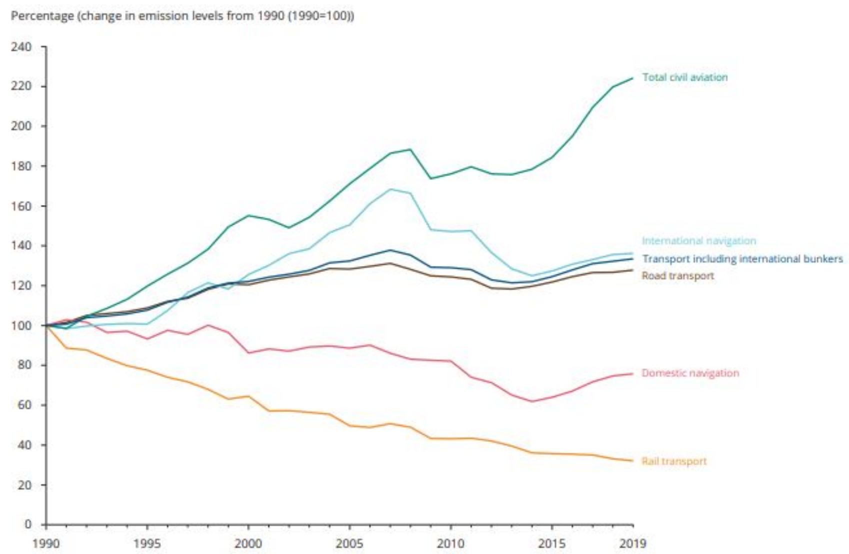


Figure 2.1: Trends in GHG emissions by transport mode in the EU-27 (1990-2019).

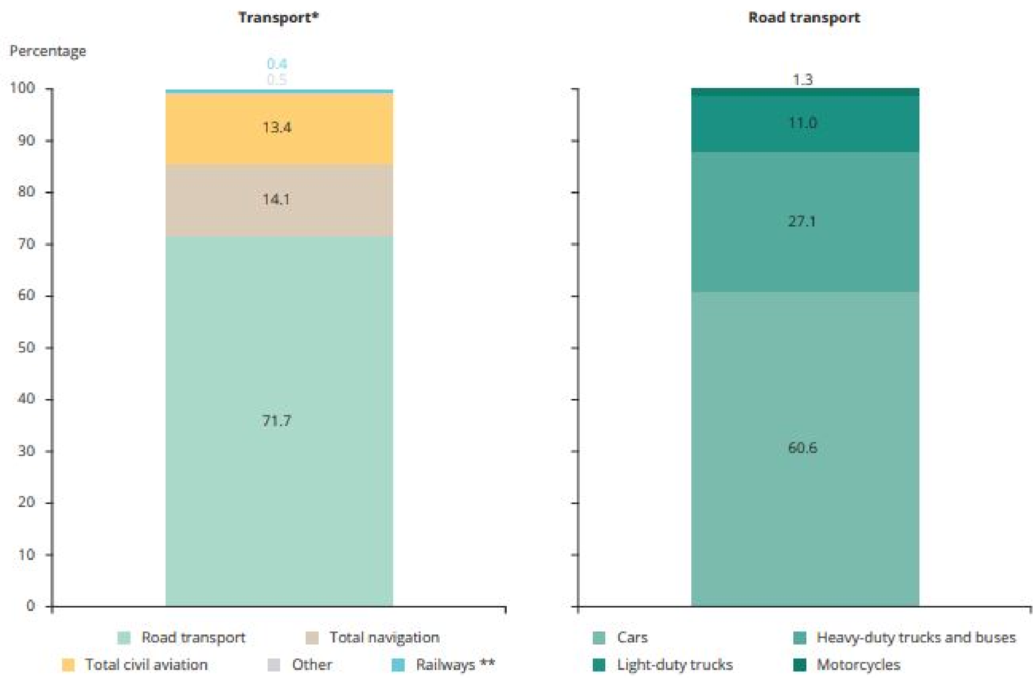


Figure 2.2: Road transport emissions as a share of EU transport GHG emissions and share of road transport emissions by mode in the EU-27, 2019.

According to the European Automobile Manufacturers' Association (ACEA) [4, 5], almost 10 million passenger cars were sold in the EU in 2021. This number makes it clear how much the automotive industry plays a fundamental role in the European economy, which makes it impossible to think of managing it only from an environmental point of view. In addition, some more data can help in understanding the importance of the automotive sector in Europe:

- 12,6 million people work in the automobile industry, accounting for 6.6% of all EU jobs.
- 11,6% of EU manufacturing jobs are in the automotive sector.
- Motor vehicles are responsible for € 398,4 billion of tax revenue for governments across key European markets.

- The automobile industry generates a trade surplus of € 76.3 billion for the European Union.
- The turnover generated by the auto industry represents more than 8% of the EU's GDP.
- Investing 62 billion euro in R&D per year, automotive is Europe's largest private contributor to innovation, accounting for 33% of the EU total.

To understand how to approach vehicle analysis it is important to properly analyse the selling data by segment and technology.
In this regard, figure 2.3 [1] shows the sales data in the European Union of passenger vehicles catalogued according to their segment. It is possible to observe how SUVs are the most popular vehicles on the market, followed by Small vehicles, which include segments A and B (city cars), and by lower medium cars (Segment C). The three segments listed cover a total of 87% of the market and will be those of main interest for this thesis, trying to include lower and upper medium segments in a unique class and excluding Luxury and Multi-purpose vehicles. In addition, due to the large amount of data found, the pickups will also be considered in the analysis, allowing the user to calculate their ownership costs.

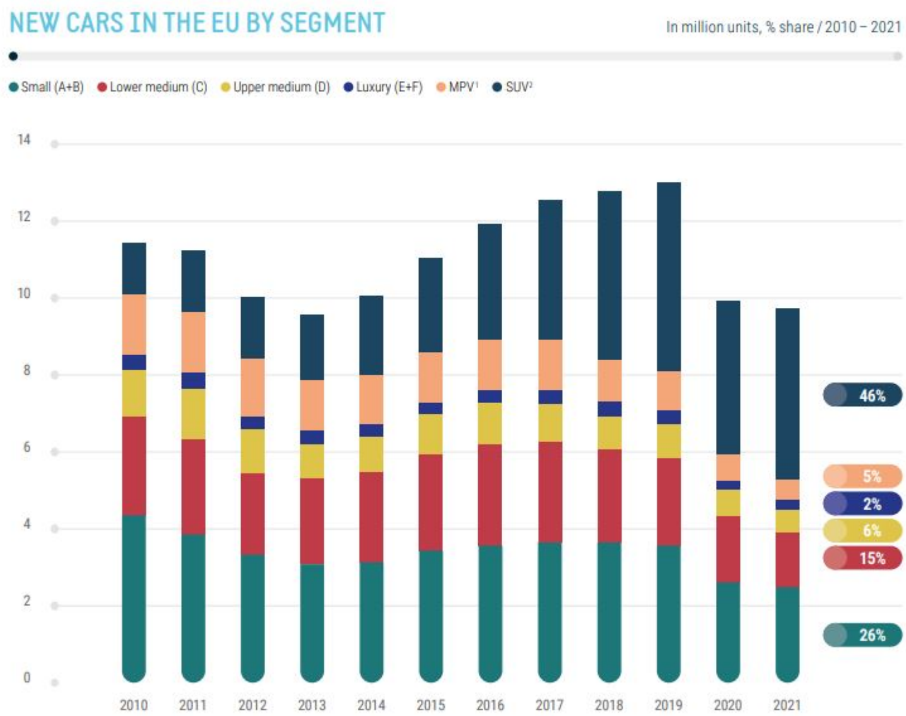


Figure 2.3: New cars in the EU by segment. (2010 - 2021)

Segments
Small
Medium
SUV
Pickup

Table 2.2: Reference segments.

From a technological point of view, Electrified vehicles have every year an increasing role in the market, they represent 37,61% of the EU car sales in 2021. This percentage is divided between BEVs and PHEVs, which together occupy 18.0 % of the European market with respectively 877.428 and 867.092 vehicles registered in 2021, HEVs, which represent 19.6 % (1.901.239 vehicles) and finally FCEV, which are the smallest portion of the market with only 0.01 % share, equivalent to 1.004 vehicles. These data are collocated in the context of great growth for zero-emission vehicles. Indeed, while the sales of diesel and petrol cars have been steadily decreasing since 2019 (respectively 48 % and 54 %), the sales figures of BEV and FCEV have increased respectively by 250 % and 109 % in the same time range. Looking at the single EU countries, the trends vary a lot from country to country. The three countries with the highest market share of BEVs are in order Netherlands (19,8 %), Sweden (19,1 %) and Austria (13,9 %), while Five EU member states (Bulgaria, Czech Republic, Slovakia, Poland and Cyprus) have a BEV market share less than 2%. Looking to the percentage of FCEVs does not reach 0,01% in any of the countries. This trend is still not enough to make zero-emission vehicles a consistent part of road vehicles. In fact, in 2020 the total number of BEVs on the road was still 0.5 % of the total number of vehicles registered in the EU.
An important factor that may or not incentivize consumers to buy a vehicle not powered by an internal combustion engine is the presence of a network of recharging facilities that allow the vehicle to be operated without too many constraints. This observation leads to a further important difference between BEVs and FCEVs. Beyond the presence of charging stations, each battery-powered vehicle can be connected to its own home socket, while the presence of a refuelling station infrastructure is essential to allow the diffusion of the FCEVs. At the same time, the BEV recharging infrastructure is easier to install, as access to the electricity grid is easier to implement than hydrogen refuelling stations.
The tables 2.3, 2.4 and 2.5 show in which countries it is possible to find the biggest number of recharging points, which should not only be observed in absolute numbers but also for their distribution over 100 km. How it is possible to see, the huge increase in Electrically-chargeable cars corresponds to a similar trend for the recharging stations but this distribution is still too unequal, indeed four countries that cover a third of the EU's total surface area (Netherlands, Germany, France and Sweden) account for 70% of all EV charging points in the EU.

Countries	ECV points
Netherlands	90.284
Germany	59.410
France	37.128
Sweden	25.197
Italy	23.543

Table 2.3: Countries with most CV points.

Countries	ECV points/100km
Netherlands	64,3
Luxembourg	57,9
Germany	25,8
Portugal	24,9
Sweden	12,2

Table 2.4: Countries with most ECV points per 100km of road.

EU total	2017	2018	2019	2020	2021	% change 17/21
ECV charging points	109.896	123.727	171.287	231.842	306.864	179.2%
Electrically chargeable cars	168.901	240.347	387.325	1.045.893	1.744.520	932.9%

Table 2.5: Number of charging points and sales volumes of EC cars – Trends over time (2021).

On the other side, the analysis of the same data for the hydrogen refuelling stations shows that the infrastructure created is still far from being fully developed. Germany leads the ranking of the countries with the most hydrogen refuelling stations with 89 stations, more than two-thirds of all filling stations in Europe. At the same time, seventeen countries did not have a single station in 2021.

Countries	Refuelling stations
Germany	89
France	19
Netherlands	7
Denmark	6
Austria	4

Table 2.6: Countries with most hydrogen refuelling stations (2021).

Years	EU total Refuelling stations
2017	39
2018	39
2019	113
2020	124
2021	136

Table 2.7: Number of hydrogen refuelling stations – Trends over time (2021).

2.1.1 Hydrogen vehicles on the market

This subsection is dedicated to the presentation of the hydrogen passenger vehicles that are commercially available in Europe, the previous models that have been removed from the market, and the ones that are currently under development.
In previous years, different firms have presented their concept of FCEV, most of the time the vehicles have never reached production in series, going to market only in a few cases, with some companies making them available for rent only, while others have made their vehicles available for purchase.
Going in order, the first hydrogen vehicle presented was carried out by Opel in 2000 with the HydroGen1 model. This first concept had a 55kW electric motor that allowed the vehicle to reach a speed 140 km/h. Two years later, Mercedes-Benz presented the A-Class F-Cell model, characterized by the autonomy of only 160 km and followed in 2005 by the Honda FCX and in 2007 by the BMW Hydrogen 7, released in less than one hundred exemplars and the first hybrid internal combustion engine vehicle capable of combusting hydrogen as fuel.
The next step in the development of modern FCEVs was taken in 2010 by Mercedes-Benz with the B-Class F-Cell, available for hire only and featuring a 100 kW electric motor and a range of 400 km. Another concept, the Volkswagen Golf HyMotion was released in 2014, with a range of 500 km. Similarly, the Audi A7 Sportback h-tron concept, followed by the Audi h-tron SUV in 2016. Looking at the vehicles that have been available on the market, the first models on sale came from Hyundai in 2013 with the SUV ix35 Hydrogen followed by the Hyundai Nexo, sold for 69.000 € and still available on the market today. Another SUV, the Mercedes GLC F-Cell is now no longer available after being offered with the rental formula with a monthly fee of 799 euros in Germany. This vehicle is still one of a kind, featuring Plug-In Hybrid technology thanks to the 13.5 kWh lithium-ion battery. In 2016 Honda returned to prominence with its Clarity Fuel Cell, available only in Japan and California. Finally, Toyota debuted in the FCEV market in 2015 with its Toyota Mirai, completely renewed in 2020 with a really innovative version also for the technological solutions implemented. As said, today Toyota Mirai and Hyundai Nexo are the only FCEVs available on the market, with the addition of more prototypes that will be launched in the coming years. Among these, Volkswagen promises to reach an autonomy of 2000 km with a single tank, promising to compete with the two giants of the hydrogen market.

Figure 2.4: Hyundai Nexo.

2.2 Policies and subsidies

In this section, the European regulation regarding sustainability is analysed by means of the database Climate Change Laws of the World [6], containing more than ten years of data collection of climate and climate-related laws, subsequently, some reference countries and their policies are taken into account to watch the argument from a national point of view.
This analysis has the final aim to let understand the perspective of the various technologies inside the

national markets, also by means of subsidies, that are going to be differentiated considering the rules for their application and the specific technology which they are intended for. In this last case, the guide "Electric vehicles: tax benefits and purchase incentives" (2021) [7] has been used to understand the owners' rights to obtain subsidies for the different vehicle typologies and to calculate their amount for the twenty-seven states of the European Union. In the end, only the countries that are going to foresee subsidies for all the zero-emission powertrains under analysis are going to be considered, to compare FCEVs and BEVs using an equal criterion.

2.2.1 European regulation

In the last three years, the European Union turned out to be very active in the creation of strategies to decrease the climate impact of fossil fuel vehicles and in the proposal of climate targets to be reached in the transport field.
The main targets that have been proposed, according to the strategy "Powering a climate-neutral economy: An EU Strategy for Energy System Integration" [8] and the regulation "Regulation (EU) 2019/631 setting CO2 emission performance standards for new passenger cars and for new light commercial vehicles" [9], are following resumed:

- 1 million charging points for EVs by 2025;[8]
- 15% zero- and low-emission vehicles' benchmark for new passenger cars and light commercial vehicles by 2025; 35% zero- and low-emission vehicles' benchmark for new passenger cars by 2030; 30% zero- and low-emission vehicles' benchmark for light commercial vehicles by 2030; [9]
- 15% reduction of the 2021 target for average emissions of new passenger cars and light commercial vehicles by 2025; 37.5% reduction of the 2021 target for average emissions of new passenger cars by 2030; 31% reduction of the 2021 target for light commercial vehicles by 2030; [9]
- reduction of 10 g CO2/km of average emissions of new passenger cars and light commercial vehicles by 31 December 2024; [9]

All these targets converge in the package 'fit for 55' [3], presented in July and December 2021 and approved at the end of June 2022, designed to realise the objectives of climate neutrality by 2050 and a 55 % reduction of net greenhouse gas emissions by 2030, compared with 1990 levels, also by means of a series of interventions on the mobility sector, including aviation, maritime transport and road transport. Regarding the latter, the package proposes stricter CO2 emission standards for new cars, aiming for 100 % zero-emissions vehicles by 2035 through a ban on new gasoline and diesel vehicles, revolutionizing the transport market and giving a definitive boost to the zero-emission vehicles market.

2.2.2 National subsidies

Given the directives approved by the European Union, each country can reach the objective imposed following its own strategy. Different countries have chosen to introduce a series of tax benefits and purchase incentives to favour the acquisition of low-emission vehicles (PHEVs or HEVs) and zero-emission vehicles (BEVs and FCEVs) given their higher price with respect to fossil fuel vehicles.
The subsidies under analysis have usually a duration of one or two years, with the prospect to be confirmed after their expiration in case of necessity, considering the evolution of the market trends. For this last reason, forecasting the evolution of benefits and subsidies can be quite complicated in the long term but, at the same time, the closer 2035 is, the more difficult is to expect the concession of incentives, being expected a complete evolution of the zero-emission vehicles market for that year, at least inside the EU.
As already explained it is important to specify that twenty-six EU members on twenty-seven (only Estonia has no incentive scheme) provide benefits for the purchase of low emissions vehicles, but in this study only countries that provide incentives to both BEVs and FCEVs are presented and taken into account for the TCO calculation. The reason for this choice is given by the fact that the absence of subsidies and benefits for FCEVs (normally the presence of incentives for BEV is much more common) premises the lack of intentions by the country to invest in the refuelling infrastructure and, of consequence, this aspects can strongly demotivate the consumer to invest in the acquisition of the vehicle. Table 2.8 illustrates the incentives scheme of Germany, France, Sweden, Spain, Netherlands and Austria; apart from the purchase incentives, it has been pointed out the difference between

acquisition tax benefits and ownership ones, not considering the tax benefits for the company vehicles and eventual scrappage schemes, which are out from the objectives of the thesis.

Country	Tax benefits		Purchase subsidies
	Acquisition	Ownership	
Austria	VAT deduction and exemption from tax for zero-emission cars.	Tax exemption for zero-emission cars.	Bonus of 3.000 € for the purchase of new BEVs and FCEVs with a gross list price lower than 60.000 €
France	Regions provide an exemption (either total or 50%) for alternatively-powered vehicles.	None.	Bonus to buy a car with emissions lower than 20g CO2/km: 7.000 € for households, if the vehicle cost is lower than 45.000 € ; 3.000 € for households buying vehicles with a cost between 45.000 € and 60.000 € or FCEV cars.
Germany	None.	10-year exemption for BEVs and FCEVs registered until 31 December 2025. The exemption is granted until 31 December 2030 at the latest.	Until 31 December 2021, the 'innovation bonus' temporarily increases the environmental bonus for new and used BEVs, PHEVs and FCEVs registered from 8 July 2020. 9.000 € for BEVs and FCEVs cars with a net list price lower than 40.000 € 7.500 € for BEVs and FCEVs with a net list price higher than 40.000 € .
Netherlands	Exemption for zero-emission cars.	Exemption for zero-emission cars.	Subsidy scheme for individuals to buy or lease a small or compact BEV car. Environmental investment deduction for BEV and FCEV light commercial vehicles. Arbitrary depreciation of environmental investments scheme for FCEV cars or taxis and BEV cars equipped with solar panels.
Spain	Exemption from 'special tax' for vehicles emitting up to 120g CO2/km.	Reduction of 75% for BEVs in main cities.	Incentive scheme in 2021-2023 for cars: 4.500 € or 7.000 € for BEVs and FCEVs, for private individuals, depending on whether a vehicle is being scrapped.
Sweden	None.	Low annual road tax for zero-emission vehicles and PHEVs.	A climate bonus of 70.000 SEK for new zero-emission cars and light trucks has been introduced from 1 April 2021.

Table 2.8: Incentive scheme in the case studies country.

As it is possible to see, almost all the countries under analysis have opted for a total cut of acquisition and ownership taxes. The same consideration can be done regarding the purchase subsidies, which have been added in all the case studies but with a much more extended range, going the value of the incentive from 3.000 € to 9.000€ depending on the country and on the price of the vehicle. All the considerations demonstrate the European country's intention to actively help introduce zero-emissions vehicles inside the transport market.

2.3 Technology review

In this section, the main features of the powertrain architectures and their components are analysed with the objective of presenting all the data that are going to be used in the next chapters. Firstly, the main powertrain technologies are presented, explaining the basics of their operation. Looking at the figures, the topology of the powertrain is represented by means of block diagrams, where the arrows symbolise the energy flow direction. Secondly, after choosing the reference configurations for this work, the main components are discussed, underlying their characteristics, advantages and drawbacks, with particular attention to the FCEV components (fuel cell and hydrogen storage), which have been also subjects of a series of interview with some reference companies in the sector. A continuous comparison between the FCEV and BEV technology is pointed out because of their many analogies.

2.3.1 Powertrain model

All the powertrains under analysis will be presented looking at their main components and the links between them with the objective of highlighting the crucial costs for their manufacturing. The reference components of the powertrain architecture considered are listed in the table 2.9.

The FCEV powertrain is powered by the fuel cell, filled by the hydrogen storage tank, together with

FCEV	Fuel Cell Stack, Hydrogen Storage, Battery, DC-DC Converter, Inverter, Power Controller, Electric Motor, Drivetrain.
BEV	Battery, DC-DC Converter, Inverter, Power Controller, Electric Motor, Drivetrain.
ICE	Internal Combustion Engine, Fuel Tank, Drivetrain.

Table 2.9: Powertrain components.

another power source, usually a battery, as the fuel cell cannot handle sudden changes in load. The role of the battery is very important because a frequent change of loads can be very stressful for the FC and they can decrease its lifetime with respect to stationary usages.
The relationship between FC and battery characterizes the different architectures that have been developed, both as prototypes and commercial products.
According to Alpaslan et al. [10], it is possible to distinguish between two main reference architectures by looking at the link between the fuel cell and the battery, other models can be considered by taking into account the use of a super-capacitor or the possible connection of the battery to the electric grid but their analysis is not performed in detail because of their low technology readiness level, characteristic that makes far their usage in a commercial vehicle.
The first configuration considered is the "Series configuration" and it is shown in figure 2.5; in this case, the fuel cell energy flow is always transmitted to the battery before arriving at the motor. In the other case, the "Parallel configuration" (figure 2.6), the fuel cell can both give energy to the vehicle without passing through the battery or recharge it after its operation. The role of the battery, depending on the energy that is capable to store, can be just to assist the FC to operate during the peaks of power (power-on or sharp accelerations), being later restored from the fuel cell's leftover energy or the kinetic energy from the regenerative braking, in some cases also the use of super-capacitors has been considered to assist the operation of the FC, but their application has still not been considered for commercial vehicles. In alternative, the battery can have also the capability of powering autonomously the vehicle, and, in this case, the battery can be also recharged by means of a direct connection with the electric grid; this solution was applied to Mercedes GLC F-Cell, equipped with a battery of 13.5 kWh. The role of the power source during the peak of consumption is controlled using a power management controller.
In both architectures, the voltage level of the power sources is adjusted by means of a DC-DC converter, which interface is going to be shown more in detail and explained in the next sections, before converting the current from DC to AC (considering an AC electric motor) using an inverter. Finally,

the electrical power is converted into mechanical power using the electric motor, which can work also as a generator during the brakes, transmitting energy to the electric storage system through a converter. The parallel configuration is the reference topology considered in this work being the one

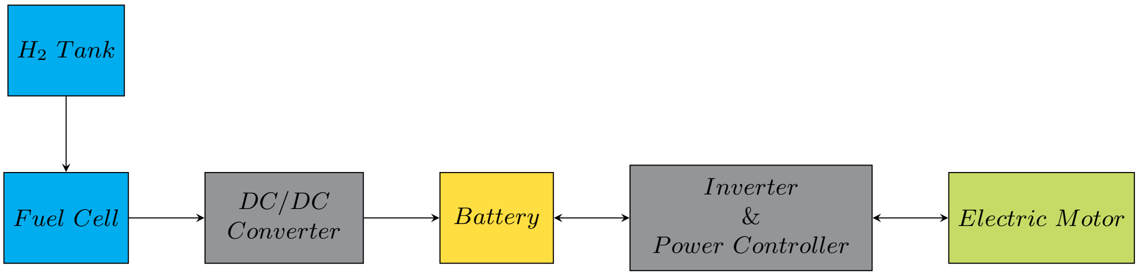


Figure 2.5: FCEV - Series configuration.

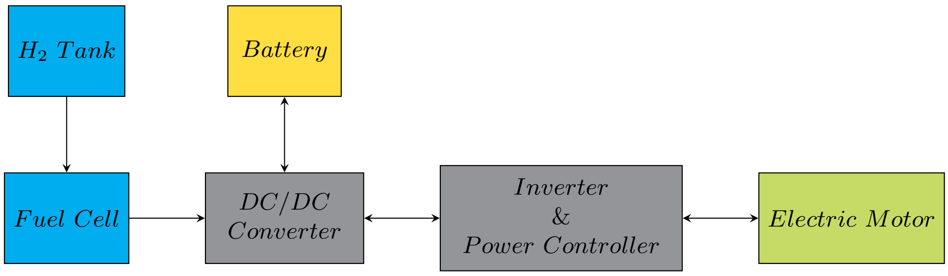


Figure 2.6: FCEV - Parallel configuration.

selected for the reference vehicle in the hydrogen vehicle market, Hyundai Nexo [11] and Toyota Mirai [12]. Furthermore, both Hyundai [13] and Toyota [14] have chosen a low size of the battery (around 1% of the total energy stored in the hydrogen tank) which only operates when peaks of energy are encountered. The power specifications of the battery and of the FC define the Degree Of Hybridization (DOH) of the vehicle, it is defined as the ratio between the maximum power of the battery and the total power of the powertrain. The equation 2.1 gives the DOH formulation, where $P_{\mathrm{b,MAX}}$ is the maximum power available from the battery and $P_{\mathrm{FC,MAX}}$ is the maximum power available from the fuel cell.

$$DOH = \frac{P_{\mathrm{b,MAX}}}{P_{\mathrm{b,MAX}} + P_{\mathrm{FC,MAX}}} \tag{2.1}$$

The BEV powertrain architecture is represented in the figure 2.7 and it has been analysed taking as reference the studies of Chandran et al.[15] and Frieske et al. [16]. In this case, the battery is always directly recharged by the electric grid; the energy passes through a battery charger that converts the current from an AC signal to a DC one. During the operation of the vehicle, the energy passes from the storage to the electric motor through an inverter. The fluxes of energy are controlled by means of a power management controller, which regulates the power flow to and from the battery pack as demanded by the driver's action. Analysing the powertrain topology, it is possible to differentiate

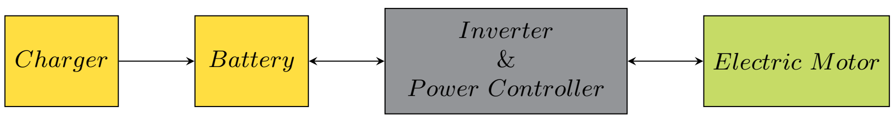


Figure 2.7: BEV - Powertrain configuration.

between a converted and dedicated system: in a converted system the BEV powertrain substitutes the fuel tank and the ICE motor of a common fossil fuel vehicle, the rest of the vehicle is totally analogous and the use of a clutch or a torque converter can be required to adapt the operation of the components; a dedicated system is designed adapting the chassis of the vehicle to the powertrain installation, that is integrated within the vehicle body. In between the dedicated systems, it is possible to distinguish four further configurations that differ for the battery pack, number of electric motors and arrangement of components:

- Out-wheel motor Rear-wheel drive: one electric motor, fixed gear and a differential.
- Out-wheel motor Front-wheel drive: one electric motor, fixed gear and a differential integrated in the front axle.
- Dual Out-wheel motors Front-wheel drive: two different motors are used with fixed gearings, the differential is eliminated.
- In-wheel motor drive: All the mechanical components are eliminated from the drivetrain. Electric motors are fitted inside all the wheels.

In the past years, the converted system has left the place to the dedicated one, which has become the main topology on the market. Among the four possible configurations, the installation of a single motor remains the most common choice between the OEMs despite the increase of vehicles with the double motor. The In-wheel motor drive remains a solution mainly adopted for luxury models.

Finally, the ICEV powertrain is studied according to the studies of Cardoso et al. [17] and Kathiresh et al. [18]. Not being an electrified technology, it is based on the direct conversion of chemical energy into mechanical one. It is possible to distinguish between two types of ICEVs: spark ignition (SI) vehicles are fueled by gasoline and are ignited by the introduction of a spark, compression ignition (CI) vehicles use diesel and are ignited by compressing the air until the auto-ignition temperature of the fuel.
As said, in this work only diesel vehicles are considered in order to go into more in detail about the cost of one precise technology. The classical topology, represented by the chain Fuel Tank - Engine - Transmission system, is considered the reference one for this thesis, it is represented in the figure 2.8. In the last years, a fairly common configuration among manufacturers provides the use of a micro

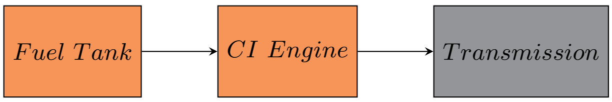


Figure 2.8: Compression ignition ICE - Reference powertrain configuration.

electric motor, usually of power around 5 kW, together with a battery, linked with a belt drive to the ICE to help it during the start-up, improving the fuel efficiency between 5% and 15% in urban driving conditions with respect to a vehicle without EM and permitting also a start-stop action. For this last topology (Micro hybrid Configuration), some improvements have been developed in the last years, previously a 12V battery was used both to power the EM and the vehicle accessories like light and air conditioning; the result of this configuration is a low efficiency due to the low voltage of the battery. Recently, the development in capacitors storage and converters allowed the transition to a 48V battery to power the EM, permitting it to recover more energy in a shorter period of time.
The use of an electric motor is not considered for the reference model taken into account in this work because, despite the fact that the vehicle is propelled only from the ICE during the travel, from a theoretical point of view this configuration belongs to the category of the Hybrid Electric Vehicles. For completeness, the MHEV powertrain is represented in figure 2.9.

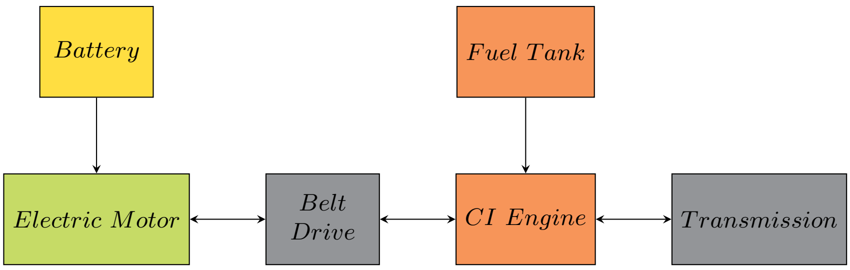


Figure 2.9: Compression ignition ICE - MHEV powertrain configuration.

2.3.2 Fuel cell

The development of fuel cell technologies has come to the fore in recent years due to the always more insistent request for no pollutant solutions. Their eclecticism coupled with their high efficiency and

capacity factor makes them the most promising technology to develop sustainable solutions both in the mobility sector and in the production of energy, indeed their use permits the production of energy obtaining water as a waste product from the reaction between hydrogen and air, also if, depending on the technologies, different fuels and reactions can be involved. The fuel cell system is composed of the union of a stack, made of many cells stacked together in series or parallel depending on the required specifications, and all the balance of plant (BOP) components. The base unit that composes the system is the MEA, made by the union of the two electrodes, the anode and cathode, and the electrolyte. The electrodes are required to have a structure that permits the continuous diffusion of the reagents and also for a high ionic and electrical conductivity, required to facilitate the development of the reactions, always helped by the presence of a catalyst which depends on the specific technology of the cell. The transport of the ions from the cathode to the anode is allowed by the electrolyte, which is required to have optimal ionic conduction and low electric conduction to avoid the short circuit between the electrodes. The cell is then completed by stacking the single units using a bipolar plate that, apart from its importance for the structural properties of the system, has the role of conducting the electrons from the anode to the cathode of two neighbours cells, containing at the same time the channels for the distribution of the reactants. The categorization of the different FC technologies is made depending on the electrolyte, the most important component because of its influence on the partial reactions at the electrodes, which depend on the ions that can be transported through it, and because of its properties, which define the FC working conditions and the Balance of Plant setup.
In this subsection, after a brief overview of the fuel cell technology [19, 20], the choice of the Polymeric Electrolyte Membrane as lead technology for automotive applications is justified before analysing its setup in the LDVs application [21], considering how the price is influenced by the production rate and which are the components that have the major role in their cost reduction.
Five FC technologies, using hydrogen as fuel have been considered:

- Proton Exchange Membrane Fuel Cells (PEMFC);
- Phosphoric Acid Fuel Cells (PAFC);
- Molten Carbonates Fuel Cells (MCFC);
- Solid Oxide Fuel Cells (SOFC);
- Alkaline Fuel Cells (AFC);

They have been catalogued in the table 2.10, highlighting their properties in terms of materials, characteristics, advantages, and drawbacks.

The most developed and diffused technologies are PEMFC and SOFC, they share the entire hydrogen-powered fuel cell market. The SOFC technology has great potential in the large distributed generation field while the PEMFC is the most diffused technology (66% of the total fuel cell market share in 2021, [22]) for its great potential in the small distributed generation and, above all, in the mobility sector. Its temperature of operation in fact is suitable for the vehicle operating conditions and the good dynamic performances, coupled with the use of a battery, suit good the power profile required from the vehicle usage.
Going more in detail about the composition of the stack (figure 2.10, [23]), the complex chemical structure of the electrolyte, made of Nafion being perfluorosulfonic acid (PFSA), permits the conduction of H^+ ions thanks to the bonds created with the water molecules, the reason why the electrolyte needs always to be hydrated. This last condition imposes the limit on the operational temperature of the system, which can not exceed 100 °C, except for the case of working pressure higher than the atmospheric one. As said, the electrodes are made of carbon, because of its capability to resist an oxidative atmosphere and platinum as a catalyst. The electrode can be divided into three layers: gas diffusion layer, microporous layer and catalyst layer. While the first two layers have the role of permitting the conduction of the electrons to the bipolar plate and the diffusion of the reactants, the catalyst layer is in direct contact with the electrolyte, it is highly porous, being required a high specific surface to permit contact between the reactants and the release of the products. Platinum has been selected because the low-temperature operation requires an outstanding catalyst but on the other side its rarity, requirement for high hydrogen purity and expensiveness are leading the research of new catalysts. The bipolar plate is made of graphite. This material, despite its brittle nature, has really good properties in terms of thermal and electrical conductivity, corrosion resistance, and gas absorbency.

Given the basic configuration of the stack, the correct operating conditions are guaranteed by all the

Type	Materials	Characteristics	Adv.&Draw.
PEMFC	• Electrolyte: Solid organic polymer poly-perfluorosulfonic acid; • Electrode: Carbon; • Catalyst: Platinum; • Interconnector: Carbon or metal;	• Ion conducted: H^+; • Operating T: 80°C; • Efficiency: 60%;	+ Reduced corrosion; + Low temperature; + Quick startup; + Good dynamic performances; - Expensive catalyst; - Sensitive to fuel impurities;
PAFC	• Electrolyte: Liquid phosphoric acid; • Electrode: Carbon; • Catalyst: Platinum; • Interconnector: Graphite;	• Ion conducted: H^+ • Operating T: 200°C; • Efficiency: >40%;	+ High fuel flexibility; + Suitable for CHP; - Expensive catalyst; - Slow startup; - Sensitive to sulphur;
MCFC	• Electrolyte: Molten carbonate salts; • Electrode: Nickel (oxide); • Catalyst: Nickel (oxide); • Interconnector: Stainless steel-based;	• Ion conducted: CO_3^2- • Operating T: 650°C • Efficiency: 45-47%;	+ High fuel flexibility; + Suitable for CHP; + Suitable with turbines; - High corrosion; - Slow startup; - Low power density;
SOFC	• Electrolyte: Yttria-stabilized zirconia; • Electrode: Yttria-stabilized zirconia cermet - Strontium-doped lanthanum-manganite; • Catalyst: nickel; • Interconnector: Steel, ceramic or nickel;	• Ion conducted: O^{2-} • Operating T: 1000 °C • Efficiency: 60-65%;	+ High fuel flexibility; + Suitable for CHP; + Suitable with turbines; - High corrosion; - Slow startup; - Sensitive to shutdown frequency;
AFC	• Electrolyte: Aqueous potassium hydroxite • Electrode: Transition metals; • Catalyst: Platinum; • Interconnector: Metal;	• Ion conducted: OH^- • Operating T: 60-70°C • Efficiency: 60%;	+ Reduced costs; + Low temperature; + Quick startup; - Low electrolyte conductivity; - Electrolyte maintenance; - Sensitive to CO_2;

Table 2.10: Fuel cell technologies categorization.

equipment which compose the balance of plant. In accordance with the Toyota Mirai setup, the BOP is made of four main parts (figure 2.11, [21]):

- Air supply system: air is cleaned, compressed and cooled before being pumped inside the cell and a muffler is used to reduce the sound. In the last years, the system has been simplified by removing the humidifier thanks to the self-humidifying behaviour of the stack. This technological choice allow also a consistent decrease in cost and space.

- Hydrogen supply system: the hydrogen is decompressed from the initial pressure of the storage tanks to the operating pressure of the stack through a series of valves. Not all the hydrogen flux is able to react inside the stack and, for this reason, a recirculation circuit is installed with the aim of recovering it.

- Cooling system: the conversion of hydrogen and air in energy and water is an exothermic reaction. For this reason, the installation of a cooling system, using water as a coolant, is

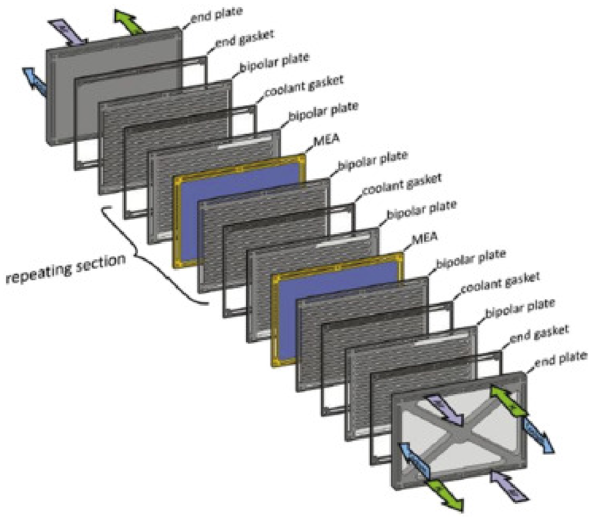


Figure 2.10: Fuel cell stack composition.

necessary to remove the heat from the stack.

- Process and controlling components: the setup is completed by a series of valves and sensors to manage the stack operation and control that all the parameters are in the correct ranges.

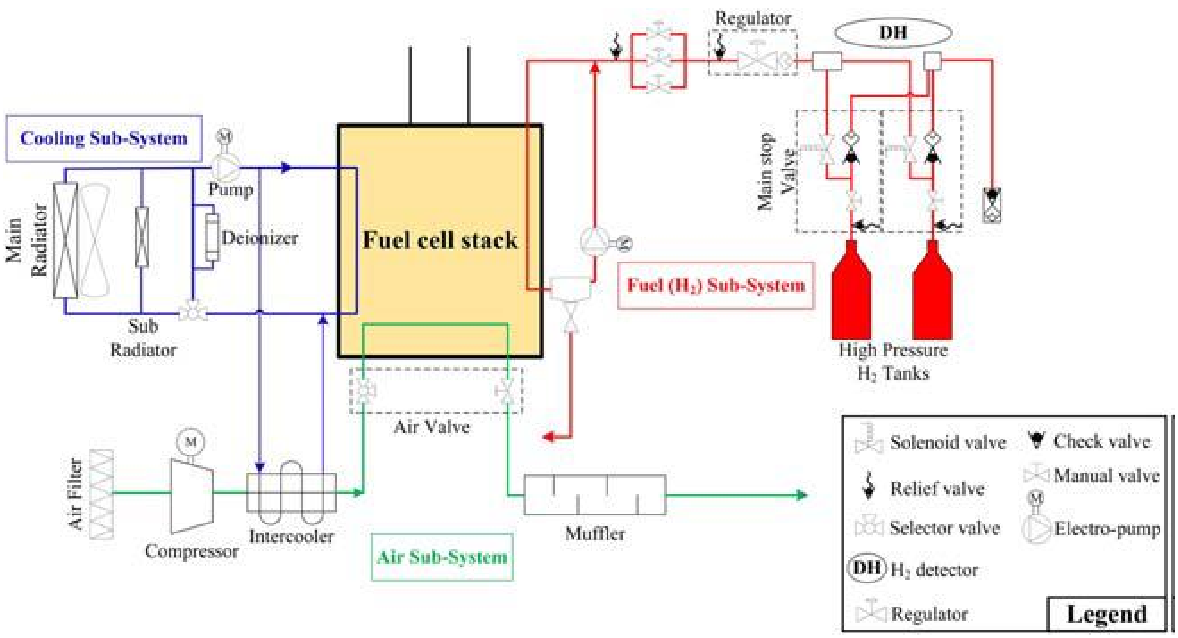


Figure 2.11: PEM fuel cells system configuration.

All the components of the BOP are crucial to allow an improvement in the system performances, indeed, the current fuel cell used in the automotive field is still far from the maximum performance in durability and from the ultimate target costs, despite the great potential reached regarding specific power and power density of the system, added to the capability of starting the fuel cell operation from a temperature of less than -20°C in less than 30 seconds. The role of the BOP is important not only from a technological point of view but also for the big share in the total cell manufacturing cost. It is important to specify that is not possible to assign a specific price to the fuel cell without considering the production rate with which the manufacturer is able to produce. So, the specific price of the fuel cell system (€$/kW$), made of the cost of the stack plus BOP and assembly and normalised respect to the maximum net power is assigned to a production rate of 1.000 systems/year in the low production scenario and to a production rate of 500.000 systems/year in the high production rate scenario. The

production rate influences the cost mainly with regards to the stack cost, which from 1.000 to 500.000 systems per year, can decrease its costs up to 85%. In this last case, the BOP becomes the most relevant cost inside the FC system (56%).
All the data containing the share of the singles components of the systems are reported in figure 2.12 according to [24], while the final cost assumptions (table 2.11) are the output of a bibliography review, where the results have been catalogued also considering the relevance of the work under analysis and subsequently compared with the data given by a relevant fuel cell company during an interview targeted to clarify current data on performances and costs.
Given the lack of data regarding all the years of the timeframe some hypotheses have to be done to

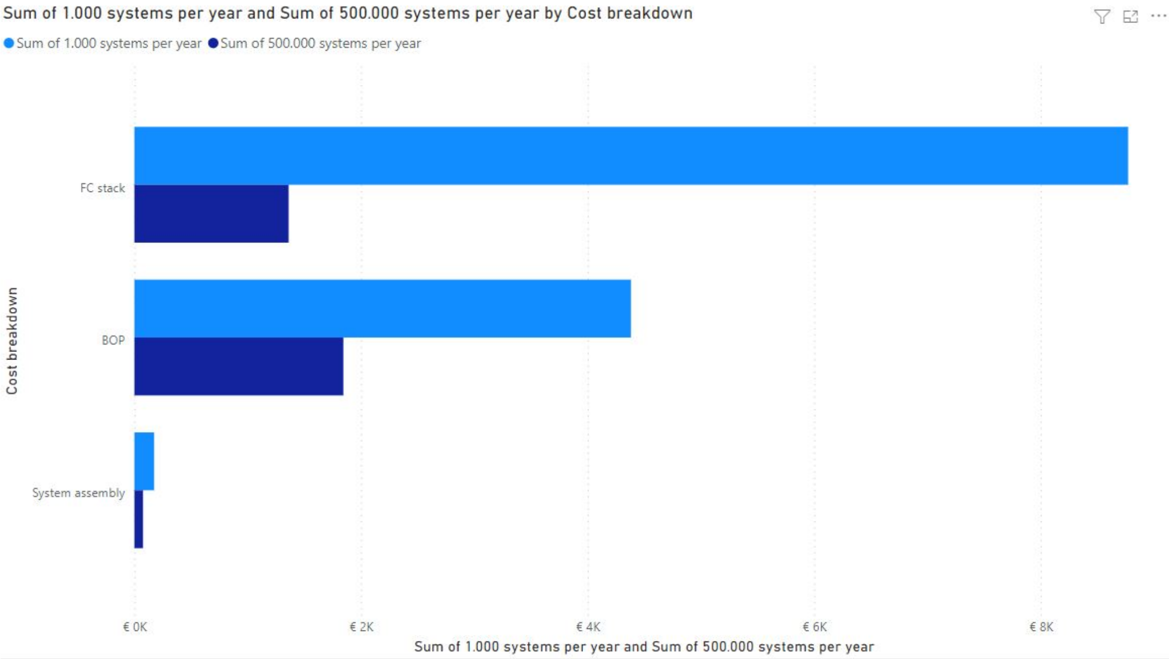


Figure 2.12: PEM fuel cell cost breakdown.

	Price (€/kW)		
Author	Low Production Rate	High Production Rate	Ultimate
Kaur et al. [21]	166,5	41,0	35,3 with HPR in 2025
IEA. [25]	184,0	-	46,0 ultimate
Thompson et al. [26]	-	41,4	36,8 in 2025, 27,6 ultimate
Nassif et al. [11]	164,7	41,4	-
Kleen et al. [24]	-	42,3	36,8 in 2025, 27,6 ultimate
Almeida et al. [27]	156,4	-	-
Average	**167,9**	**41,5**	**36,3 in 2025, 33,7 ultimate**

Table 2.11: Fuel cell price bibliography review.

create a valid trend for the fuel cell cost forecast:

- A complete diffusion of the fuel cell technology is supposed also for the low production rate scenario.
- The ultimate price is supposed to be reached in 2035 for the low production rate scenario and in 2030 for the high production rate scenario.
- The price obtained for the year 2025 is considered valid for the high production rate only.
- A linear interpolation is supposed to link the data.

Considering the hypothesis just exposed the final assumptions for the fuel cells cost are given in table 2.12:

	Price (€/kW)	
	Low Production Rate	High Production Rate
2020	167,9	41,5
2025	123,2	36,3
2030	78,4	33,7
2035	33,7	33,7
2050	33,7	33,7

Table 2.12: Fuel cell final price assumption.

2.3.3 Hydrogen storage

In this subsection, state-of-the-art and perspectives on hydrogen storage technologies are exposed in accordance with [28, 29, 30, 31, 32, 33]. To understand the main characteristics and critical issues of this topic it is necessary to start from the hydrogen properties. Hydrogen, indeed, is characterized by a good energy density of 33,33 kWh/kg but its low volumetric density and liquefaction temperature, respectively 0.0899k g/m3 (1 atm and 0°C) and -253°C, make impossible its storage at ambient pressure and temperature, resulting in a final volumetric energy density 3490 times lower than gasoline (0,01 MJ/L with respect 34,90 MJ/kg). This condition toke out the necessity of finding strategies to store hydrogen obtaining optimum results in terms of energy for volume of storage, total weight and efficiency. The main existing technologies are resumed in the following item:

- Established technologies:
  - Compressed gas hydrogen (CGH2): physical-based technology used to store the hydrogen in gaseous form in a range from 20 bar to 1000 bar. It is mainly used for delivery and automotive applications in tanks of 350 bar and 700 bar, depending on the usage. In the LD applications, due to the lack of spaces, a pressure of 700 bars is generally required, in contrast with the 350 bars that are allowed by the HDV powertrains;
  - Liquid hydrogen (LH2): physical-based technology consisting in a thermodynamic cycle aimed to liquefy hydrogen reaching a temperature of 20,3 K. The liquid hydrogen has a really high density (79,9 kg/m3 at 1 atm) but it is characterized by losses, due to the evolution of the para/ortho equilibrium with temperature, which has to be minimized by means of a special vacuum-insulated tank. The main limit of this technology is the high quantity of energy required for the conversion. The use of LH2 storage technology is no longer considered for automotive applications after some attempts made by BMW and other constructors.
- Under investigation:
  - Cryo-Compressed Hydrogen (CcH2): this solution is an average between the two solutions already exposed, compressing low-temperature hydrogen to store it obtaining lower losses and lower energy consumption with respect to LH2. The technology is under development but has been already demonstrated that better storage densities and lower costs can be obtained with respect to the CGH2;
  - Metal hydrides (MH): Material base solution, consists of the usage of the absorption properties of some materials to store hydrogen in a solid form, releasing heat during the H2 absorption and requiring a heat supply during the desorption. Regarding the usage as storage for LDVs, this technology guarantees optimal results in terms of compactness, simplicity and low-pressure operation with some problems linked to the operation during peaks of power, for this last reason hybrid solutions with both MH and CcH2 are under development.
  - Liquid Organic Hydrogen Carriers (LOHC): this technology consists in liquid carriers capable to store hydrogen with chemical bonds. This technology shows advantages linked

to its low flammability, low explosive and toxic nature, characteristics that classify it as not dangerous by the ADR regulation. On the other side its usage is only possible for the transport of hydrogen, with a lack of application in the LDVs field;

As explained, the only technology of current interest for the LDVs and for this reason also the unique that is going to be considered in this study is the CGH2. It is characterized by the possible use of five typologies of tanks (figure 2.13, [34]), characterized by different structures and materials which lead to different results in terms of cost and weight and which can be convenient or not depending on the final application of the tank or on the pressure level required.

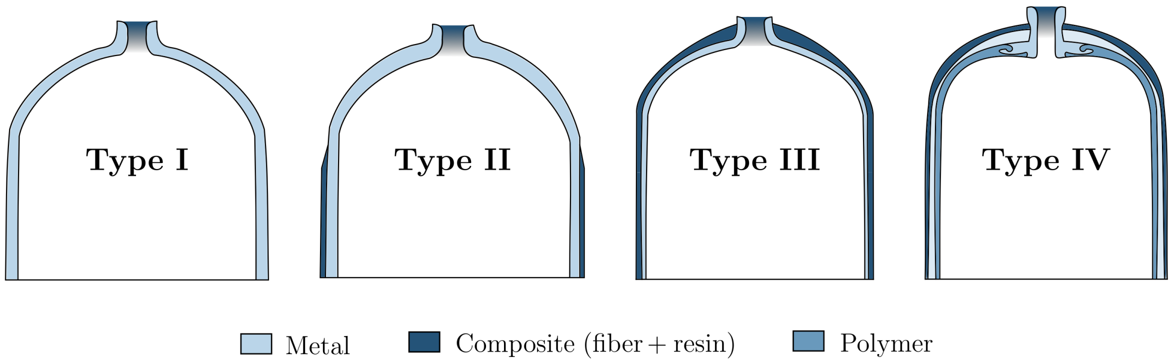


Figure 2.13: Hydrogen storage tank typologies.

- Type I: completely done of metal, typically steel, it is really heavy but inexpensive because of the low cost materials and the already mature technology. Its heaviness makes it not adapt to the on-board storage, reason why it is mainly used for the stock of hydrogen in industrial applications with a maximum pressure of 50 bar. The presence of metal in the internal layer makes this tank subjected to hydrogen permeation and prone to hydrogen embrittlement.
- Type II: in this type of tank the metal vessel is wounded with a resin-impregnated continuous filament of carbon fiber in order to increase its robustness and distribution of the load. This design results in a higher cost (around 50%) but also in a stronger and lighter (weight 30-40% lower) tank with respect to a Type I tank.
- Type III: The entire metal structure is covered by the resin-impregnated continuous filament of carbon fiber. The metal structure has mainly sealing purposes, sharing just the 5% of mechanical load. This configuration results in a lower weight and in a higher cost with respect to the previous technologies.
- Type IV: non-load-bearing polymeric liner axial and hoop wrapped with resin-impregnated continuous filament. Significant reduction in weight and increase in cost. The use of polymers for the internal layer allows this technology to have a low rate of hydrogen permeation through the walls. Type IV pressure vessels can withstand pressures up to 100 MPa.
- Type V: In the last years some prototypes of tanks without a liner and entirely done with composite materials have been produced, trying to offer a further 10-20% weight reduction with respect to Type IV vessels. This type of tank is still pre-commercial and it is not going to be analysed in this work, having an operational pressure of 13 bar, far from the onboard applications.

The Type IV tank is the one on which this work is focused because of its major use in onboard applications despite its higher cost, due to its lower weight, which allows a better fuel economy and a higher load-carrying capacity for Heavy Duty vehicles. It can operate in a temperature range between -40°C and 85°C and it is usually programmed to activate the safety procedure with a temperature of 110°C. The tank is usually created to last 20 years also if the lifetime can be influenced by the operation in low-pressure conditions, which can damage the liner. For this last reason, the manufacturers consider usually a minimum pressure operation of 20 bars that permits the use of only 92% of the tank considering a maximum pressure of 700 bar. Looking at the onboard application of storage tanks inside LDVs, the storage system is composed of one or several high-pressure tanks and one on-tank valve for each of them. The number of vessels is chosen in accordance with the problems of space, position and integration. An example of a vessel for Onboard applications is represented in figure 2.14 [35]. Looking at the costs of the single components of the storage, a consistent share of the

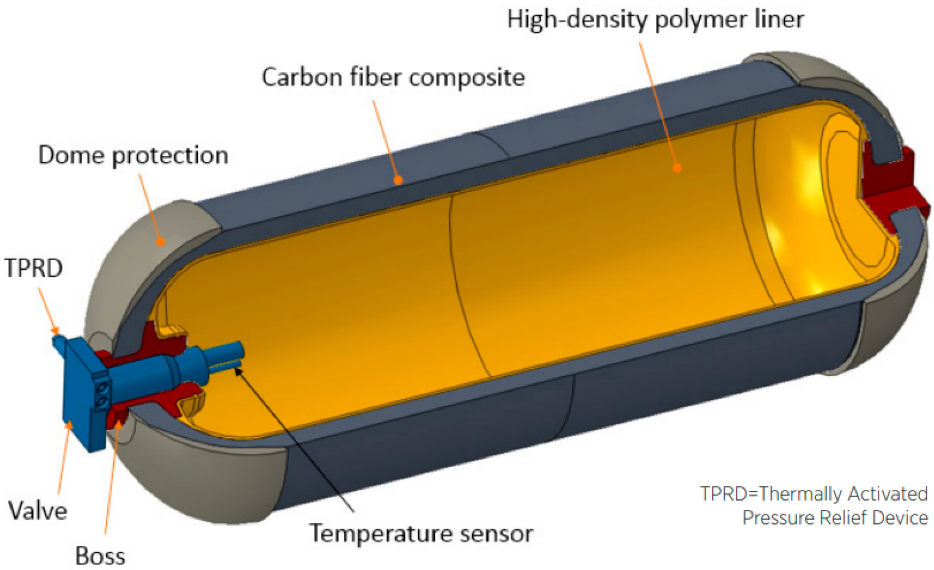


Figure 2.14: Hydrogen storage tank system.

cost is given by the valve system, in particular for low production rates. In automotive applications, the installation of a valve for each tank is mandatory for safety reasons; the thermal pressure release device (TPRD) ejects all the content of the vessel when an external temperature of 108°C-110°C is reached. Once activated the installation of a new TPRD is required to refuel again the tank.
As previously mentioned, the cost of the tank, as the fuel cell, is really sensitive to its production rate and, for this reason, a bibliography review has been performed (table 2.13) to assess the cost of the storage for both a "low production rate" (10.000 systems/year) and a "high production rate" (500.000 systems/year) scenarios, together with the "Ultimate" price that consists in the final forecasted price when the hydrogen storage market will be completely developed. In both the actual scenarios, the cost of the carbon fiber is the biggest percentage of the storage cost (42% for the LPR and 55% for HPR, figures 2.15 and 2.16 [11]), this trend is given by the 53% decrease in the BOP cost, the most sensitive part to the change in production rate.

	Price (€/kWh)		
Author	Low Production Rate	High Production Rate	Ultimate
Houchins et al. [36]	24,6	14,7	-
Rivard et al.[37]	13,8	9,2	7,4
IEA [25]	15	-	9
Strategic Analysis et al.[38]	-	13	-
Nassif et al.[11]	18,4	13,8	7,4
Elementenergy [39]	19,4	14,5	9,1
Hua et al. [40]	17,2	12,4	-
Average	**18,1**	**12,9**	**8,2**

Table 2.13: Hydrogen tank price bibliography review.

Given the prices for the three scenarios, the following assumptions have been done to assign a price for each year of the timeframe:

- The total penetration of the storage tanks inside the market is assumed to happen in the year 2035.
- The Ultimate price is assumed as reached with both scenarios.

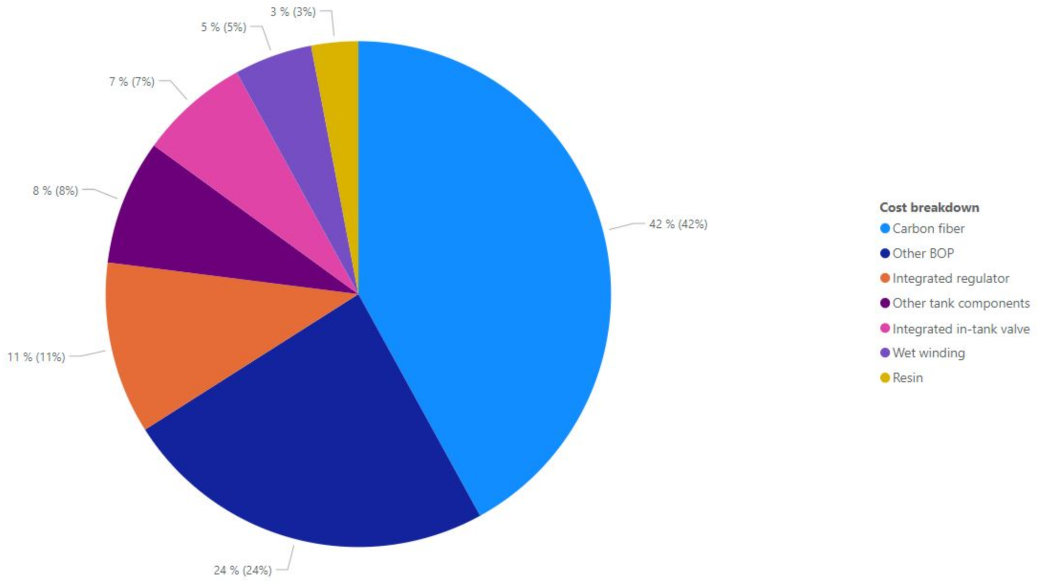


Figure 2.15: Hydrogen storage tank cost breakdown 10.000 systems/year.

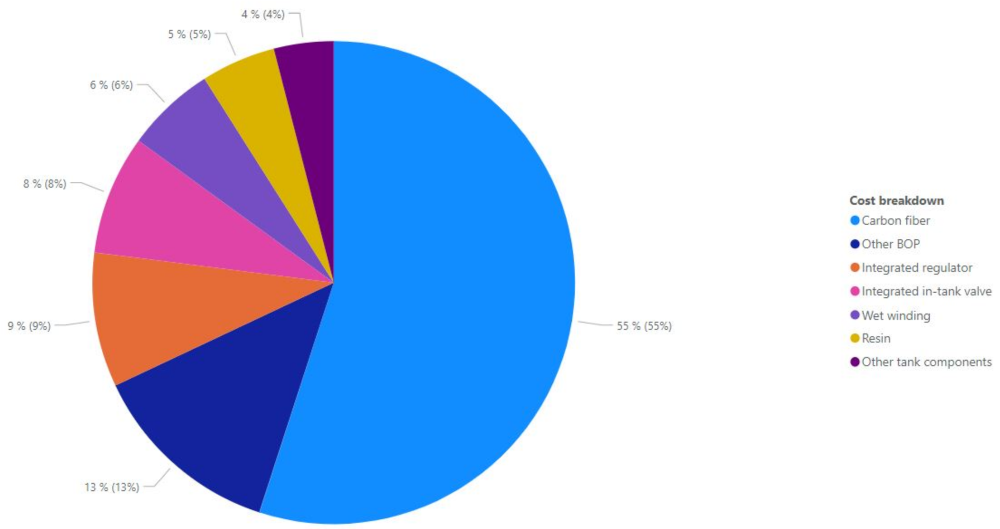


Figure 2.16: Hydrogen storage tank cost breakdown 500.000 systems/year.

- The price is considered constant after 2035.
- A linear interpolation is used to calculate the prices for the time interval between 2020 and 2035.

Given the itemized assumption the final prices assumed for the TCO calculation are resumed in the table 2.14.

2.3.4 Electric motor

In this subsection, an overview of all the types of electric motors that suit the requirements for LDV is given, explaining which technology is currently mainly used in the market following the studies of Chandran et al. [15], Frieske et al. [16], Agamloh et al. [41], Chau et al. [42], and Kathiresh et al.

	Price (€/kWh)	
	Low Production Rate	High Production Rate
2020	18,1	12,9
2025	14,8	11,3
2030	11,5	9,8
2035	8,2	8,2
2050	8,2	8,2

Table 2.14: Hydrogen tank final price assumption.

[18] and the internet pages [43, 44, 45].
The difficulties in this argument are given by the fact that many EV manufacturers do not publish a technical review on the design of their EM and, also when technical papers are published, the design details are not always explicated. Due to the necessity of handling different driving tasks, the EM must be characterized by high maximum torque, high power, high efficiency through a wide range of speeds, small size, low cost, robustness against high temperatures and vibrations and good reliability independently from the motor type. In addition, considering that the motor operates as a generator during the brakes, converting the kinetic energy into electricity, also the efficiency of the regenerative braking must be considered. Once analysed all these parameters, the motor type, size, weight, and performance are given considering also the overall powertrain specifications.
As previously said for what regards the position of the motor inside the vehicle, considering the BEVs it is possible to choose between different powertrain configurations that provide different positions of the EM inside the chassis. Looking at the FCEVs, the position of the motor is subjected to more constraints, because of the bigger volume occupied by the hydrogen storage and the fuel cell which makes it easier, also for safety reasons, the positioning of the motor in the front of the vehicle.
From the bibliography, five different types of EM are been identified and they are described in the following item:

- DC Motor: Widely used in the 1990s, it is featured by high torque at low speed. The stator is made by a permanent magnet while the power is provided to the rotor using brushes. This kind of motor is no longer used, despite its low cost, because of its high heat generation, low lifetime, high maintenance cost, and bulkiness; characteristics due to the direct contact of the brushes with the stator. This technology is the only one that requires a commutator between all the listed.

- Brushless DC Motor: The operating principle of this motor is the same as the brushed one but the absence of brushes, substituted by an amplifier activated by a switching device, results in higher efficiency, lower maintenance cost, longer lifetime and better heat dissipation. It can be used in a vehicle that requires a maximum power of 60 kW and, for this reason, it has not been taken into account for the vehicle modelling of this study.

- PM Synchronous Motor: the PMSM is a brushless AC motor characterized by a compact design, which makes them eligible for in-wheel configurations. In this case, a three-phase supply is used to energize the stator winding, creating a rotating magnetic field which excites the poles of the rotor, made by permanent magnets. It can operate without gearing at a wide range of speeds ensuring a high efficiency (90-95%), high effectiveness and high power density, reason for which it has been chosen by many makers. The main drawback of the motor is its high cost, caused by the materials used for the magnet, together with the lower productivity at large speeds and losses at the stator caused by the requirement for additional current segment used for field debilitating.

- Switched Reluctance Motor: The SRMs, known as doubly salient motors, are simple and typified by high reliability and robustness, which added to their low cost, high operational speed, high constant power range and power density, have attracted the attention of recent times because of the high cost of the PM motors. Its working principle is based on the creation of a rotating magnetic field with the help of a power electronics switching circuit inside the stator with the rotor movement based on the variable reluctance principle. On the other side, large size, noisy operation and heaviness inspire the makers to continue researching and developing this kind of motor.

- Induction Motor: In the three-phase AC induction motor (IM), the electric current in the rotor needed to produce torque is obtained via electromagnetic induction from the rotating magnetic field of the stator winding. It has very good characteristics in terms of reliability and quality, but disadvantages concerning power density, efficiency, volume/weight ratio and controllability. It is possible to distinguish between two types of IM: wound rotor and cage rotor. Because of its higher cost and need for maintenance, the wound rotor is less attractive than the cage rotor, which is used for EVs because of its maturity and low-cost both in maintenance and capital expenditure.

The main characteristics of the motors presented are resumed in the table 2.15 ([42]), to compare them in terms of power density, efficiency, controllability, reliability, maturity, cost level, noise level and maintenance on a scale from 1 to 5 where 1 is the worst score and 5 the best. At the same time, the motor type of some commercial EV is resumed in the table 2.16 ([42]).

	DC	BLDC	PM Syn	SR	Ind
Power density	2	5	4,5	3,5	3
Efficiency	2	5	4,5	3,5	3
Controllability	5	4	4	3	4
Reliability	3	4	4	5	5
Maturity	5	4	5	4	5
Cost level	4	3	3	4	5
Noise level	3	5	5	2	5
Maintenance	1	5	5	5	5
Total	25	35	35	30	35

Table 2.15: Comparison between motor technologies.

Motor type	Car models
DC	Fiat Panda Elettra, Citroen Berling Electrique, Reva g-Wiz DC
Brushless DC	Smart Forttwo ED, Honda Civic Hybrid
PM Synchronous	Nissan Leaf, Mitsubishi i-MiEV, Citroen C-Zero, Peugeot iOn, BYD e6, Toyota Prius, Ford Fusion Hybrid
Switched Reluctance	Chloride Lucas, Holden ECOmmodore
Induction	GM EV1, BMW Mini E, Tesla Roadster, Reva G-Wiz i, GM Chevy Volt, Imperia GP

Table 2.16: Motor type in some commercial EV.

The analysis shows that the IM and PMSM are the main technologies chosen from the Electric Vehicle manufacturers. The bibliography review evidences how the use of Permanent Magnet Synchronous Motors with respect to Induction Machines is preferred, giving primary importance to power density and efficiency with respect to reliability and cost. This trend is expected also for the future, given the always increasing request for energy efficiency to have a limited impact on the environment, with Reluctance Machines, which utilization is quite rare in the current applications, as possible outsiders being expected their penetration inside the market after solving the main drawbacks of the technology.

Once analysed the technical features, it is possible to switch to cost estimation of the motors. Regarding it, different results have been found by all the authors. All the data catalogued, normalized for the peak power of the motor, are reported in the table 2.17. The different magnitude of the prices is given by the different components considered inside the price, which sometimes does not include just the EM but also other components like the inverter, the transmission system or the controller. Considering this last aspect, the prices are quite coherent among all the authors. Finally, an average between all the values including just the general EM price estimation has been considered, with a view to obtaining an estimation of every single component without aggregating their prices in order to use the most precise approach possible. Unfortunately, the literature does not provide price differentiation between the different kinds of electric motors, apart from Fries, that however includes also the transmission costs. In the end, after calculating an average price of 8,9 € for the general EM an 11% (calculated considering the relative difference of the EM prices from the average in Fries's study) has been added as hypothesis to differentiate between the PMSM, chosen as reference technology for this work in accordance with the literature, and the IM. The final price, equal to 9,9 €/kW has been considered constant during the timeframe, being the technology already affirmed.

Author	Price
Handwerker [46]	Cost of 7 €/kW for general EM.
IEA [25]	Cost of 13 €/kW for general EM.
Lutesey [47]	Cost of 7,5 €/kW for general EM.
Elementenergy [39]	Cost of 24,7 €/kW for EM, controller and inverter.
Fries [48]	Cost of 10 €/kW for PMSM and transmission, 8 €/kW for IM and transmission.
Hill [49]	Cost of 8 €/kW plus a fixed cost of 50 € for general EM and 460 € for the EV transmission.

Table 2.17: Motor price bibliography review.

2.3.5 Battery

A battery is an electrochemical device for the storage of electrical energy. It is composed of many cells stacked together, each one made, in its basic configuration, by two electrodes (anode and cathode) physically divided from a permeable electrically insulating layer and submerged in an electrolyte. The presence of a slow discharge also when the system is not working makes this technology not appropriate for long-term storage. [15]
This sector is of great importance in the current energy transition, having a crucial role not only in E-mobility but also as stationary energy storage for the production of energy from renewable energy sources. The great request for better performances and specifications is boosting the research in this matter, looking for new materials and solutions. Being required lightweight, high power, fast charging cycle or low cost depending on the final usage of the storage, the materials that compose it and its morphology can vary and, for this reason, there is no winner between all the battery technology available. This subsection exposes the main technology available in the market, their field of application, and their future perspective. Finally, a review of cost is made to assess the current cost and their future evolution, which correct evaluation is fundamental to calculate actual and future BEVs costs.
From the bibliography, six main chemistries have been listed in the table 2.18 [18] together with their advantages and drawbacks. Of all the technology presented, the Lithium-ion one is the one that took the electric vehicle market for its really good performance in terms of efficiency, lifetime and energy and power density which permits limiting the weight of the storage inside the vehicle. Despite the still high cost, their massive use in electric vehicles decreased the price since their first usage and the great current investment in their R&D can make performances and prices still more convenient for automotive applications. A general battery configuration inside an EV is represented in figure 2.17, [50]. Inside the Lithium-ion battery family, it is possible to distinguish six different chemistries that are available in the market:

- Lithium Cobalt Oxide (LCO);

Type	Advantages	Drawbacks
Lead-acid	• Low cost; • Fast recharge capability; • High specific power; • Robustness to temperature variation;	• Low specific energy; • Low energy density; • Limited cycle life;
Alkaline	• Long cycle life; • Rapid recharge capability; • Wide operating temperature range; • Low self discharge rate;	• High initial cost; • Poor specific energy;
Nickel Metal Hybrid	• High specific energy; • High energy density; • Long cycle life; • Environmentally friendly; • Fast recharge capability; • Wide operating temperature range;	• High starting cost;
Nickel-Zinc	• High specific energy; • High Power density; • Cheap cost materials; • Depp cycle capability, • Resonably wide operating temperature range;	• Low cycle life;
Lithium-ion	• High energy density; • Great performances at high temperatures; • High specific power; • High specific energy; • Long cycle life;	• High cost; • Rapid self-discharge rate;
Sodium-Nickel Chloride	• Sodium as advantageous material;	• High-temperature operation;

Table 2.18: Battery technologies advantages and drawbacks.

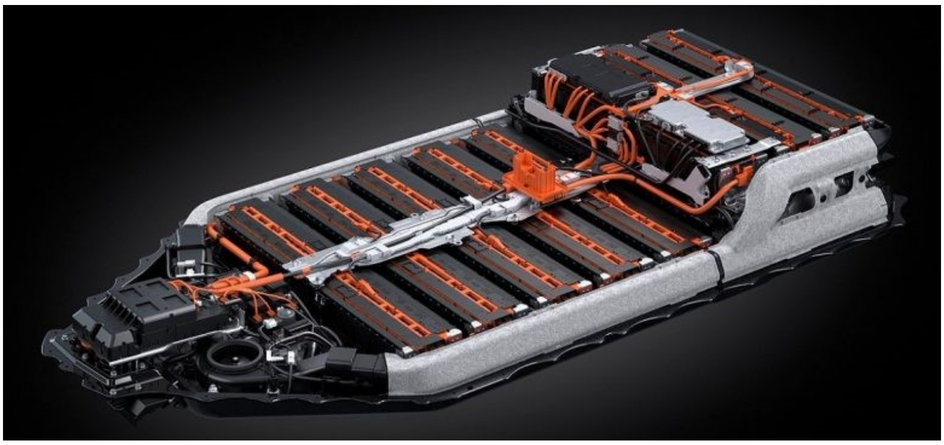


Figure 2.17: Battery in BEV applications.

- Lithium Manganese Oxide (LMO);
- Lithium Iron Phosphate (LFP);

- Lithium Nickel Cobalt Aluminium Oxide (NCA);
- Lithium Nickel Manganese Cobalt Oxide (NMC);
- Lithium Titanate (LTO);

The difference among them is basically given by the material which composes the cathode, being the anode made of graphite in the first five chemistries, only the LTO has the cathode made of graphite and the battery technology receives its name from the material in the anode. The difference between the chemistries presented is evaluated accordingly with six parameters: Performance, Specific Power, Cost, Safety, Lifetime and Specific Energy (figure 2.18, [51]). Figure 2.18 highlights the difference be-

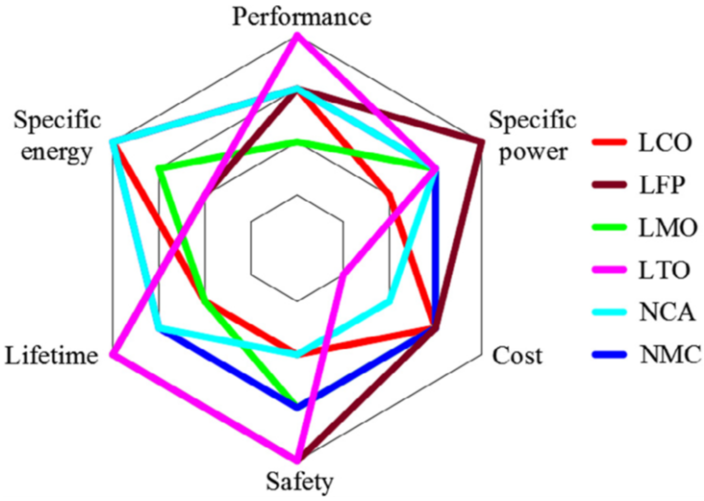


Figure 2.18: Lithium-ion chemistries characteristics.

tween the chemistries that contain cobalt, characterized by a higher energy density and power capacity but also with criticalities linked to safety and lifespan, and LFP and LTO batteries which excel in cyclability and safety and suffer in energy and power densities. These considerations are not valid for LMO and NMC, in fact, the former is the poorest chemistry among the ones presented, and the latter is applicable in every field, being the best compromise considering all the parameters. The choice of favourite chemistry for the automotive application is bonded to the considerations just done, the lack of stability that characterize the LCO batteries makes them not suitable for their usage in vehicles, despite their important role in consumer electronics, and so the most relevant potential for the use in the vehicle market is assigned to LMO, NMC, NCA and LFP, not only for their better stability (apart from NCA, preferred to LCO probably for its longer lifetime) but also for lower cost and abundant resources. These chemistries have been used by many car makers in the last years, such as Tesla, BMW, BYD, Chevrolet, Mercedes Benz-Daimler, Volkswagen and Nissan. In 2016 the 83% of the total Lithium market share was taken by NMC, LFP and LCO; statistical data that, considering the lead role of the LCO in electronics, makes NMC and LFP the leaders in the automotive market, with the former that is expected to reach a 41% share in 2025 from the actual 26%.
However, the use of NMC batteries is seen just as a short-term solution for the EV market, indeed the limit in their specific energy (350-400 Wh/kg) makes necessary the development of new technologies such as all-solid-state batteries (SSBs), lithium-sulfur batteries, and lithium-air batteries. Furthermore, the probable demand-supply mismatching for the Lithium resources in the long term makes crucial the improvement of the extraction technologies and the development of a proper recycling infrastructure.[52]
Also in this case, the actual prices and their forecast has been estimated by means of a bibliography review. This time, cataloguing prices for a unique scenario has been the selected strategy, considering as sure the diffusion of batteries with a high production rate. After the analysis of different authors, only the works and the data referred to the EV sector have been selected. This last choice has been done for the difficulty in obtaining data referring to the technology identified as the most convenient for the mobility sector, of consequence the different range of costs can lead to results reliable for the general estimation of the Lithium battery costs but not that accurate for the sector analysed in this work. Also in this case, the actual prices and their forecast has been estimated by means

of a bibliography review. This time, cataloguing prices for a unique scenario has been the selected strategy, considering as sure the diffusion of batteries with a high production rate. After the analysis of different authors, Mauler's review analysis [53] stands out among all the literature, identifying 53 relevant publications from an initial number of more than 2000 studies related to battery cost. The study outcome is a trend for the cost of the battery pack with an outlook to 2050 and it is resumed in the table 2.19.

Price (€/kWh)				
2020	2025	2030	2035	2050
215	155	121	100	65

Table 2.19: Battery cost final trend.

2.3.6 DC-DC and DC-AC converter

DC-DC and DC-AC (Inverters) converters have a crucial role inside the powertrain architecture, being the power electronics really important to optimize the functioning of the main components. For this reason, after a brief introduction, their application in the automotive field will be discussed, concluding the subsection with an estimation of their costs. All the considerations done are based on Katiresh et al. [18], Han et al. [54], Onar et al.[55] and Wang et al.'s [56] works.

The main components of the DC-DC converter include the electronic switch, inductor, capacitor and resistive load. Additionally, it is possible to distinguish between isolated and non-isolated converters. The isolated converters, using a transformer, permit isolating the primary circuit from the secondary circuit avoiding the travel of voltage spikes and obtaining a more secure system. The non-isolated systems do not have this last characteristic but they are preferred for automotive applications because of their lower cost and space requirements. The main non-isolated topologies are Buck, used to step down the voltage level, Boost, used to step up the voltage level, and Buck-Boost which can have both functions depending on the duty cycle.
The DC-DC converter, used in automotive applications to change the voltage level without changing the electrical power transmitted, is considered in this work for its important role inside the EVs powertrain. Indeed a bidirectional converter is always required to boost the voltage of the battery, which can vary from 100 to 400 V, to the level required from the DC bus, around 600 V. As said, the exchange of power happens in both directions, boosting the voltage during the normal operation and decreasing it during the regenerative braking and, for this reason, this converter has always to be bidirectional. The converter optimizes the powertrain operation, reducing the ripple current in the battery and helping the link voltage to the inverter.

Regarding the interface between the fuel cell and the high voltage bus in the FCEVs, the first versions of FCEVs proposed by Toyota, Honda and Hyundai, respectively Toyota FCHV-adv, Honda FCX-Clarity and Hyundai Tucson ix35, did not contain a DC-DC converter connecting the FC and the high voltage bus. The second generation of FC vehicles produced showed two different trends, Hyundai decided to continue with the same choice of not using a converter for Hyundai Nexo, while Toyota and Honda decided to introduce for Toyota Mirai and Honda Clarity Fuel Cell a boost converter between FC and DC link. This choice permitted the two manufacturers to obtain great results such as increasing motor voltage level and enhancing PEMFC power density and reliability. This last configuration, represented in figure 2.19, is the reference one selected for this thesis because of its clear advantages, making it the most probable configuration for future models.

Following, the role of the inverters inside the EV powertrain can be studied. Under the hypothesis of AC electric motor, a bidirectional DC-AC is always required in both FCEVs and BEVs to convert the current signal. Additionally, the BEV require an additional bidirectional AC-DC converter that permits the connection of the battery to the electric grid to recharge it. Also in this case the converter has to be bidirectional to allow the injection of power into the grid during the Vehicle-to-Grid mode. The charger is connected directly to the high-voltage bus, adjusting the voltage level from the 230 V of the grid to the one of the DC link. The reference scheme of the power electronic of a BEV is

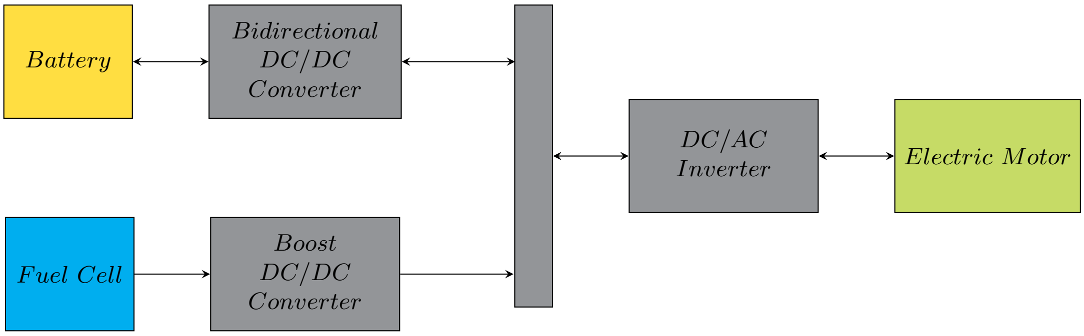


Figure 2.19: FCEV - Double DC-DC converter configuration.

reported in figure 2.20.

Finally, after considering the role of the power electronics inside the powertrain, it is possible to

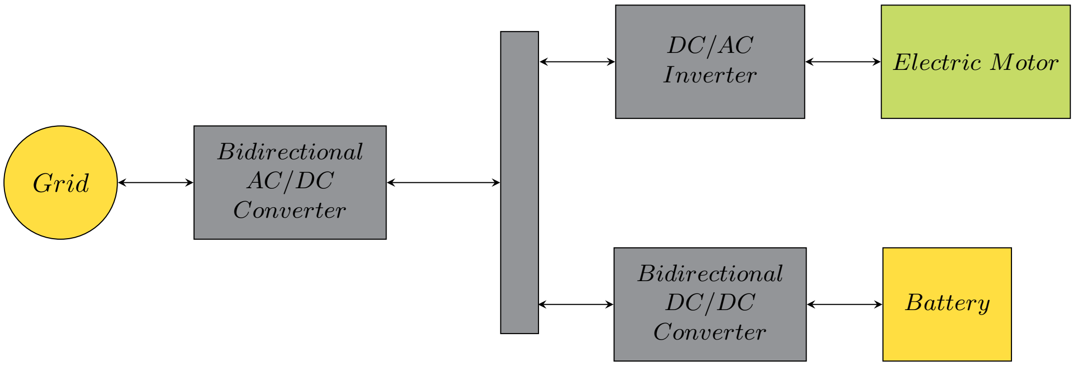


Figure 2.20: BEV - Power electronic reference configuration during charge.

evaluate its weight inside the total manufacturing cost of the vehicle. All the data obtained from the bibliography are resumed in the table 2.20. As it is possible to see, the price of the onboard charger

Author	Price
Hummel et al. [57] through Liu et al. [58]	Cost of 4,67 €/kW for the inverter, 165 € for on-board charger, 179 € for the DC-DC converter.
Lutesey et al. [47]	Cost of 251 € for the on-board charger, 138 € DC-DC converter and 641 € for the inverter of a 150 kW peak power motor.
Elementenergy [39]	Cost of 24,7 €/kW for EM, controller and inverter, 1.705 € for the additional electric powertrain components.
Fries et al.[48]	Cost of 500 € the on-board BEV charger, 190 € for a DC-DC converter and 3 €/kW for the inverter for a 90 kW nominal power motor.
Hill et al. [49]	Cost of 350 € the on-board BEV charger, 3 €/kW plus 10 € of fixed expense for a DC-DC converter and 10 €/kW plus 50 € of fixed expense for the inverter, all the data normalized on the peak power.

Table 2.20: Power electronics bibliography data.

and DC-DC converter are mostly expressed as a fixed price for the total component while the price of the inverter can be expressed as a price for a unit of peak power. Being all the analyses on the same

level of detail, there is no reason for choosing one author with respect to the others, so, an average between all the values has been done to obtain the input values for the TCO study, excluding only Elementenergy [39] for the difficulty in calculating a price for the single component, being all the powertrain costs aggregated in just two values.
The following methodology has been used:

- Arithmetic average of the total price for the onboard charger, in accordance with the literature;
- Arithmetic average of the total price for the DC-DC converter, when a price for a unit of power has been found the total cost has been calculated considering a motor peak power of 150 kW;
- Arithmetic average of the price for a unit of peak power for the inverter, when a total price has been found the cost for unit has been calculated considering a motor peak power of 150 kW, when the price provided was referred to as the nominal power the value has been normalized considering a ratio between peak power and nominal one of 2;

In the table 2.21 are resumed all the final data used for the TCO study.

DC-DC converter	Onboard charger	Inverter
241,8 €	316,5 €	5,1 €/kW

Table 2.21: Power electronic cost.

2.3.7 Other components

The intention of performing a bottom-up analysis for the definition of the total vehicle price makes necessary the cost estimation of other components of the powertrain, important to correctly assess its price.
The elements considered are:

- The engine cost for the diesel ICEV.
- The fuel tank cost for the diesel ICEV.
- The power control unit for FCEVs and BEVs.
- The transmission cost for both EVs and ICEVs.

The operating principle of the listed components is not further exposed, as it is already mentioned in the previous sections and widely consolidated. The data discovered are resumed in the table 2.22 with their references, price evolution is not considered due to the high level of development of the technologies presented. The completion of knowledge and data needed to assess the total powertrain cost makes it possible to move on to the discussion of the methodology to be used, which will be studied in the next chapter.

Component	Price	Authors
Diesel engine + transmission	37 €/kW	[49, 48, 25]
Diesel tank	125 €	[49]
Power control unit	150 €	[49]
EV transmission	430 €	[49]

Table 2.22: Other components bibliography review.

Methodology

3.1 TCO analysis

The aim of this chapter is to introduce the reader to the methodology selected and to all the hypotheses that have been used in order to reach the fixed goals. The TCO analysis permits the estimation of the total amount of money required to purchase and operate a vehicle during its entire lifetime, it is expressed in Euro but it is usually normalized on the total mileage of the vehicle. So, in the end, the final output of the study is expressed as a price for a travelled kilometer, the Levelized Cost of Driving (LCOD), in order to allow easier comparison between the different vehicles. The analysis can be carried out from different perspectives and using different approaches. Burnham et al.[59] suggests the LDVpossibility to choose between a private or societal perspective and between a 100 % quantitative or a partially qualitative approach. In this work a private perspective is preferred to a societal one, being the final aim to assess the advantages for consumers of owning a particular technology rather than another one. Furthermore, a 100 % quantitative approach has been selected with respect to a partially qualitative one, setting the goal to estimate a mathematical model for all the costs and benefits given in this study. The analysis is performed by dividing the total cost of the vehicle into seven basic components and creating a model based on recorded data or on a mathematical formulation for each of them. The components which constitute the total cost are the same for every author that has been consulted, apart from the financing term that is not always considered, and they are reported in the figure 3.1, followed by a short explanation of their meaning:

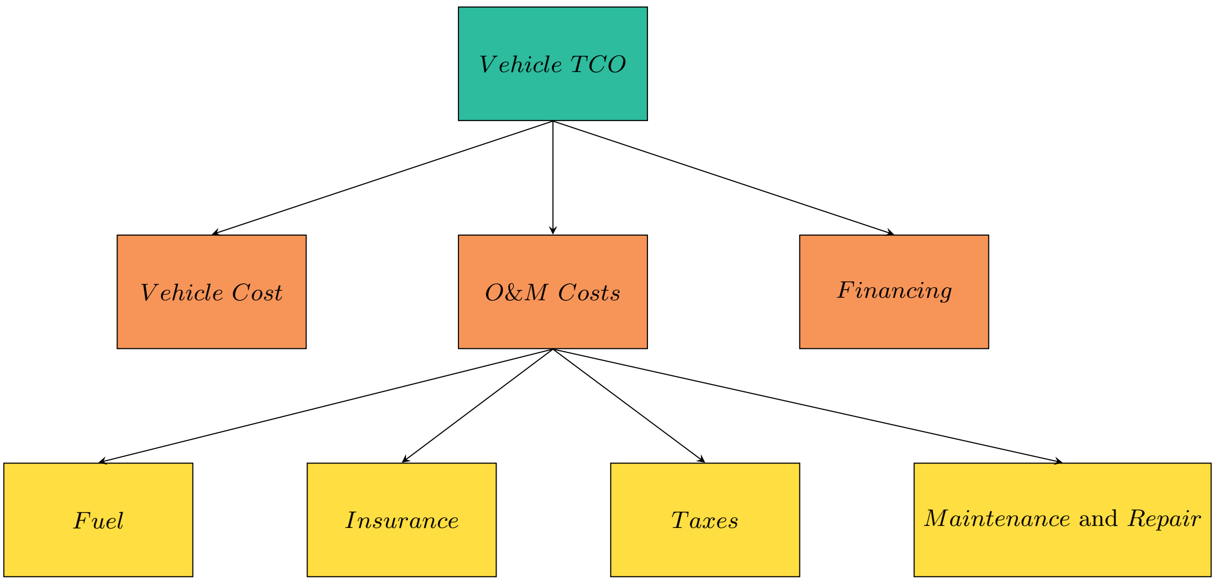


Figure 3.1: TCO components.

- Vehicle cost: The vehicle cost is estimated considering the retail price of the vehicle, the presence of incentives and its depreciation over time. It can be estimated on an annual basis or considering the net income in the year when the vehicle is bought or sold.

- Financing: This term considers the interests behind the payment of the vehicle in case of a loan;
- Fuel: The total cost of the fuel, it is estimated considering the annual mileage, the specific cost of the fuel and the fuel economy of the vehicle;
- Insurance: The insurance costs for a basic cover have to be considered and estimated;
- Taxes: All the taxes paid in the lifetime of the vehicles, including annual taxes and registration fees;
- Maintenance: This term includes only the cost of periodic maintenance of components;
- Repair: All the costs linked to the extraordinary maintenance of components;

Every category is characterized by its own hypothesis and assumptions in order to consider the influence of different parameters on the costs (Manufacturer Suggested Retail Price, Incentives, Size class, Powertrain model, Weight, Fuel, Vehicle total mileage, Manufacturing Year). A complete overview of the dependency of the categories from these parameters is given in the table 3.16.

Vehicle cost	MSRT, Powertrain, Size class, Incentives, VTM, Performance
Financing	MSRP, Financing parameters
Fuel	Powertrain, MY, VTM
Insurance	MSRP, Size class, VTM
Taxes	MSRP, VTM, Powertrain, Size class, Weight
Maintenance	Powertrain, Size class, VTM
Repair	MSRP, Powertrain, Size class

Table 3.1: Parameter dependencies.

About the formula used to calculate the TCO, all the authors agree on the method to use, with only some differences linked to the vehicle cost, which can be considered with different models depending on the grade of detail of the analysis and its hypothesis. Hagman et al.[60] and Jones et al.[61] use the equation 3.1 to calculate the TCO:

$$TCO(€) = CE - PS - RV + \sum_{n=1}^{N} \frac{Fuel_n + Insur_n + Taxes_n + Maint_n + Repair_n}{(1+r)^n} \tag{3.1}$$

Where:

- CE is the Capital Expenditure, which is mainly composed of the retail price of the vehicle but also some registration fees can be included.
- PS are the Purchase Subsidies, they variate for powertrain technology, country and retail price.
- RV is the residual value of the vehicle at the end of the lifetime.
- N is the total lifetime of the vehicle. The ownership can be analyzed considering the entire life of the vehicle or, in alternative, considering the first ownership. In both cases, it is important to consider the residual value of the vehicle. A lifetime of 15 years is analyzed to include also the growth of the costs for maintenance. But a short time period could be useful to understand the POV of a first owner.
- r is the assumed discount rate. It is used in economic analysis to correctly discount the flux of money.

In their formulation, the purchase price is totally attributed to the first year of life of the vehicle and the depreciation to the last. This approach is correct just in case the vehicle is entirely paid when it is bought. Looking at the data from Nextcontinent [62] and Zabritski et al. [63] it results that the possibility that a vehicle is financed is not negligible. It has been estimated that 60 % of the vehicles purchased in France has been financed in 2015 [62], the percentage is also bigger looking at the American market where 87 % of the vehicles sold in 2019 has been bought by means of a loan or a lease [63]. As consequence, the financing price has to be added to the cost of purchasing the vehicle and this latter is divided in all the time period of the loan. The possibility of including also the loan is considered by Burnham et al.[59], whose equation 3.2 is the one considered in the current study:

$$TCO(€) = \sum_{n=1}^{N} \frac{Vehicle_n + Finan_n + Fuel_n + Insur_n + Taxes_n + Maint_n + Repair_n}{(1+r)^n} \tag{3.2}$$

In this case, the annual cost of the vehicle can be considered in two different ways; as the effective cost paid every year for the vehicle, in this case at the end of the lifetime the money gained from the reselling or from the scrapping of the vehicle has to be considered. The alternative is to consider the annual depreciation that characterizes the vehicle as its cost. In this last case, the value at the end of the life has not to be subtracted from the TCO. The two possibilities are completely equivalent for the final result from the point of you of the undiscounted cash flow. This last way to estimate the annual price of the vehicle is the chosen one because it permits the visualization of the effect of the depreciation in the evolution of the cost, pointing out continuously along their lifetime the difference between all the powertrains under this aspect.

3.2 Vehicle sizing

Chosen the segments and the powertrain technologies, the main specification of the vehicles has been selected in order to have all the data required to calculate the retail price of the vehicle and its operational costs. The specifications required change with the technology and they are resumed in the table 3.2.

Fuel Cell EV	Electric motor power, Fuel Cell power, Fuel Economy [a], Autonomy
Battery EV	Electric motor, Fuel Economy, Autonomy
ICE	Engine power, Fuel Economy, Autonomy

Table 3.2: Specification required for powertrain technology

[a]The fuel economy of the vehicle is defined as the fuel consumption, usually normalized in equivalent liters of gasoline, for every kilometer travelled.

Subsequently to the definition of the fuel economy and the autonomy of the vehicle it is possible to design also the storage size, considering the energy content of the fuel. The average data for autonomy and fuel economy have been calculated by means of a Statistical analysis on the database of the site fueleconomy.gov [64]. The approach has been selected looking at the great variance of data inside the same segment. The mean has been done by distinguishing between different technologies and segments for autonomy and fuel economy. The average data for the EM peak power, catalogued by segment, have been taken from Hill et al.[49]; they concern the year 2013, but looking at the EEA Report [65] the trend from 2013 to 2018 can be assumed as constant. Regarding the fuel cell power, given the presence of only Toyota Mirai and Hyundai Nexo as reference models in the market, it has been chosen as a constant percentage of the total power of the vehicle (84%). All the data are catalogued in the tables from 3.3 to 3.5.

Another important point is to forecast the evolution of these parameters. Indeed, according to some authors ([66, 67]), technological progress and the average decrease in weight will influence the vehicles' specifications and energy consumption. The author taken as reference is Islam et al. [66]

Fuel Consumption (L/100 km)			
	FCEV	BEV	ICE
Small	3,18	2,13	6,27
Medium	3,01	2,05	6,85
SUV	4,10	2,35	7,93
Pickup	5,00	3,40	9,66

Table 3.3: Fuel Economy.

Autonomy (km)			
	FCEV	BEV	ICE
Small	-	259	660
Medium	650	352	735
SUV	750	436	638
Pickup	-	466	957

Table 3.4: Autonomy.

Motor Power (kW)	
Small	62
Medium	102
SUV	150
Pickup	180

Table 3.5: Motor Power.

because of the more recent release of the study (2020). In his work, an algorithm is used to simulate the effect of aerodynamic improvements, efficiency improvements and light weighting on the powertrain sizing and on energy consumption. The final results seem to be overestimated and incoherent with the market trend of the last years, being for example supposed a decrease of 20% in the motor maximum power for BEV400. The reason is considered linked to the fact that the outcome of the study is more similar to a potential decrease of power that the LDV can reach in the next years and not a market forecast, which should be influenced also by other factors of not technological nature. For this reason, power and autonomy have been considered constant for all the time frame.

For what regards the fuel consumption, the technological driver can be significant, being the cut of emissions and consumption a constant objective for all the companies. For this reason, the fuel economy is considered in evolution over the years, following low technological progress, according to Islam's work, to avoid overestimating the effect of weight loss.
The assumptions about the fuel economy evolution are resumed in table 3.6.

	FCEV	BEV	ICE
2025	-15%	0%	-5%
2030	-24%	-12%	-5%
2035	-24%	-12%	-5%
2050	-32%	-19%	-19%

Table 3.6: Fuel consumption evolution.

3.3 Vehicle retail price

As said, the price of the vehicle is the most weight full component inside the TCO. It is possible to calculate it following two different approaches: bottom-up analysis and top-down analysis. In the first case, the single costs of components and services are summed together in order to obtain the total price of the vehicle, in the second one the analysis starts from the final price, subtracting the cost of the known elements in order to obtain a full picture of the single costs. Given the collection of data in the previous chapter, the bottom-up analysis looks the most straightforward strategy, considering that the uncertainty about the coefficients that link the final cost of the vehicle to the manufacturing one can influence the reliability of the results and also the intention of forecasting the evolution of the costs in the next years. The figure 3.2 shows the selected scheme for the vehicle economic analysis, at the powertrain cost of the vehicle has to be added the cost of the glider and assembling and all the external costs due to transport, manufacturer income, retailer income and VAT.

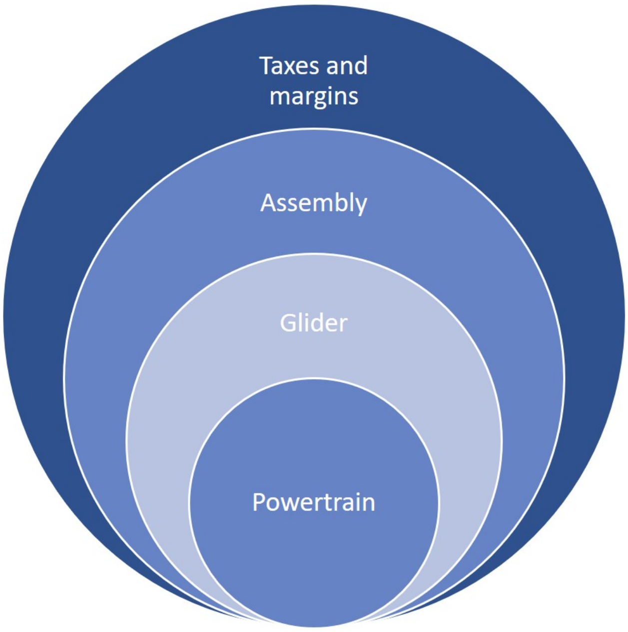


Figure 3.2: Composition of the vehicle cost.

In the following sections, these costs are going to be analyzed and all the hypotheses about their entity will be explained.

3.3.1 Manufacturing cost

Looking at the information in the previous section, the manufacturing cost of the vehicle is composed of the sum of the powertrain cost plus glider and assembly costs.
The technology review of the previous chapter gives all the information to compose the powertrain cost of the vehicles by means of a bottom-up analysis. As seen, the components are made by a fixed cost plus a cost dependent on the autonomy of the vehicle or the total power of the engine. In the following tables, all the powertrain components for the different technologies are resumed together with their cost.

FCEV		
	Fixed	Variable
FC system	-	167,9 € /kW
Hydrogen tank	-	18,1 € /kWh
Battery system + DC-DC converter	242,0 €	215,0 € /kWh
EM+ Inverter + PCU	150,0 €	15,0 €kW
Boost converter	242,0 €	-
EV Transmission	430,0 €	-

Table 3.7: FCEV powertrain cost composition

BEV		
	Fixed	Variable
Battery system + DC-DC converter	242€	215,0 € /kWh
EM+ Inverter + PCU	150,0 €	15 € /kW
EV Transmission	430,0 €	-

Table 3.8: BEV powertrain cost composition.

ICEV		
	Fixed	Variable
Engine + Transmission	-	37,0 € /kW
Fuel tank	125,0 €	-

Table 3.9: ICEV powertrain cost composition.

The glider cost is defined in this work as the cost of all the components that are not included in the powertrain, this definition is not shared between all the authors, which sometimes excludes costs like braking system and air conditioning from it. The glider cost is dependent on the maker and also on the optional equipment that is present in the vehicle. For simplicity and coherently with all the authors, the cost has been assumed equal for all the technologies and only standard vehicles have been considered, without including the possibility to add optional components. At this point, the main task for the glider cost estimation is to correctly differentiate the cost of the various segments.
For this objective, Sharma et al. [68] proposes a cost of 15.928 € for the class E vehicles glider and of 11.292 € for the class B ones, slightly lower than the one used by Nassif et al. [11] and Elementenergy [39] in their studies, equal respectively to 17.520€ for a Hyundai IX35 FCEV and to 22.000 € for an E/H class. A calculation of a reference cost for a general midsize vehicle is given by Graham et al. [69] that, summing the labour cost to the materials costs required for the glider, calculates a cost of 14.000 €. These values are not coherent with the reference segments chosen in this work and, for this reason, Islam et al.'s work [66] has been selected, indeed it gives reference prices for small, medium, SUV and pickup vehicles, reported in the table 3.10; the costs, being lower than the other authors, may be underestimated, with the author that does not give information about the origins of the data or if they include the manufacturer markup or are referred to as the net cost of the glider. In every case, priority was given to correctly calculate the difference in price between the various segments, with the underestimation of the cost that, being shared among all the technologies under analysis, will not have an effect on the comparison between them.

Small	Medium	SUV	Pickup
7.356 €	9.917 €	11.960 €	14.826 €

Table 3.10: Reference glider costs.

Finally, an estimation of the assembly cost has been done. The difficulty of this evaluation is that the cost of the assembly is directly linked not only to the hours required to assemble the vehicle, but also to the country where it is assembled, due to the change in salary between the different countries. Two possible approaches have been found in the literature; the first one is proposed by Fries et al. [48] that estimates the number of hours for different ICE vehicle sizes and a labour cost for hour for a list of countries. The difficulty of this approach is that the labour cost varies a lot between countries, from 46 €/h in Germany to 23 €/h in Spain and 11 €/h in east Europe. At the same time is not possible to assume the vehicles as mainly produced in one of the countries in the list, indeed, according to the Acea's interactive map[70], the vehicle assembly and production plants are distributed almost equally all around Europe, also considering one single maker. Oliver Wyman via Financial Time [71] estimates, coherently with the previous author a cost of 1.700 € (which corresponds to a labour cost of 33 €/h for the labour in USA) for the assembly of an ICE segment C vehicle and of 1500 € for the assembly of an EV one, the latter value is lower than the former one due to the higher complexity of the ICE powertrain with respect to the BEV one. These values have been taken as reference for the medium vehicles and scaled with respect to the Fries labour to obtain the costs for the other sizes. The cost for the FCEV assembly is considered equal to the BEV one as a first approximation, being the two powertrain technologies of the same complexity. The results are highlighted in the table 3.11.

	Small	Medium	SUV	Pickup
ICE	1.063 €	1.700 €	2.125 €	2.125 €
BEV	937 €	1.500 €	1.875 €	1.875 €
FCEV	937 €	1.500 €	1.875 €	1.875 €

Table 3.11: Assembly cost.

3.3.2 Additional costs

Given the cost of manufacturing the vehicle, all the margin costs have to be added in order to obtain the final retail price: distribution and marketing costs, manufacturer margin, retailer margin and VAT. This quest has some complications due to the fact that all these terms do not depend only on segment, technology and country but also on the specific manufacturer.
From the bibliography review, two main approaches have been noted and they are going to be listed. A first approach is to define a coefficient that includes all four terms, usually with a value between 1,5 and 1,7. This approach is the most simple but at the same time is quite general, so the possibility of estimating all the single components has been taken into account.
Despite the fact that different authors ([72, 73, 39, 48, 47]) group the costs in different ways, it is possible to distinguish between four main subcategories: logistics and marketing, manufacturer margin, dealer margin and VAT.

The logistic and marketing cost includes all the expenses linked to the distribution, advertising and dealer support and it is expressed as a percentage of the manufacturing price. Fries et al.[48] considers in his work a distribution cost between 5% and 15%; these numbers are coherent with Elementenergy2011 [39], which estimates a cost of logistics and marketing of 6,7%. Finally, Cuenca et al. [72] estimates the costs for distribution, advertising and dealer support close to 30%, this study is the most accurate analysis but at the same time is really dated (1999) so its data are not considered as reliable.

The manufacturer margin is the margin that the manufacturer obtains for each vehicle sold. The difficulties in the research about this parameter have been given by the fact that some authors ([47],[39]) define it as the profit from each car, in this case, it can be used to pay other expenses, not directly linked to the vehicle manufacturing, that the manufacturer has to effort and only a part of it becomes the net profit from the vehicle selling. This is the definition intended in this work, due to the fact that the cost is seen from the point of view of the consumer.
In other cases, a part of the vehicle price is assigned to the payment of the other expenses, not directly linked to the vehicle, and the manufacturer margin is only referred to as net margin.
All the results of the bibliographic research are resumed in the table 3.12.

The retailer margin is solely defined as the profit that the retailer obtains from selling the car and, according to Cuenca et al. [72], it can be divided into the money gained from the single car sold and a premium given by the quantity of car sold but in this work only the first quantity, as a percentage of the manufacturing cost is considered. Also in this case, all the results of the bibliographic review are presented in the table 3.13.

After considering all the literature under analysis, it is possible to select the value of the parameters by looking at the full picture. All the data are quite coherent between themselves but, among all

Author	Manufacturer margin
Lutsey et al.[47]	5% for cars; 15% for SUV
Elementenergy2011 [39]	7,5%
Fries et al.[48]	Between -5% and 9%
Elementenergy2016 [73]	Total margin[a] of 23,4% for cars and 31,6% for SUV
Berger et al.citeberger2017	7,3% of company net annual profit [b]
KPMG[74]	6,8% of company net annual profit

Table 3.12: Manufacturer margin bibliography.

[a]It includes both the OEM margin and the dealer, logistics and marketing margins.
[b]Some hypothesis should be done to convert the net annual profit of the car to the one of a single car.

Author	Retailer margin
Lutsey et al.[47]	15%
Elementenergy2011 [39]	13%
Fries et al.[48]	Between 5% and 15%
Elementenergy2016 [73]	Total margin[a] of 23,4% for cars and 31,6% for SUV

Table 3.13: Retailer margin bibliography.

[a]It includes both the OEM margin and the dealer, logistics and marketing margins.

the authors, Elementenergy2011 [39] has been chosen, preferring to select all the data from a unique author, for coherence, and to maintain all the parameters separated to allow those who will use the tool in the future to be able to refine their estimate in the presence of more information.
The final hypothesis follows:

Logistic and marketing	Manufacturer	Retailer
6,7%	7,5%	13%

Table 3.14: Additional cost hypothesis.

Finally, the VAT is the only term that is possible to know without uncertainties, its value change with the country and all the values for the countries under analysis are listed in the table 3.15.

Germany	19%
France	20%
Sweden	25%
Spain	21%
Netherlands	21%
Austria	20%

Table 3.15: VAT values.

3.3.3 Depreciation

A precise estimation of the depreciation rate is fundamental to correctly assess the residual value of the vehicle during its lifetime, mostly in its first years of life .
Its characterization can be quite complex because it is dependent not only on the initial price of the vehicle, manufacturer, model, model year, mileage, powertrain technology and overall conditions but also on the market demand, economic fluctuations and incentives. Furthermore, regarding the specific powertrain technologies, improvements and innovation (for example in battery longevity) can influence depreciation.
Different approaches have been identified in the bibliography, they are presented as follows and the final hypotheses chosen are justified.

A first approach is to calculate a depreciation rate by looking at the sources that provide vehicle listing prices, this approach is followed by many authors ([73],[60],[75],[76],[77]) because it is the simplest but, at the same time, it is difficult to ascertain the relationship between listing price and transaction price. Elementenergy [73] analyses the UK data for Nissan and Mitsubishi vehicles, obtaining, as a result, an assumption of equal percentage annual depreciation that is independent of the powertrain technology; indeed the initial differences in the depreciation rate disappear when the purchase incentives in the UK market are considered. A similar interpretation is given by Hagman et al.[60], that, after the study of a Nissan Leaf SV, bought in the US in 2012, considers a depreciation rate of 50% after three years, independently from the technology.
The main lack in the analysis of the authors mentioned is that FCEVs are not considered, being a technology characterized by a market demand completely different from the others. As consequence, the hypothesis of a constant depreciation rate along the powertrains is not appropriate in the conditions under analysis.

Another approach is the one selected by Burnham et al.[59], who, in his study, uses Edmund.com [78] to collect the true market values, based on real transactions, of twenty-three different makes and ninety-eight different vehicles and uses them to quantify the general LDV depreciation trends by vehicle class and powertrain type.
Also this author highlights the importance of considering in the calculation the subsidies obtained when the vehicle was purchased, defining the adjusted retention rate (ARR) as a more objective metric with respect to normal depreciation.
The ARR and the correspondent definition of Depreciation follow:

$$ARR_i(\%) = \frac{P_0 - I - \Delta_i}{P_0 - I}; \tag{3.3}$$

$$Depr_i(€) = (P_0 - I) \cdot (1 - ARR_i); \tag{3.4}$$

Where:

- ARR_i is the adjusted retention rate at the year i;
- P_0 is the original retail price;
- I is the subsidy applicable to the purchasing;
- Δ_i is the depreciation at the year i;

The data obtained are modelled by means of an exponential function:

$$ARR_{i,p}(\%) = b_p \cdot \exp(k_p \cdot i) \cdot (1 - \frac{S_p}{2}); \tag{3.5}$$

Where

- b_p is a coefficient that takes into account the first year depreciation for a vehicle of powertrain p, this choice is given by the fact that the residual value at the end of the first year is not representative of the depreciation over the rest of the lifetime;
- k_p is a characteristic coefficient of each powertrain technology;
- $(1 - \frac{S_p}{2})$ is a factor used by the author to take into account the different depreciation of LDV with respect to light trucks;

	b_p	k_p	S_p
FCEV	71%	-0,22	14%
BEV	92%	-0,21	22%
ICE	80%	-0,12	3%

Table 3.16: Depreciation coefficients

All the data listed are collected in the table 3.16 and the trend is shown in the image 3.3:

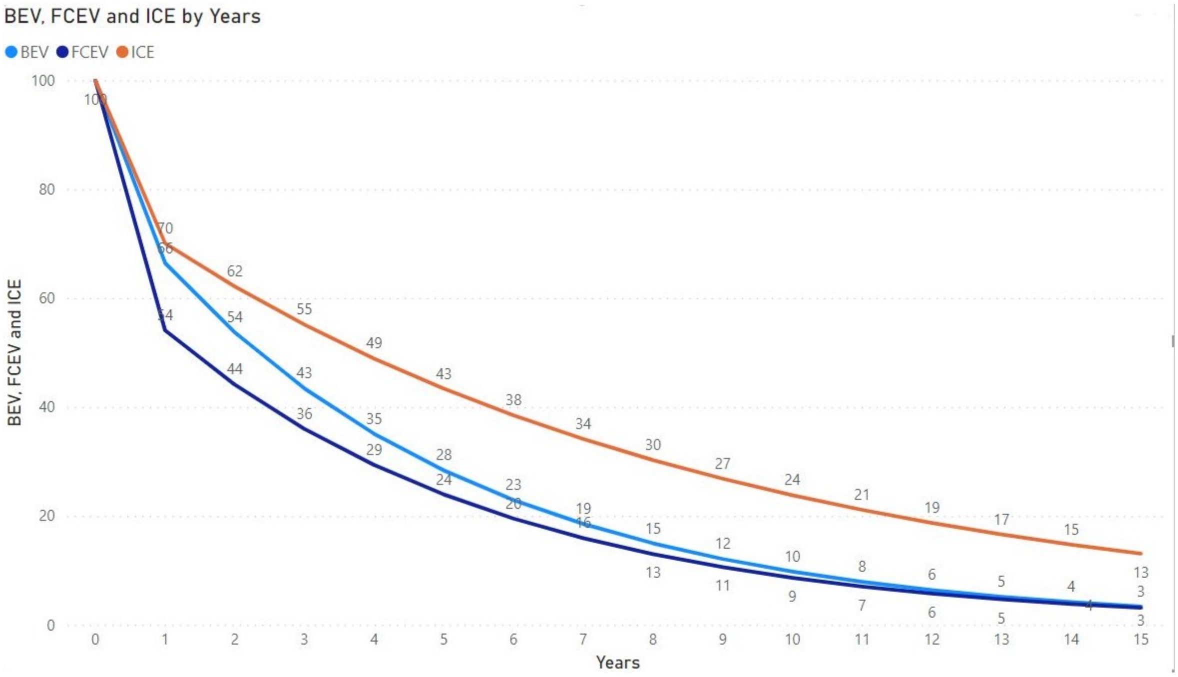


Figure 3.3: Depreciation trends.

From the figure is clear that there is a net difference among the various technologies. The ICE vehicles are the ones characterized by the lowest first-year depreciation (30% with respect to the 34% that characterizes the BEVs), also losing value over the years with the lowest rate. On the opposite, the FCEVs are characterized by a high first-year devaluation (46%), which makes the technology the one with the lowest residual value at the end of its lifetime. This result is due to the low penetration of the FCEVs technology inside the market.
Additionally, ICE is the only technology having a relevant value at the end of the lifetime (13%), indeed the choice of considering a lifetime of 15 years makes the effect of the depreciation not crucial for the final results. A completely different output would be obtained considering the effect of depreciation at the end of the first ownership of the vehicle (three years), when the difference between the residual values of ICEs, BEVs and FCEVs is much more evident (respectively 55%, 43% and 36%).

3.4 Operation and Maintenance Model

3.4.1 Fuel price

In this subsection, the main differences among the different fuels required from the vehicles studied are going to be shown and their cost is going to be estimated and forecasted until the year 2050.
Regarding electricity, it average "European price for 2020", taken from the Eurostat site [79], has been selected as the reference price for this work. This choice has been done considering that the average European price has been constant up to 2020 and this price can well represent the base case for the electricity cost. Looking at the diesel trend, the year 2020 represents a minimum for the cost of diesel

given the onset of the pandemic. For this reason, it was preferred to consider the average of the period 2017-2022 [80] in order to obtain a more truthful price. Regarding the evolution of the chosen prices, as seen, they are dependent on parameters of social, environmental and political nature that are difficult, if not impossible with the instruments at disposal, to predict in a long time range. For this reason, their prices have been supposed constant for all the time frame under analysis but the user of the tool has been left free to choose a trend for their evolution.

The hydrogen price is subjected to the same condition of the other two fuels but, in addition, hydrogen production is a technology not fully established. This last consideration permits to assume a decrease in its cost looking at the technological improvement in its production.
A bibliographic study has been done in order to assess the current price for the in € for kg and to forecast its evolution in the next years. All the data used to calculate the final price for hydrogen are shown in the table 3.17 together with the resume of the fuel prices used for this study (table 3.17).

Authors	2020	2025	2030	2035	2050
Nassif et al. [11]	14,50	-	3,68	-	-
Elementenergy2021 [76]	12,10	8,49	4,87	4,87	-
IEA [25]	8,50	-	-	-	4,60
Burnham et al. [59]	12,70	8,70	4,60	-	-
Islam et al.[81]	9,20	7,70	6,10	4,60	4,60
Average	11,40	8,30	4,80	4,70	4,60

Table 3.17: Hydrogen price data (€/kg).

	2020	2025	2030	2035	2050
Hydrogen (€/kg)	11,40	8,30	4,80	4,70	4,60
Electricity (€/kWh)	0,21	0,21	0,21	0,21	0,21
Diesel (€/L)	1,70	1,70	1,70	1,70	1,70

Table 3.18: Fuel price data.

Given the price of the fuel, the fuel economy of the vehicle and the mileage it is possible to calculate the total annual fuel cost for the year n:

$$Fuel\,Cost_n(\text{€}) = Fuel\,Price(\text{€}/unit) \cdot Fuel\,consumption(unit/km) \cdot Mileage_n(km); \quad (3.6)$$

3.4.2 Maintenance cost

As previously explained, the maintenance cost of a vehicle is the cost due to the periodical maintenance of components that have a lifetime lower than the one of the vehicle, in order to prevent its damage. In this work, this term is separated from the cost linked to unexpected maintenance. This choice has been made for the intrinsic difference between the two terms, indeed the regular costs can be approximated considering the expected lifetime of the single powertrain components, which can be considered constant independently from the year. Differently, the repair cost has a more random nature and, above all, they cannot be regarded as constant during the lifetime of the vehicle. This last differentiation makes the comparison between authors difficult because of the different definitions given to the maintenance term.

The maintenance cost, being proportional to the mileage of the vehicle, is usually expressed in €/ km and, also in this case, the values are taken from the literature.
The method created by Burnham et al.[59] has been taken as a reference for the hypothesis in this

sub-chapter. In his work the total maintenance cost is calculated considering twenty-four different components of the vehicle that require maintenance, it is possible to divide them into six categories: powertrain maintenance, filter replacement, fluid changes, brake maintenance, suspension maintenance, tire maintenance, and general service items.
No complete description of the FCEV maintenance cost has been provided, because of the lack of data about them. Despite it, it is possible to approximate their cost equal to the BEVs one because their powertrain architecture is equal, unless the power sources (fuel cell and battery), which lifetime is considered equal to the vehicle one. The same approximation is done with the hydrogen tank that, according to the manufacturers, does not require maintenance during its lifetime.
The cost for kilometer of every component is extrapolated by estimating their total price and dividing it considering typical OEM service schedules. The final results could be overestimated because many drivers do not respect the suggested intervals to change or adjust the components.
The outputs of the analysis are shown in the figures 3.4 and 3.5.

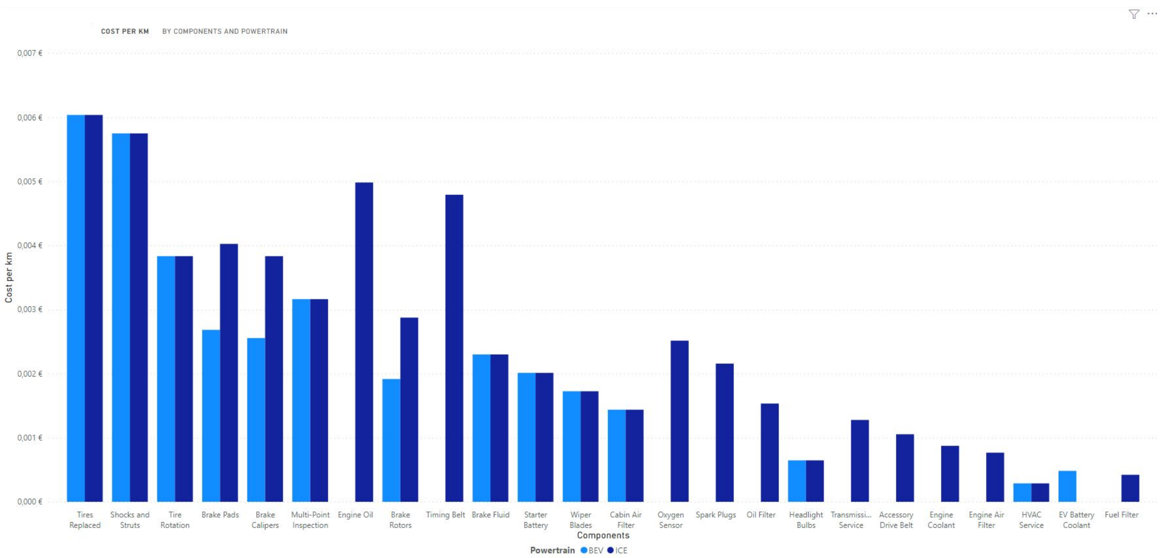


Figure 3.4: Component cost for kilometer

As it is possible to observe, the cost of BEVs maintenance is 41% lower than the ICE vehicles one, 35 c€/km with respect to 58 c€/km. This characteristic is mainly due to a lower cost for powertrain maintenance because fewer mechanical parts are present; apart from this, the battery powertrain is characterized by lower costs also in the other categories. No particular difference has been found among the different sizes of vehicles and, for this reason, the cost of maintenance is going to be considered equal for all of them.

3.4.3 Repair cost

The repair cost requires a different approach with respect to the maintenance one. It is due to the unexpected damages to the components during the lifetime of the vehicle and it has a more random nature, depending on the driving style, the conditions of the road or other parameters independent from the vehicle that can solicit it to damages normally unexpected. Despite this, a time dependency is also expected, tending the vehicles to break more with the age and being the unexpected damages usually covered by a warranty in the first years of life.

Also in this case the analysis made by Burnham et al.[59] is the one considered to be coherent with the analysis on ordinary maintenance, for his completeness and for the solidity of his hypothesis. In the end, the total result of maintenance and repair is going to be compared with the other authors, to find similarities and differences in their approaches.
The big Edmund's database [78] is used again to collect the cost for the extraordinary maintenance as a function of the selling price of the vehicle in a time window of ten years. The data are then fitted by means of an exponential function that permit the calculation of the cost per kilometer in the year

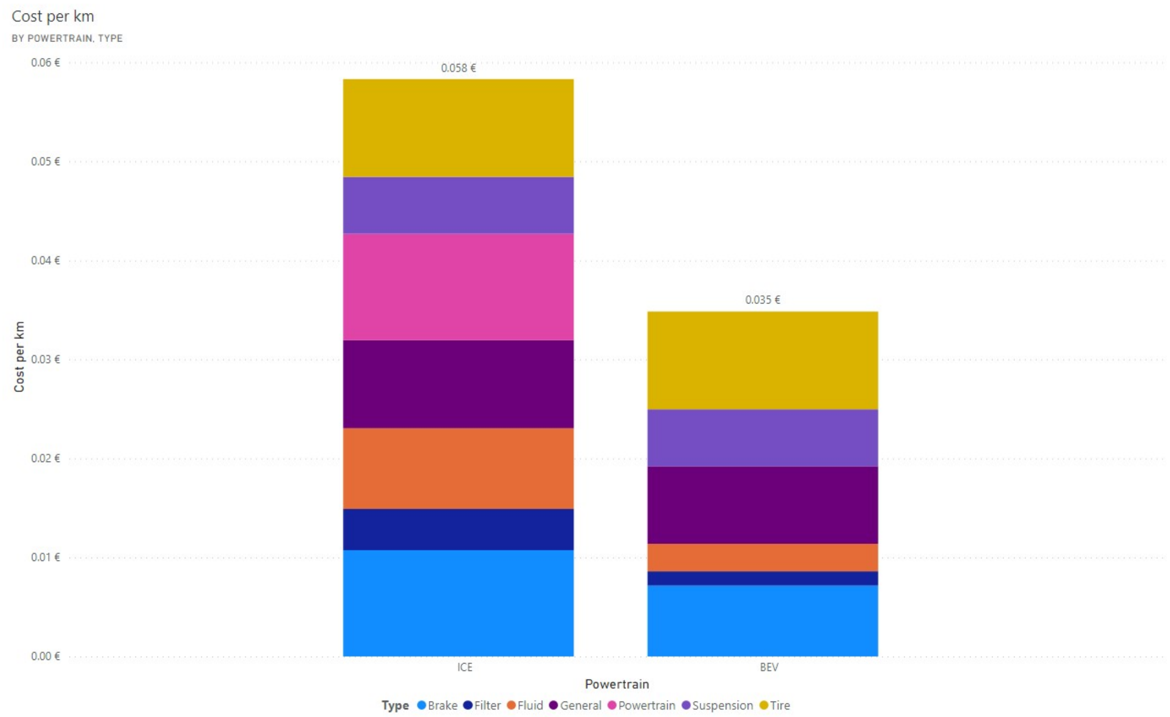


Figure 3.5: Maintenance cost per km.

i :

$$Repair_i = v \cdot p \cdot a_i e^{bx}; \tag{3.7}$$

Where:

- $Repair_i$ is the cost in €/km for the year i;
- a_i is a coefficient dependent on the year of life of the vehicle, it is expressed in €/km and it has a value of 0 in years 1-2, 0.00190 in year 3, 0.0058 in year 4, 0.0096 in year 5 and then increases by 0.0019 for each subsequent years. The trend is supposed constant also after the tenth year;
- b is a constant coefficient equal to 0,000022 1/€;
- x is the suggested retail price of the vehicle;
- v is the coefficient that takes into account the type of vehicle, it is equal to 1 for cars, 0,91 for SUVs and 0,70 for Pickups. The reason for the difference between the sizes is probably due to the higher margin that characterizes pickups and SUVs or, in alternative, the difference between repair frequency and/or cost between various OEMs and their model availability for each vehicle type;
- p is the coefficient that takes into account the powertrain type, it is equal to 1 for ICE vehicles and to 0,67 for BEV and FCEV. As for ordinary maintenance, the difference between ICE and BEV is due to the minor quantity of mechanical parts that is present in the latter. Because of the lack of data, the price for the FCEVs is considered equal to the one of the BEVs;

At this point, the results obtained for regular and extraordinary maintenance with the method used can be compared with the rest of the bibliography in order to validate the approach selected. A Medium segment car is going to be used as a reference model for each powertrain technology, to obtain an average annual number for the maintenance costs that can be easily compared with the rest of the bibliography.
The results obtained are resumed in table 3.19 together with the comparison with the other authors in table 3.20.
The results obtained and shown are coherent with the rest of the bibliography, in particular with the IEA results, with the advantage that the method used permits to consider the change of cost along

Year	FCEV (c€/km)	BEV (c€/km)	ICE (c€/km)
1	3,49	3,49	5,77
2	3,49	3,49	5,77
3	4,02	3,88	6,07
4	5,10	4,68	6,68
5	6,17	5,49	7,29
6	6,71	5,88	7,59
7	7,24	6,28	7,90
8	7,77	6,67	8,20
9	8,30	7,07	8,50
10	8,83	7,46	8,80
11	9,36	7,86	9,10
12	9,89	8,25	9,40
13	10,42	8,65	9,70
14	10,96	9,05	10,00
15	11,49	9,44	10,30
Average	7,55	6,51	8,07

Table 3.19: Annual average maintenance and repair cost.

Authors	FCEV (c€/km)	BEV (c€/km)	ICE (c€/km)
Reference values	7,6	6,5	8,1
IEA [25]	7,8	6,5	8,0
Redelbach[82]	-	5,9	7,2

Table 3.20: Maintenance and repair cost comparison.

time, discounting correctly the flux of money without overestimating the expense in the first years of ownership.

3.4.4 Insurance cost

In this analysis, insurance is the parameter with the most complex estimation because of its dependency on a lot of variables that are difficult to model from a mathematical point of view: location, density of population, age of the driver, annual mileage, retail price of the vehicle and powertrain. Not all the authors take into account the insurance cost inside their analysis because adding it to the TCO, the relative difference between the different technologies is less evident. In this thesis neglecting the cost of insurance has been considered not correct for the estimation of the order of magnitude of the results. For this reason, a basic formulation for the annual insurance cost is formulated.

First of all, it is possible to distinguish between different kinds of insurance:

- Third party liability: if a car is registered in a European country it must be insured for third party liability, an insurance that covers damages to property or injuries to anyone apart from the driver. It does not cover the damages to the driver's vehicle.
- First party liability: this optional insurance extends the cover to other injuries to the driver, damage to the driver's vehicle, theft of vehicle, vandalism, and legal assistance.

Insurance Europe widely analyzed the insurance market in its work "European Motor Insurance Market" [83]. As said, a wide range of factors of influence the calculation of the premium and, taking into account that the insurance has to cover also operational and administrative costs, which strongly depend on the country, the cost can differ widely from one country to another. For this reason, every country under analysis is analysed separately and the statistics about the average premium in each of them are reported in the table 3.21.

Country	Average premium
Germany	500 €
France	400 €
Sweden	200 €
Spain	350 €
Netherlands	400 €
Austria	300 €

Table 3.21: Average premium values.

The next objective is to find a way to take into account the effect of cost, size and powertrain on the premium. A deep analysis is again performed by Burnham et al. [59], whose results point out a negligible influence of the powertrain type and a linear dependence on the Retail price. The analysis is performed on the American market, for this reason the coefficients that link the retail price to the premium value are not supposed to be valid for the European one. Regarding the dependency on the segment, the analysis shows unexpected results, being the cost for the insurance of SUV and Pickup lower than the one of the cars, at parity of prices. The result is unexpected because the size of SUVs and pickups is larger than the one of cars and as consequence, a bigger possibility to do expensive damage during an accident is expected. This result, according to the author is probably due to the higher presence of SUVs and pickups in the low population density zones or, as an alternative, to the higher manufacturer margin that characterizes these vehicles and which leads to a lower repair cost in case of an accident. In this work the dependency from the segment has been considered negligible, amounting the difference in the annual premium to 20$ at the beginning of the trend, up to a maximum of 300$ for a retail price of about 100.000$. This amount can be considered negligible as a first approximation.

A model for the dependency of the premium on retail price and segment has not been founded for the European market and so a relationship between the premium and the retail price has been created considering a fixed price of the premium equal to half of the average price for the country under analysis and a liner trend that reach the average price of the country selected for a retail price of 30.000€, as shown in the equation 3.8.

$$AP = ACP \cdot 0,5 + \frac{ACP \cdot 0,5}{30.000} \cdot RP \tag{3.8}$$

Where:

- AP is the annual premium;
- ACP is the average country premium;
- RP is the vehicle retail price;

3.4.5 Taxes

In this subsection, all the expenses linked to the registration and the usage of the private vehicle are going to be considered. The analysis has been done taking as reference the ACEA tax guide 2021 [84] to have a full picture of the cost of taxes in every European country. The registration tax is of complex formulation in almost all countries: it depends on the region in France, on the CO2 emissions in Austria and Spain and on CO2 emissions and fuel efficiency in Netherlands. On the other side, its amount is not significant with respect to the uncertainty of the retail price, being it in the order of 26 € in Germany, between 25 € and 50 € in France, slightly lower 200 € in Austria (maximum amount), 100 € in Spain (no registration tax expected in Sweden). For this reason, the registration tax has been considered negligible for the aim of this study. Looking at the annual taxes the situation is different, their dependency is resumed in the table 3.22. In each of these cases, the calculation of the tax is

Germany	CO_2 emissions and cylinder capacity
France	Fiscal power (hp) and CO_2 emissions
Sweden	CO_2-emission and fuel type
Spain	Engine rating (hp)
Netherlands	GVW, province, fuel, CO_2 emissions
Austria	Engine power (kW) and CO_2 emissions

Table 3.22: Annual taxes dependency.

based on different assumptions that is difficult to translate from one country to the other. For this reason, and noting that the order of magnitude of the results is the same for each country, Germany has been chosen as a reference case study for this section. As said, the calculation of the ownership tax in Germany is based on the CO_2 emissions and on the cylinder capacity. At this moment the zero emissions passenger vehicles are exempted from taxation for ten years and then are taxed at 50% according to their cylinder capacity. The average annual cost is going to be calculated assuming an average emission of 120 g/km, taxed at 2,20 € for every gram over 95 g/km, and cylinder capacity of 1000cc, taxed at 9,5 € for every 100cc for a diesel car. The final annual cost for diesel vehicles and the annual cost after year 10 for electric vehicles is resumed in the table 3.23.

ICE Diesel	BEV & FCEV
150 €/yr	60 €/yr

Table 3.23: Annual taxes.

3.4.6 Financial parameters

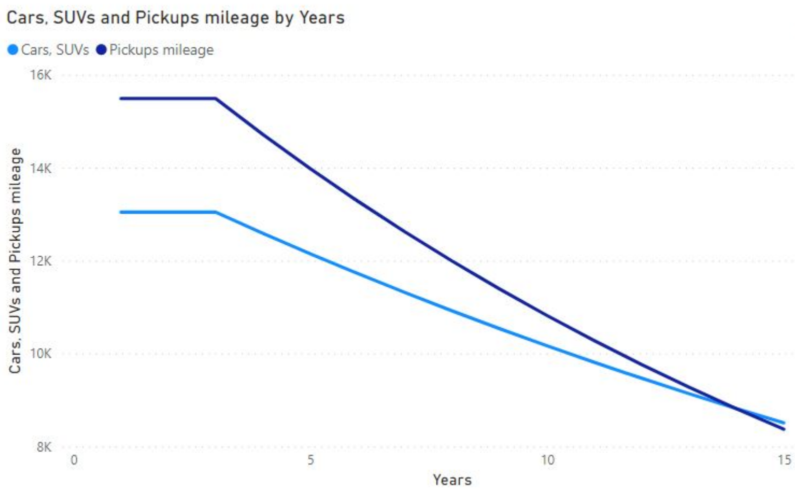
In every economic analysis is necessary to discount the amount of money to take into account the fact that it loses value with the passage of time. In this work, all the values are expressed with respect to a single price year (2020). Subsequently, the money is discounted by choosing between the nominal discount rate that, differently from the real one, takes into account also inflation.
According to Lebeau et al. [77], a real discount rate is recommended for TCO calculations in order to avoid the complex accounting for inflation.
Research about the actual value of discount rate in the European market has been done and, following the interest rate for households' loans statistics, a value of 3 % has been assumed.
Consequently, the loan parameters for the simulation can be chosen, since the interest rates of the loans are higher than the discount rate. In all the simulations under analysis, a 5-year loan with an interest rate of 5% is assumed.

3.4.7 Mileage

The mileage is a crucial parameter for the analysis, being fuel, maintenance and repair costs dependent on it. The correct assumption has to be done about the first-year mileage and its trend during the lifetime; this choice has an important influence on the TCO because it means to give different weight to the costs during the years, indeed the same total mileage can give different results from an economic point of view, both for the lower value of money and for the different cost of fuels and repair over the years.

Different approaches come out from the bibliography review, many TCO studies ([85] ,[75], [76], [48], [86], [87],[77]) use a constant mileage along the lifetime of the vehicle, differently the Burnham's approach [59], based on the Final Regulatory Impact Analysis (FRIA) from the Safer Affordable Fuel-Efficient (SAFE) Vehicles Rule published by NHTSA and EPA, shows a decreasing trend over the years for different segments. All these studies are referred to the American market. The trend is confirmed for Europe by Dun et al. [88], which shows a constant trend in the first three years of

lifetime that subsequently decreases every year. In Dun's study, a big difference in mileage is pointed out between the first three years of the lifetime of diesel cars with respect to petrol cars. The author highlight how the difference is due to the fact that diesel cars are often used as company cars in their first years and successively they pass to the second-hand market, characterized by lower mileage.
In this study, the point of view of a private consumer is taken into account and so the final choice is to consider the trend discovered by Dun for the petrol cars as reference mileage for all the medium segments, independently from the technologies, as hypothesised by Burnham et al.; also the difference between the different segment is considered as proportionally the same with respect to his hypothesis, with the biggest segments that begin from a higher mileage reaching approximately the same annual kilometers as cars at the end of their lifetime.



Years	Cars, SUVs	Pickups mileage
1	13.045,00	15.490,94
2	13.045,00	15.490,94
3	13.045,00	15.490,94
4	12.588,43	14.716,39
5	12.147,83	13.980,57
6	11.722,66	13.281,54
7	11.312,36	12.617,47
8	10.916,43	11.986,59
9	10.534,36	11.387,26
10	10.165,65	10.817,90
11	9.809,86	10.277,00
12	9.466,51	9.763,15
13	9.135,18	9.275,00
14	8.815,45	8.811,25
15	8.506,91	8.370,68

Figure 3.6: Annual mileage (km).

Tool design

In this chapter, the appearance and the main functions of the tool are going to be shown. All the output exposed has the objective to demonstrate how the tool works and which outputs are possible to extrapolate from it without discussing quantitative results, which will be the subjects of the next chapter.
The tool has been developed using Excel, it is divided into seven sheets, each one with a different task, and, as said, its future perspective is to be translated into python language, with the final aim to integrate it into a bigger tool regarding hydrogen mobility. The user is guided to the use of the tool by the different colours of the cells, that differentiate between five different kinds of cells: customizable values in green, the intermediate calculations in light blue, the suggested values in orange, the output of the sheet in yellow and, finally, the cells that are not available for the vehicle selected in red.
Furthermore, the Excel Virtual Basic Assistant has been used, by means of the Excel "Developer" section, to create buttons containing Macros, some functions that permit to automatize the sheets, making them more user-friendly.

4.1 List of data

The first sheet is the "List of data", which has the aim of resuming all the data used inside the tool in order to give the user a full overview of the hypotheses of the work and recall them in the other sections of the tool when they are needed, this aspect can be very useful in case of future changes in the assumptions used; in that case only the change of the values inside the section under analysis will be required.
The sheet is mainly composed of non-customizable cells, apart from the one linked to the fuel costs, which are modifiable by the user, and it is divided into three parts.
The first part is shown in the figure 4.1, the reference cases among which is possible to choose inside the green cells are listed: timeframe, powertrain technologies, segments, countries (with the correspondent values for subsidies, VAT and average insurance premium), technology evolution and the change Euro/Dollar in 2020.

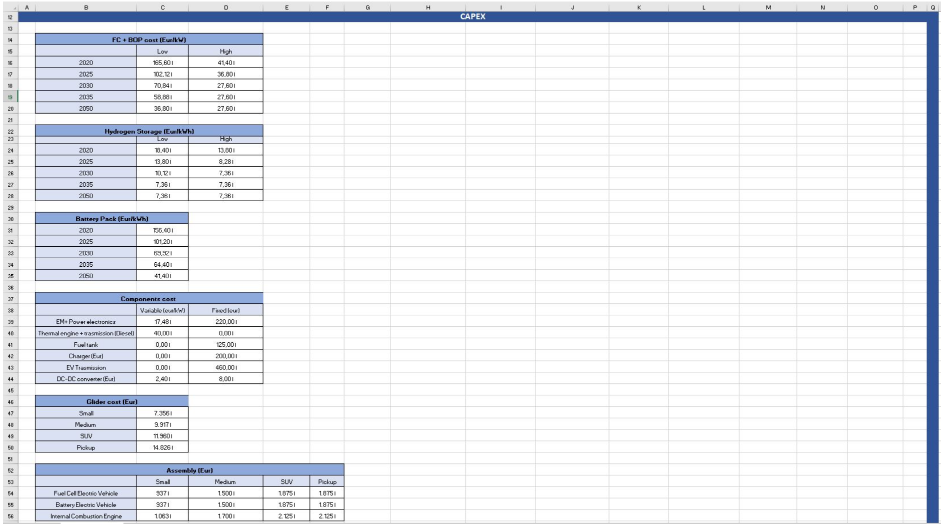
Reference cases

Timeframe	Powertrains	Segment	Countries	VAT	Purchase subsidies	Insurance	Technology Evolution	Change Eur/$
2020	Fuel Cell Electric Vehicle	Small	Germany	19%	9.000 €	500 €	Low	0,92
2025	Battery Electric Vehicle	Medium	France	20%	3.000 €	400 €	High	
2030	Internal Combustion Engine	SUV	Sweden	25%	6.000 €	200 €		
2035		Pickup	Spain	21%	4.500 €	350 €		
2050			Netherlands	21%	6.586 €	400 €		
			Austria	20%	3.000 €	300 €		
			NONE	0%	0 €	350 €		

Figure 4.1: List of data - Reference cases.

The second part contains all the data regarding the manufacturing cost of the vehicle components (fuel cell, hydrogen storage, battery other components, battery and assembly), catalogued for technology evolution, technology type, segment or timeframe depending on the component. This part is displayed in the image 4.2.
The third and last part (figure 4.3) has the same aim as the previous one but it regards the operation and maintenance costs and function coefficients. As said, it is the only one that contains cells (the ones referred to electricity and diesel cost trend evolution) that is possible to custom from their default

value of 0%. The other tables contain the price values and coefficients, also in this case properly catalogued, regarding fuel, depreciation, fuel economy, maintenance and repair that have been presented in the previous chapters.



CAPEX

FC + BOP cost (Eur/kW)		
	Low	High
2020	165,60ı	41,40ı
2025	102,12ı	36,80ı
2030	70,84ı	27,60ı
2035	58,88ı	27,60ı
2050	36,80ı	27,60ı

Hydrogen Storage (Eur/kWh)		
	Low	High
2020	18,40ı	13,80ı
2025	13,80ı	8,28ı
2030	10,12ı	7,36ı
2035	7,36ı	7,36ı
2050	7,36ı	7,36ı

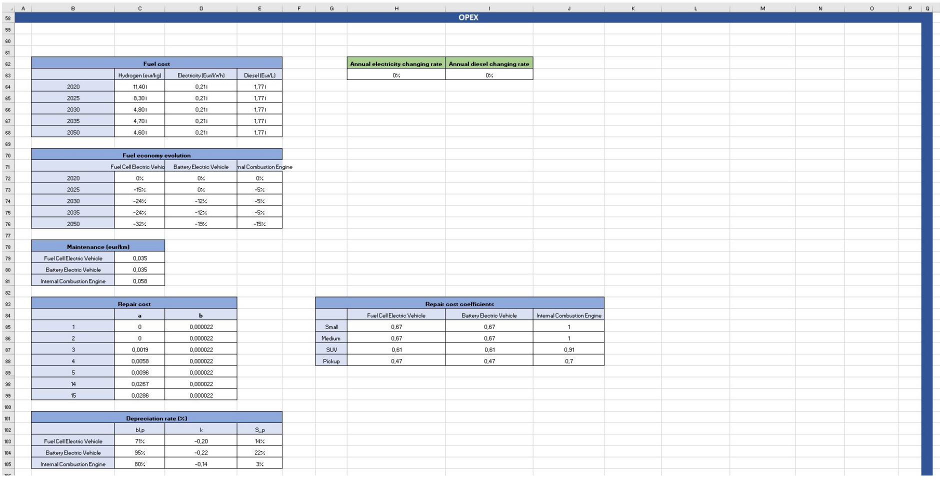
Battery Pack (Eur/kWh)	
2020	156,40ı
2025	101,20ı
2030	69,92ı
2035	64,40ı
2050	41,40ı

Components cost		
	Variable (eur/kW)	Fixed (eur)
EM+ Power electronics	17,48ı	220,00ı
Thermal engine + trasmission (Diesel)	40,00ı	0,00ı
Fuel tank	0,00ı	125,00ı
Charger (Eur)	0,00ı	200,00ı
EV Trasmission	0,00ı	460,00ı
DC-DC converter (Eur)	2,40ı	8,00ı

Glider cost (Eur)	
Small	7.356ı
Medium	9.917ı
SUV	11.960ı
Pickup	14.826ı

Assembly (Eur)				
	Small	Medium	SUV	Pickup
Fuel Cell Electric Vehicle	937ı	1.500ı	1.875ı	1.875ı
Battery Electric Vehicle	937ı	1.500ı	1.875ı	1.875ı
Internal Combustion Engine	1.063ı	1.700ı	2.125ı	2.125ı

Figure 4.2: List of data - CAPEX values.



OPEX

Fuel cost			
	Hydrogen (eur/kg)	Electricity (Eur/kWh)	Diesel (Eur/L)
2020	11,40ı	0,21ı	1,77ı
2025	8,30ı	0,21ı	1,77ı
2030	4,80ı	0,21ı	1,77ı
2035	4,70ı	0,21ı	1,77ı
2050	4,60ı	0,21ı	1,77ı

Annual electricity changing rate	Annual diesel changing rate
0%	0%

Fuel economy evolution			
	Fuel Cell Electric Vehic	Battery Electric Vehicle	nal Combustion Engine
2020	0%	0%	0%
2025	-15%	0%	-5%
2030	-24%	-12%	-5%
2035	-24%	-12%	-5%
2050	-32%	-19%	-15%

Maintenance (eur/km)	
Fuel Cell Electric Vehicle	0,035
Battery Electric Vehicle	0,035
Internal Combustion Engine	0,058

Repair cost		
	a	b
1	0	0,000022
2	0	0,000022
3	0,0019	0,000022
4	0,0058	0,000022
5	0,0096	0,000022
14	0,0267	0,000022
15	0,0286	0,000022

Repair cost coefficients			
	Fuel Cell Electric Vehicle	Battery Electric Vehicle	Internal Combustion Engine
Small	0,67	0,67	1
Medium	0,67	0,67	1
SUV	0,61	0,61	0,91
Pickup	0,47	0,47	0,7

Depreciation rate (%)			
	bl,p	k	S_p
Fuel Cell Electric Vehicle	71%	-0,20	14%
Battery Electric Vehicle	95%	-0,22	22%
Internal Combustion Engine	80%	-0,14	3%

Figure 4.3: List of data - OPEX values.

4.2 Design of the vehicle

The second sheet is dedicated to the definition of the case study needed by the user. Firstly it is necessary to define all the boundary conditions of the case study, selecting the reference country and choosing segment, powertrain technologies, technology evolution and if subsidies are considered or not. Subsequently, all the specifications of the vehicle must be specified, together with its consumption profile and, as a consequence, its storage profile. In this process some cells are only available for certain kinds of vehicles: it is possible, for example, to select a power of the fuel cell only for FCEV. Another characteristic of this sheet is the presence of two tables with the suggested values for fuel economy and autonomy, which are useful to define these characteristics of the vehicle if real data are not available. At the same time, the values are not been automatically inserted to leave the user free to do his estimations in the value to use, being the variance in the average values not negligible.
Furthermore, the Excel Virtual Basic Assistant has been used to create two commands: one to automatically reset the cells before starting to use the tool and one to save the vehicle in the "List of vehicles" sheet, which is going to be presented in the next section.

Once completely defined the characteristics of the vehicle, the data are used to calculate its retail price, choosing the share of cost due to transportation, manufacturer margin and retail margin, which can be left as default or changed on the basis of the information known from the user. The final cost is calculated by summing the cost of each component and differentiating between the price with and without incentives in case they are considered. Both the results are stored in the "List of vehicles" sheet if the vehicle under analysis is saved. All this part of the sheet is shown in the figure 4.4.
At the end of the sheet some charts are produced (figure 4.5), they are part of the results under analysis, highlighting the components of the final retail price both in absolute value (column chart) and in relative value (pie chart).

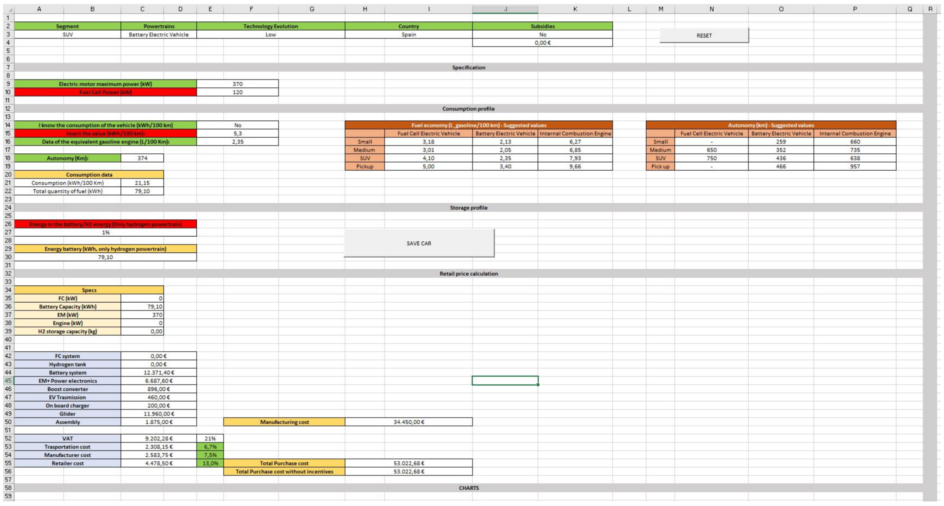


Figure 4.4: Vehicle design - Part 1

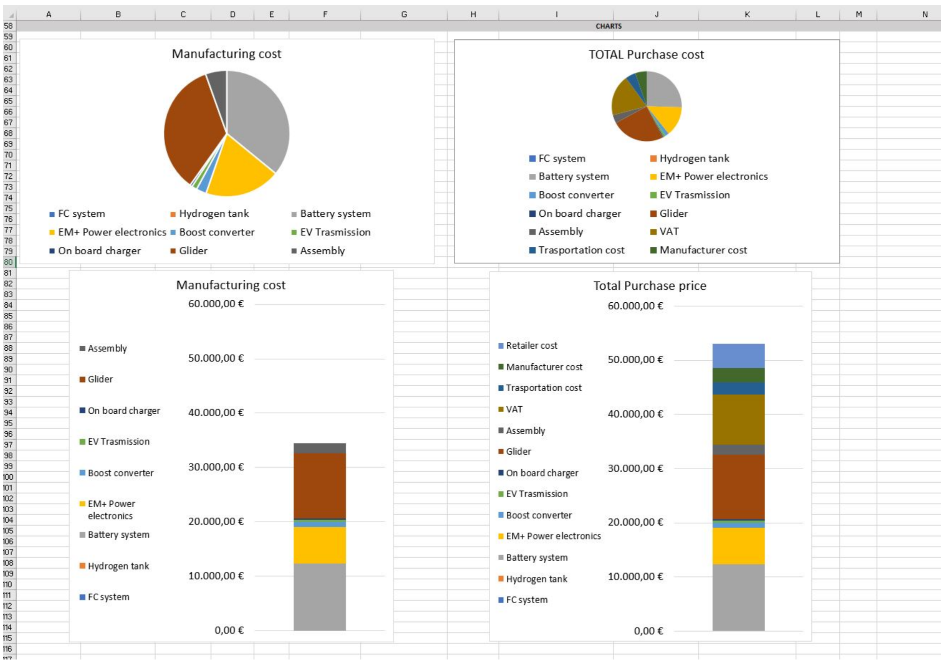


Figure 4.5: Vehicle design - Part 2

4.3 List of vehicles

"List of vehicles" is the sheet, organized as a big table, where all the vehicles that have been designed are stored in order to permit the comparison between them in the subsequent sections. The table stores twelve vehicles divided into four segments and three technologies, reporting their power, storage, consumption, autonomy and price. This section of the tool permits to have a complete overview of the case studies before passing to the TCO evaluation and forecast.

	Powertrains	Engine Power (kW)	Power EM (kW)	Power FC (kW)	Hydrogen tank capacity	Energy battery (kWh)	Range	Consumption (/100km)	Manufacturing cost	Purchase Cost	Purchase cost wtout incentives
					Small						
Small	Fuel Cell Electric Vehicle	0	100	80	4,7	1,6	550	0,86	27.923 €	31.206 €	40.206 €
	Battery Electric Vehicle	0	96	0	0,0	57,9	302	19,17	20.144 €	31.005 €	31.005 €
	Internal Combustion Engine	100	0	0	0,0	0,0	660	5,67	13.081 €	18.836 €	18.836 €
					Medium						
Medium	Fuel Cell Electric Vehicle	0	120	134	5,6	1,9	700	0,80	40.407 €	61.677 €	61.677 €
	Battery Electric Vehicle	0	150	0	0,0	64,9	352	18,45	25.444 €	27.637 €	36.637 €
	Internal Combustion Engine	150	0	0	0,0	0,0	735	6,20	17.642 €	25.402 €	25.402 €
					SUV						
SUV	Fuel Cell Electric Vehicle	0	95	120	6,4	1,5	756	0,84	40.410 €	62.196 €	62.196 €
	Battery Electric Vehicle	0	370	0	0,0	79,1	374	21,15	34.450 €	53.023 €	53.023 €
	Internal Combustion Engine	96	0	0	0,0	0,0	750	5,30	18.050 €	27.781 €	27.781 €
					Pickup						
Pick up	Fuel Cell Electric Vehicle	0	180	150	9,5	1,6	700	1,35	52.674 €	66.845 €	75.845 €
	Battery Electric Vehicle	0	180	0	0,0	183,6	650	30,60	50.707 €	64.013 €	73.013 €
	Internal Combustion Engine	180	0	0	0,0	0,0	800	8,74	24.951 €	35.927 €	35.927 €

Figure 4.6: List of vehicles.

4.4 Retail price comparison

Once created all the case studies needed, it is possible to move to a comparison of their manufacturing cost (figure 4.7), to highlight differences and analogies in the total cost of different segments and technologies, this aspect has been considered important being the expenditure for the vehicle the biggest cost during lifetime. The sheet requires firstly the choice of technology evolution, country and if subsidies are considered or not; secondly three vehicles from the list have to be selected with the apposite cells, a little table resume their specifications, which are finally used to calculate the manufacturing cost by means of the cost of the single components. Also in this case a chart is produced to resume the results obtained, which are going to be discussed in the next chapter.

Scenario selection

Technology Evolution	Country	Subsidies
High	France	Yes

Vehicle retail price comparison

	Segment	Segment	Segment	
	Medium	Medium	Medium	
	Powertrains	Powertrains	Powertrains	
	Fuel Cell Electric Vehicle	Battery Electric Vehicle	Internal Combustion Engine	
	Specs			
FC (kW)	134	0	0	
Battery Capacity (kWh)	1,87	64,94	0,00	
EM (kW)	120	150	0	
Engine (kW)	0	0	150	
H2 storage capacity (kg)	5,60	0,00	0,00	
FC system	5.547,60I	0,00I	0,00I	
Hydrogen tank	2.575,74I	0,00I	0,00I	
Battery system	291,92I	10.157,24I	0,00I	
E + Trasm+ Tank"/"EM+ Electronic	2.317,60I	2.842,00I	6.125,00I	
Boost converter	296,00I	368,00I	0,00I	
EV Trasmission	460,00I	460,00I	0,00I	
On board charger	0,00I	200,00I	0,00I	
Glider	9.916,68I	9.916,68I	9.916,68I	
Assembly	1.500,00I	1.500,00I	1.700,00I	
VAT	5.827,17I	6.472,93I	4.513,48I	20%
Trasportation cost	1.534,67I	1.704,74I	1.188,69I	6,7%
Manufacturer	1.717,92I	1.908,29I	1.330,63I	7,5%
Retailer	2.977,72I	3.307,71I	2.306,42I	13,0%
Total Purchase cost	34.963,02I	38.837,60I	27.080,90I	
tal Purchase cost without incentiv	34.963,02I	38.837,60I	27.080,90I	
	Medium -FCEV	Medium -BEV	Medium -ICE	

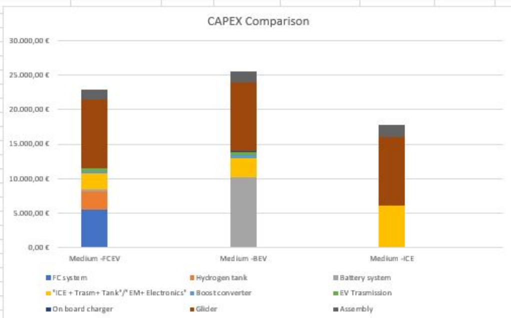


Figure 4.7: Retail price comparison.

4.5 TCO calculation

Once that a full picture of the capital expenditure for the vehicle has been obtained, it is possible to move on to the calculation of TCO and LCOD. Also in this case is previously required to choose the vehicle under analysis, the country, if subsidies are considered and, differently from the previous case, how many kilometers are travelled during the first three years, in accordance with the trend chosen in the previous chapter, together with the trend in all the years after the third.
Following this, it is necessary to specify the data required for the financial term (if a loan is considered, its annual percentage rate and its duration) and the discount rate along the life of the vehicle.
At this point, the TCO and the LCOD are calculated making explicit the annual cost of all the single terms that compose their formulation. Also in this case the proper graphs are used to correctly show the results to the user. All functions explained and described are illustrated in the figure 4.8.

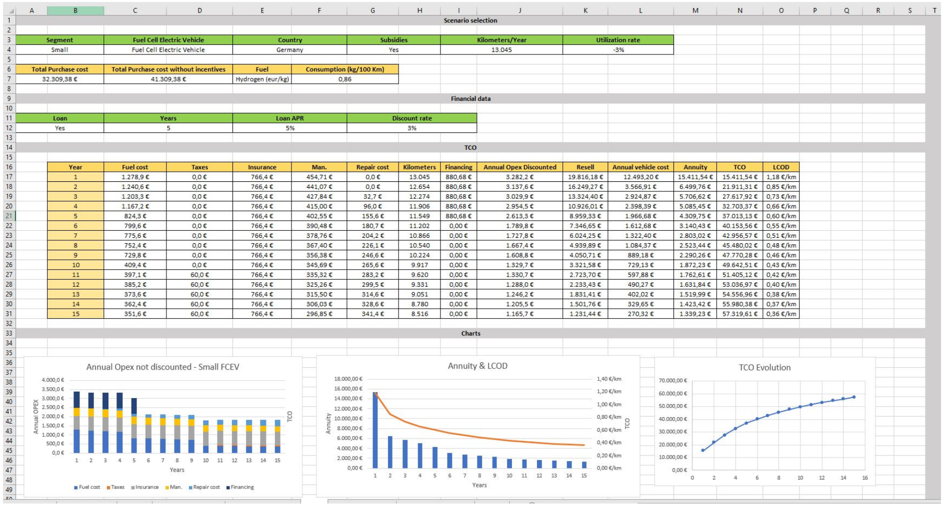


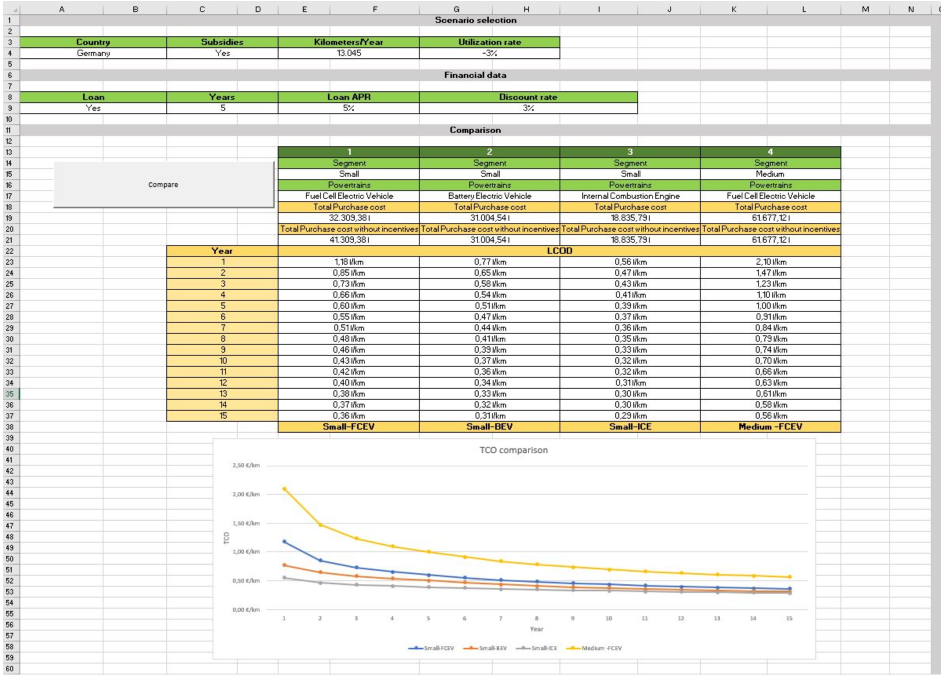
Figure 4.8: TCO calculation.

4.6 TCO comparison

Another important point of the study performed is the comparison between the TCO of the different LDVs, for this reason a section of the tool has been dedicated to this aspect (figure 4.9). The sheet has the same organization as the previous one; at the beginning the data regarding vehicle, country, mileage and finance are required, following, the choice of four vehicles to analyse is required. In the end, the retail price and the LCOD are calculated by means of the command "compare" created using the VBA Excel tool. The results are again shown using a proper graph.

4.7 Forecast up to 2050

The last section of the tool is dedicated to the forecast of the TCO up to 2050. In the first part of the sheet (figure 4.10), the data required to define the contest are inserted again to calculate the retail price for the five vehicles selected, with the difference respect to the previous sections that the insertion of the reference year is required to correctly assess the difference in the price due to the evolution of the technology. Once compiled all the green cells, the button "Forecast" has to be used to run the section and permit all the calculations. At this point, in the second part of the sheet (figure 4.11) all the results are represented, firstly with a table containing the LCOD data and secondly with a series of figures which represent the retail price and the evolution of the cost of ownership along the years.



Scenario selection

Country	Subsidies	Kilometers/Year	Utilization rate
Germany	Yes	13.045	-3%

Financial data

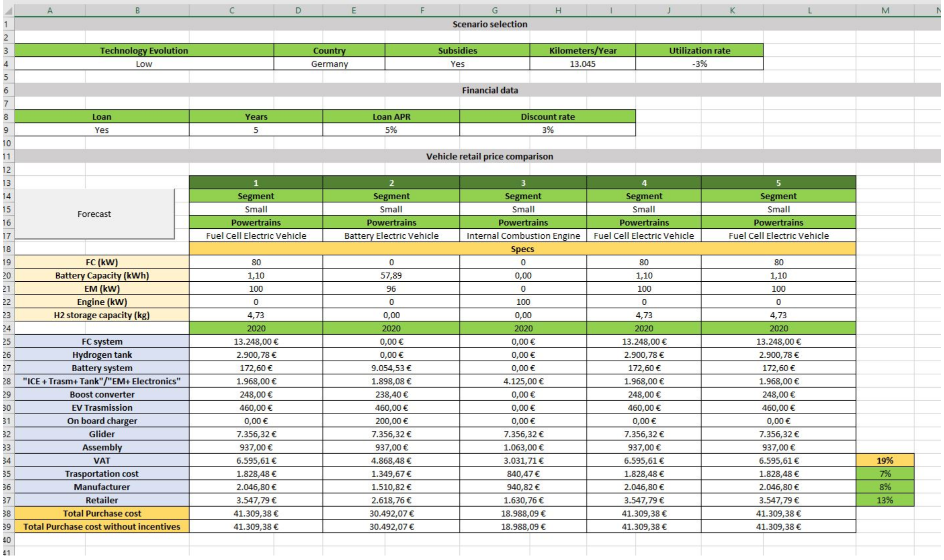
Loan	Years	Loan APR	Discount rate
Yes	5	5%	3%

Comparison

Compare

	1	2	3	4
	Segment	Segment	Segment	Segment
	Small	Small	Small	Medium
	Powertrains	Powertrains	Powertrains	Powertrains
	Fuel Cell Electric Vehicle	Battery Electric Vehicle	Internal Combustion Engine	Fuel Cell Electric Vehicle
	Total Purchase cost	Total Purchase cost	Total Purchase cost	Total Purchase cost
	32.309,38	31.004,54	18.835,79	61.677,12
	Total Purchase cost without incentives	Total Purchase cost without incentives	Total Purchase cost without incentives	Total Purchase cost without incentives
	41.309,38	31.004,54	18.835,79	61.677,12
Year	LCOD			
1	1,18 l/km	0,77 l/km	0,56 l/km	2,10 l/km
2	0,85 l/km	0,65 l/km	0,47 l/km	1,47 l/km
3	0,73 l/km	0,58 l/km	0,43 l/km	1,23 l/km
4	0,66 l/km	0,54 l/km	0,41 l/km	1,10 l/km
5	0,60 l/km	0,51 l/km	0,39 l/km	1,00 l/km
6	0,55 l/km	0,47 l/km	0,37 l/km	0,91 l/km
7	0,51 l/km	0,44 l/km	0,36 l/km	0,84 l/km
8	0,48 l/km	0,41 l/km	0,35 l/km	0,79 l/km
9	0,46 l/km	0,39 l/km	0,33 l/km	0,74 l/km
10	0,43 l/km	0,37 l/km	0,32 l/km	0,70 l/km
11	0,42 l/km	0,36 l/km	0,32 l/km	0,66 l/km
12	0,40 l/km	0,34 l/km	0,31 l/km	0,63 l/km
13	0,38 l/km	0,33 l/km	0,30 l/km	0,61 l/km
14	0,37 l/km	0,32 l/km	0,30 l/km	0,58 l/km
15	0,36 l/km	0,31 l/km	0,29 l/km	0,56 l/km
	Small-FCEV	Small-BEV	Small-ICE	Medium -FCEV

Figure 4.9: TCO comparison.



Scenario selection

Technology Evolution	Country	Subsidies	Kilometers/Year	Utilization rate
Low	Germany	Yes	13.045	-3%

Financial data

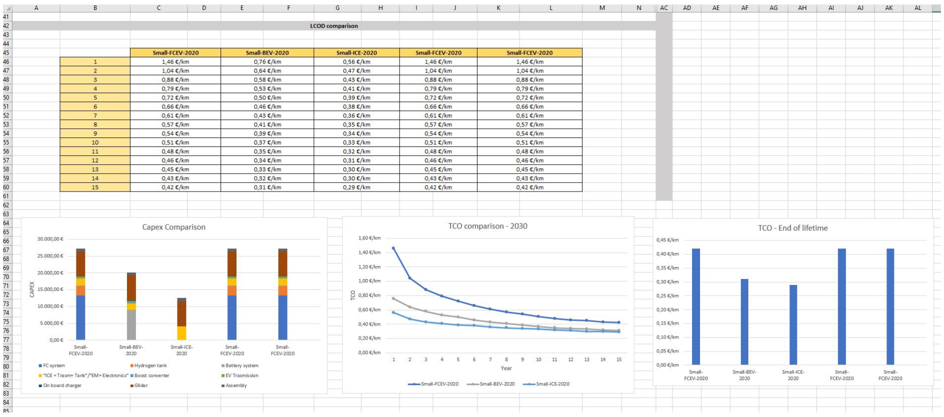
Loan	Years	Loan APR	Discount rate
Yes	5	5%	3%

Vehicle retail price comparison

Forecast

	1	2	3	4	5	
	Segment	Segment	Segment	Segment	Segment	
	Small	Small	Small	Small	Small	
	Powertrains	Powertrains	Powertrains	Powertrains	Powertrains	
	Fuel Cell Electric Vehicle	Battery Electric Vehicle	Internal Combustion Engine	Fuel Cell Electric Vehicle	Fuel Cell Electric Vehicle	
	Specs					
FC (kW)	80	0	0	80	80	
Battery Capacity (kWh)	1,10	57,89	0,00	1,10	1,10	
EM (kW)	100	96	0	100	100	
Engine (kW)	0	0	100	0	0	
H2 storage capacity (kg)	4,73	0,00	0,00	4,73	4,73	
	2020	2020	2020	2020	2020	
FC system	13.248,00 €	0,00 €	0,00 €	13.248,00 €	13.248,00 €	
Hydrogen tank	2.900,78 €	0,00 €	0,00 €	2.900,78 €	2.900,78 €	
Battery system	172,60 €	9.054,53 €	0,00 €	172,60 €	172,60 €	
"ICE + Trasm+ Tank"/"EM+ Electronics"	1.968,00 €	1.898,08 €	4.125,00 €	1.968,00 €	1.968,00 €	
Boost converter	248,00 €	238,40 €	0,00 €	248,00 €	248,00 €	
EV Trasmission	460,00 €	460,00 €	0,00 €	460,00 €	460,00 €	
On board charger	0,00 €	200,00 €	0,00 €	0,00 €	0,00 €	
Glider	7.356,32 €	7.356,32 €	7.356,32 €	7.356,32 €	7.356,32 €	
Assembly	937,00 €	937,00 €	1.063,00 €	937,00 €	937,00 €	
VAT	6.595,61 €	4.868,48 €	3.031,71 €	6.595,61 €	6.595,61 €	19%
Trasportation cost	1.828,48 €	1.349,67 €	840,47 €	1.828,48 €	1.828,48 €	7%
Manufacturer	2.046,80 €	1.510,82 €	940,82 €	2.046,80 €	2.046,80 €	8%
Retailer	3.547,79 €	2.618,76 €	1.630,76 €	3.547,79 €	3.547,79 €	13%
Total Purchase cost	41.309,38 €	30.492,07 €	18.988,09 €	41.309,38 €	41.309,38 €	
Total Purchase cost without incentives	41.309,38 €	30.492,07 €	18.988,09 €	41.309,38 €	41.309,38 €	

Figure 4.10: Forecast up to 2050 - Part 1.



LCOD comparison

	Small-FCEV-2020	Small-BEV-2020	Small-ICE-2020	Small-FCEV-2020	Small-FCEV-2020
1	1,46 €/km	0,76 €/km	0,56 €/km	1,46 €/km	1,46 €/km
2	1,04 €/km	0,64 €/km	0,47 €/km	1,04 €/km	1,04 €/km
3	0,88 €/km	0,58 €/km	0,43 €/km	0,88 €/km	0,88 €/km
4	0,79 €/km	0,53 €/km	0,41 €/km	0,79 €/km	0,79 €/km
5	0,72 €/km	0,50 €/km	0,39 €/km	0,72 €/km	0,72 €/km
6	0,66 €/km	0,46 €/km	0,38 €/km	0,66 €/km	0,66 €/km
7	0,61 €/km	0,43 €/km	0,36 €/km	0,61 €/km	0,61 €/km
8	0,57 €/km	0,41 €/km	0,35 €/km	0,57 €/km	0,57 €/km
9	0,54 €/km	0,39 €/km	0,34 €/km	0,54 €/km	0,54 €/km
10	0,51 €/km	0,37 €/km	0,33 €/km	0,51 €/km	0,51 €/km
11	0,48 €/km	0,35 €/km	0,32 €/km	0,48 €/km	0,48 €/km
12	0,46 €/km	0,34 €/km	0,31 €/km	0,46 €/km	0,46 €/km
13	0,45 €/km	0,33 €/km	0,30 €/km	0,45 €/km	0,45 €/km
14	0,43 €/km	0,32 €/km	0,30 €/km	0,43 €/km	0,43 €/km
15	0,42 €/km	0,31 €/km	0,29 €/km	0,42 €/km	0,42 €/km

Figure 4.11: Forecast up to 2050 - Part 2.

Results

Once all the data have been collected and after constructing the methodology to be used, the TCO calculation can be performed. In this chapter, all the outcomes are exposed and commented with a focus on their interpretation and meaning. At the same time, the second important aspect that has to be taken into account is the assessment of the reliability of all the outcomes obtained.
The first step is the calculation of the vehicle retail price of the reference vehicles under examination. The results are compared between them with the aim to understand which components are crucial for the difference in price between the technologies. As said, to validate the results the data of some real vehicles available on the market have been inserted in the tool, comparing the outcomes with the real retail price available on the site of the manufacturer.
The second section, dedicated to the TCO calculation, gives the first answer to the question at the base of this work, assessing the most convenient technology considering the lifetime of the vehicles under analysis.
The same path is followed in the third section, dedicated to the forecast of the TCO up to 2050, this section is expected to show in which year is possible to expect a change in the current trend, with the cost of the FCEVs that are expected to decrease up to a level comparable with the other technologies. Finally, seeing the uncertainty in the outcomes given by the existence of different scenarios of interest for the hydrogen field, the sensitivity analysis is performed to assess which parameters have a major influence on the final results and, consequently, how much the results are reliable.
The data for the calculation performed are resumed in the table 5.1. In the cases where two scenarios are electable, the hydrogen tank and the fuel cell, a low production rate scenario has been considered more representative of the current market, letting the evaluation of other scenarios to the sensitivity analysis. The simulation is performed according to the hypothesis of no incentives on the purchase, because of the intention of comparing the retail prices considering the real cost of the technology. Additionally, German taxation and insurance schemes are considered and all the models are assumed in their base version, without any kind of optional component. All the figures presented to show the results represent the medium segment vehicles, considered the most representative segment of the current market. The outcomes coming from other segments are listed in the appendix if no relevant differences are highlighted.

5.1 Retail price

As said, the calculation of the retail price is the foremost step of this analysis, being the first and, at the same time, the biggest expense that has to be faced up by the consumer. The results for the medium segments are shown in figure 5.1. As expected, the FCEV is the most expensive vehicle due to the considerable cost of both the hydrogen tank and the fuel cell. The latter is the most expensive component among the three vehicles. In this scenario, independently from the results of the TCO calculation, a so high price difference already alone risks discouraging the diffusion of hydrogen vehicles so the role of subsidies and incentives for the purchase is crucial. The high cost of the battery makes the BEV the second technology on the market, quite detached from the ICEV cost which is more than 11.000 € lower, despite the higher cost of its engine with respect to an electric motor. The difference between these components is amplified by taxation and all the costs due to manufacturer and retailer markups and transportation, being expressed as a percentage of the total manufacturing cost. As it is possible to see a consistent part of the total price is independent of the technology, composing a base cost that is in common between all the cars studied. As anticipated, to confirm the capacity of the tool of assessing the retail price of different vehicles with a good degree of approximation, eight

Powertrain	Motor (kW)	FC (kW)	H_2 tank (Kg)	Battery (kWh)	Range (Km)	Cons. (/100km)
			Small			
FCEV	62	49	4,7	1,1	550	0,86 Kg
BEV	62	0	0	49,5	259	19,1 kWh
ICE	62	0	0	0	660	5,7 L
			Medium			
FCEV	102	81	5,3	1,2	650	0,81 Kg
BEV	102	0	0	64,8	352	18,4 kWh
ICE	102	0	0	0	735	6,2 L
			SUV			
FCEV	150	119	8,3	1,9	750	1,1 Kg
BEV	150	0	0	92,2	436	21,2 kWh
ICE	150	0	0	0	638	7,2 L
			Pickup			
FCEV	180	142	11,5	2,7	850	1,3 Kg
BEV	180	0	0	142,5	466	30,6 kWh
ICE	180	0	0	0	957	8,7 L

Table 5.1: Data for the base case simulation.

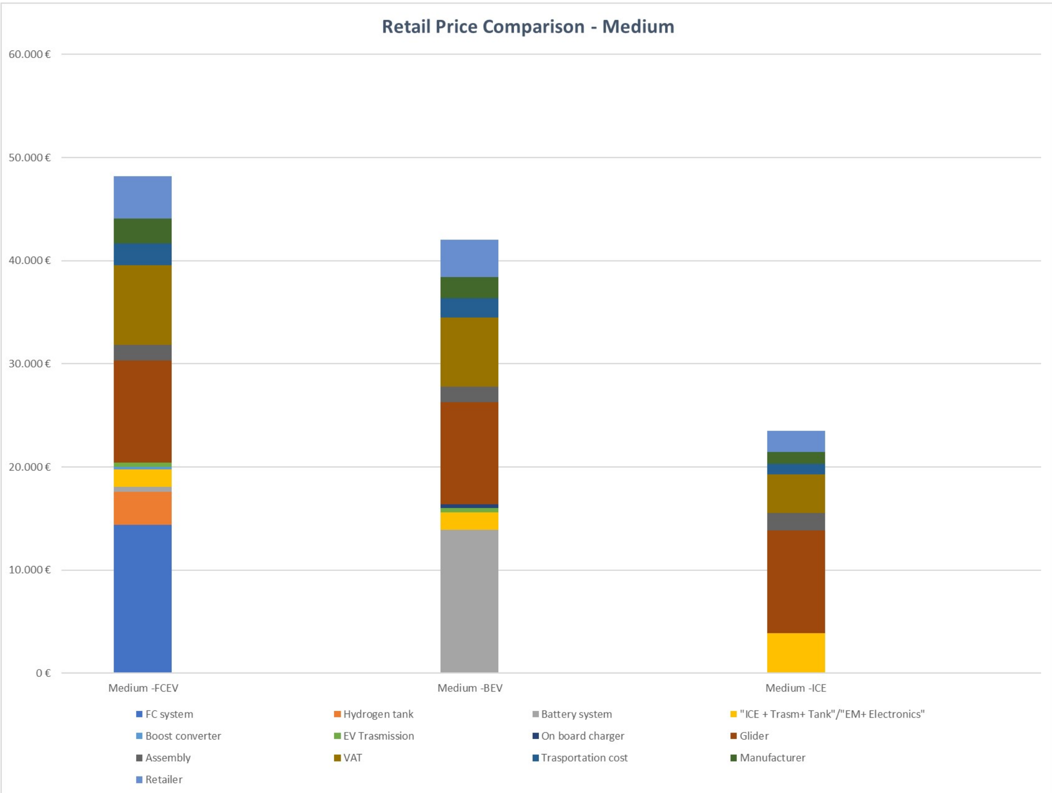


Figure 5.1: Retail price comparison- Medium segment.

vehicles, representing some of the combinations of segments and technology available in the market and listed in the table, have been inserted in the tool, comparing the outcomes obtained with the real prices proposed from the manufacturers. The comparison, resumed in table 5.2 and shown in figure 5.2, highlights how the tool has a good resolution in assessing the retail price of almost all the technologies. In general, the results lie in a 10% of precision when the vehicles fit all the hypotheses that have been made. An exception is found in those models that do not fall within the segments taken into consideration, like the BMW i4 (luxury segment) which even in the basic version has optional components included which invalidate the assumptions made for the estimate of the cost of the glider. Another unexpected trend is that of the Hyundai Nexo which is characterized by a price 15.000 € higher than Toyota Mirai, despite the higher motor power and fuel cell power than the latter. The reason for this result is probably associated with the fact that not having a fully developed market yet, the strategies within the price of hydrogen cars do not yet follow the conventional strategies. In light of this, behind the higher price of the Hyundai model, there may be the need to return to a higher investment in research and development of the vehicle or costs for the fuel cell and the tank not yet fully optimized.

Model	Size	Powertrain	Real price	Tool result	Uncertainty
Volkvagen T-Roc Diesel	SUV	Diesel	27.945 €	26.270 €	6%
Toyota Mirai	Medium	Hydrogen	63.900 €	58.138 €	9%
Hyunday Nexo	SUV	Hydrogen	77.290 €	55.496 €	28%
Renault Zoe E-Tech	Small	Electric	36.840 €	33.865 €	8%
Fiat 500	Small	Diesel	16.990 €	15.789 €	7%
Peugeot eSUV 2008	SUV	Electric	37.900 €	41.000 €	-8%
BMW i4	Medium	Electric	56.500 €	47.432 €	16%
Ford Fiesta Active	Medium	Diesel	23.400 €	21.980 €	6%

Table 5.2: Results reliability study

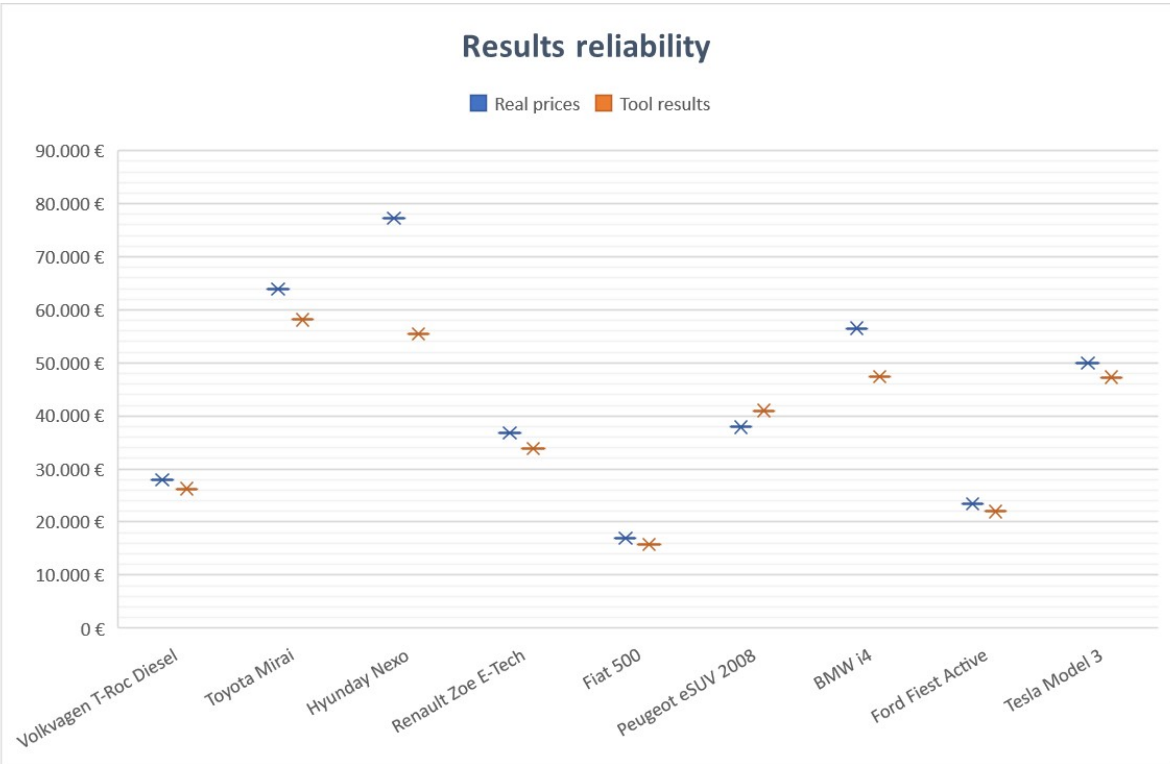


Figure 5.2: Results reliability study.

5.2 TCO

The following figures show the results that compose the TCO calculation. In the first group (figures 5.3) the annual O&M costs composition is examined in order to highlight the most expensive terms among the selected and the difference in the annual cost for each vehicle. In the second group of figures (5.4) the depreciation of the vehicles is added and the total annuity obtained is discounted, highlighting on the secondary axis the variation of the LCOD. Finally, the evolution of the vehicle TCO and LCOD is displayed.

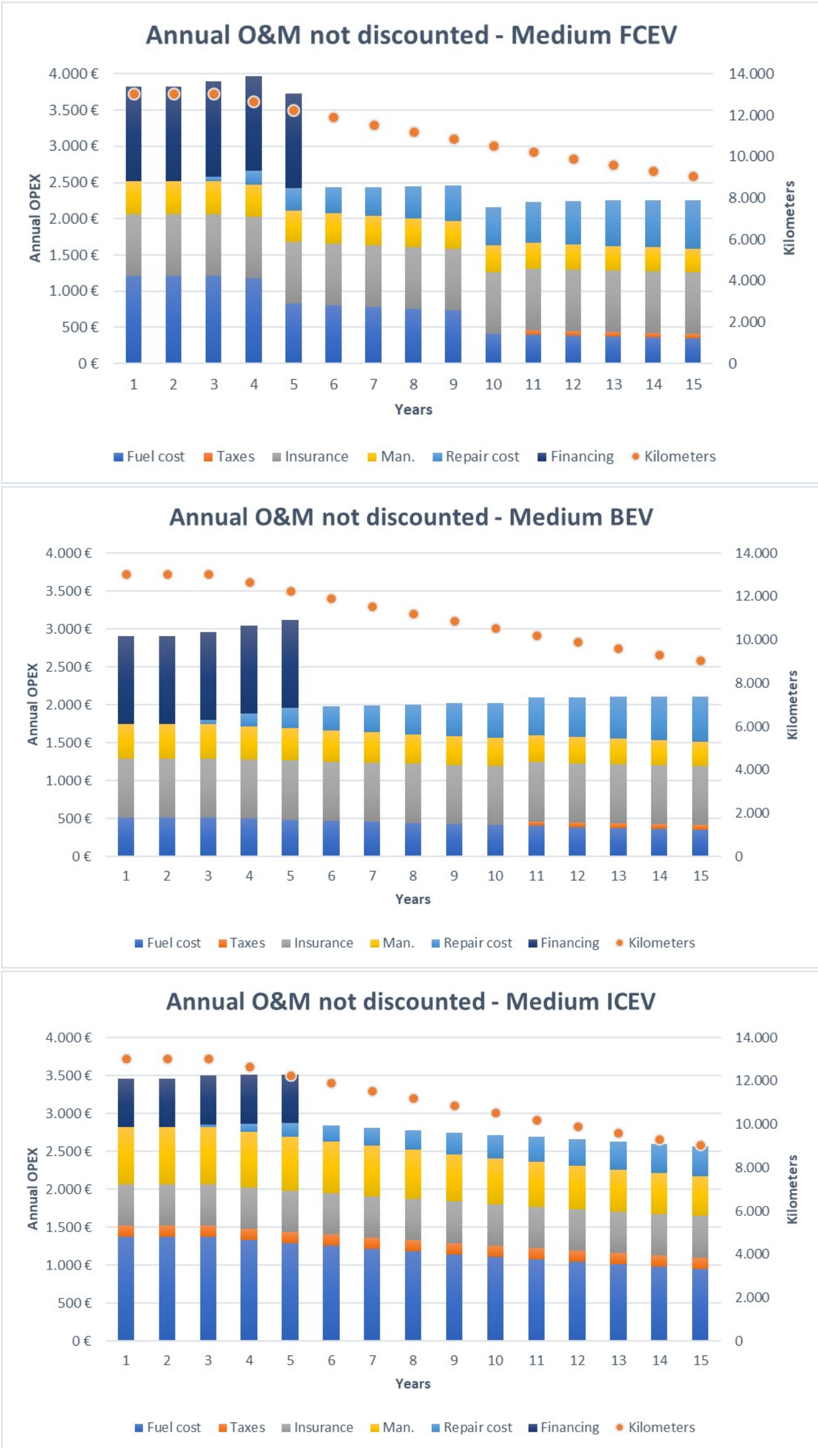


Figure 5.3: Annual O&M cost not discounted.

After analysing the not discounted annual O&M the most relevant outcomes can be resumed in the following item:

1. In the case of a loan, the higher retail price of the EVs results in a huge difference in the financing term that makes the FCEV the most expensive vehicle in the first years of lifetime.
2. Not considering the payment for the interest of an eventual loan, the vehicle characterized by the higher annual cost is the ICEV because of the higher expenses for fuel and maintenance. On the other side, the cheapest technology is the BEV, characterized by the lowest annual cost of fuel. The FCEV can compete with the BEV at the end of its lifetime, in accordance with the expected decrease in the hydrogen cost.
3. The only technology which shows an increasing trend in the annual cost is the battery one, where the increase in the repair cost overcomes the decrease of the fuel cost due to the decrease of the annual mileage.
4. The calculation of taxes is not relevant to the TCO.

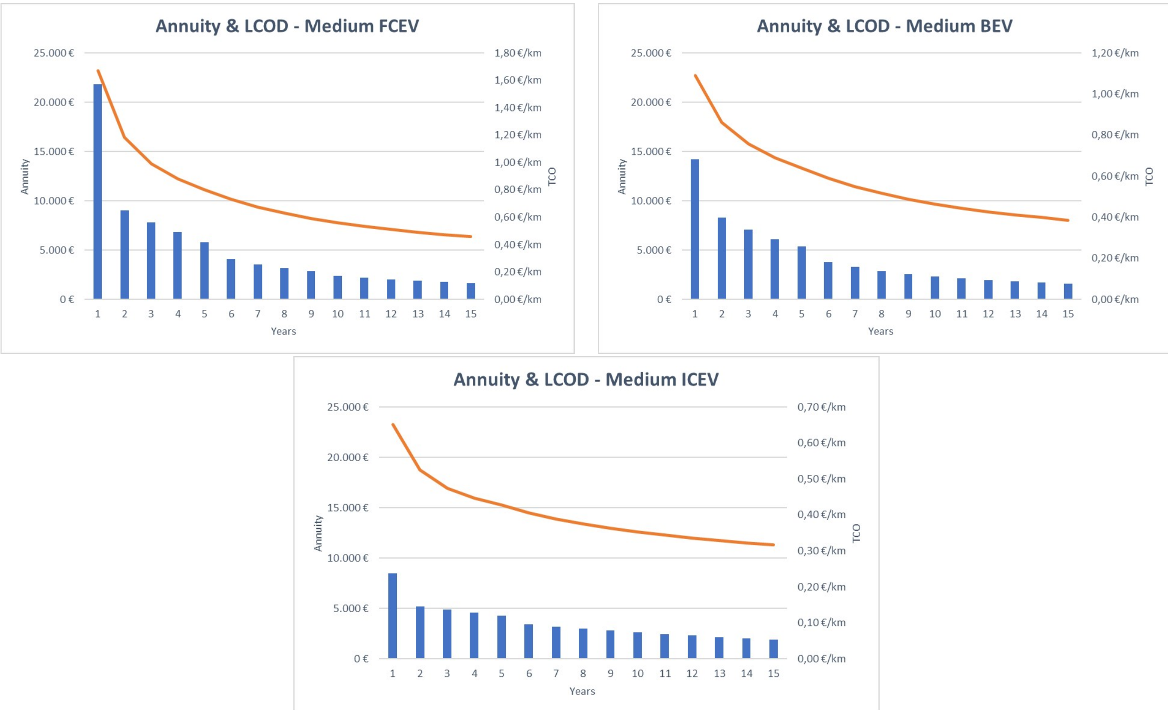


Figure 5.4: Discounted annuity and LCOD.

Looking at the second series of figures, it is possible to deduce that the cost of the vehicle is the most relevant cost in the analysis. The three technologies show the same trend, indeed the annuity decreases over the years because of the lower impact of the vehicle cost. In the case of the FCEV the combination of the high retail price and the high first-year depreciation results in a really high cost, higher than 20.000 € for the first year of life which is crucial in electing the FCEV as the most expensive technology to own.
Finally, looking at the figures 5.5 and 5.6 is possible to comment on the trends of TCO and LCOD. The figures confirm that currently there is a marked difference between the three different kinds of powertrain over the lifetime. As said, the FCEV is the most expensive technology, followed by the BEV, this result, considering the lower O&M cost of the zero-emission technologies, confirms how the retail price is the most important cost to cut to compete in the market. Going more into detail, figure 5.7 shows how the difference in the total cost between FCEV/BEV and ICE reaches a maximum and then progressively decreases when the O&M costs start to have more weight than the vehicle depreciation. Differently, the difference between FCEV and BEV constantly increases because of the both lower price and O&M costs of the battery technology.

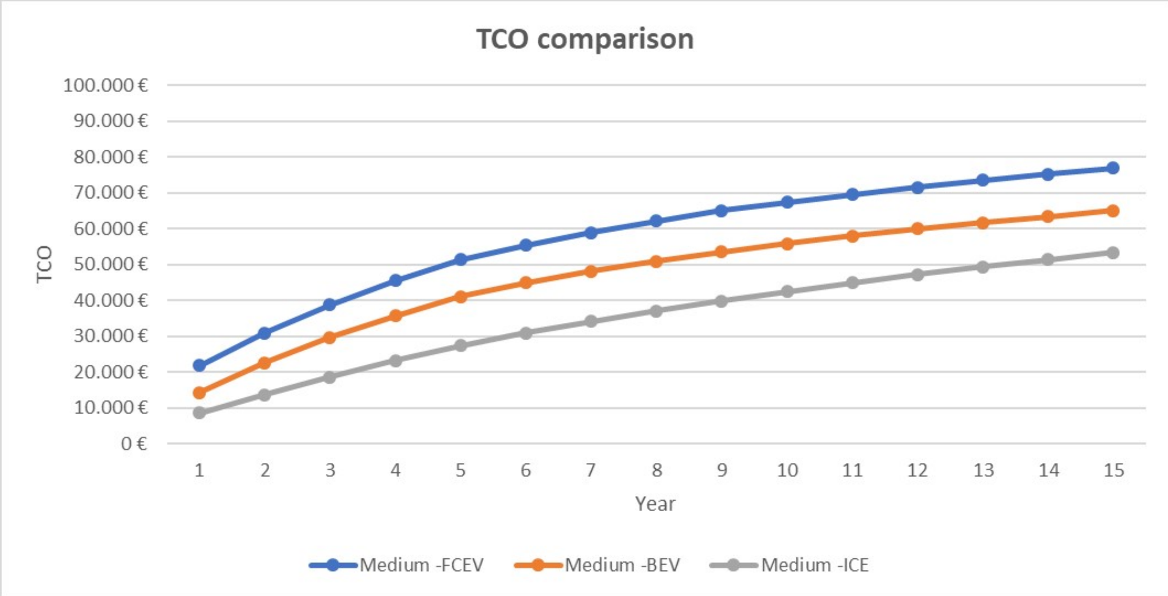


Figure 5.5: TCO comparison - Medium segment.

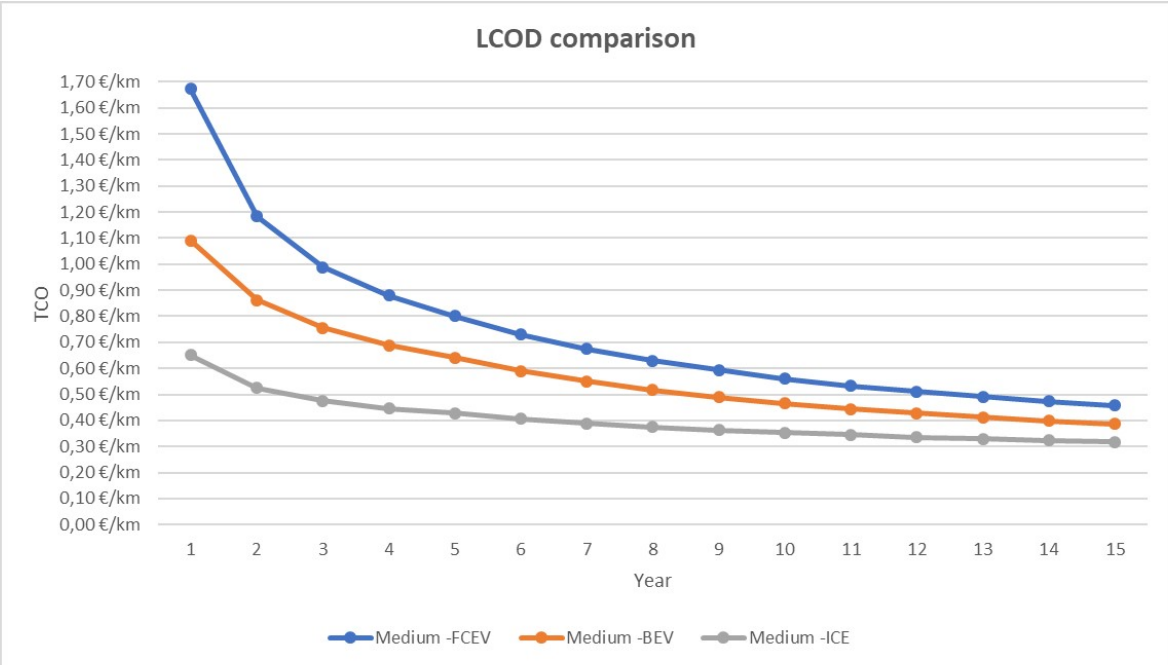


Figure 5.6: LCOD comparison - Medium segment.

5.3 Forecast up to 2050

In this section, the evolution over the years of the indicators considered is shown and commented on. In the first three subsections, the technologies under analysis are singularly considered and, for each of them, the evolution in the timeframe of the retail price, LCOD and TCO are represented. The aim of this first part is to understand the amount of the cost decrease that will characterize the considered technologies. The last subsection is dedicated to the comparison of the results obtained in the first part of the section, concluding if the decrease in ownership costs can be translated into a future economic convenience in using FCEV with respect to BEV and ICEV. To fully understand the results proposed is important to take into account that the year proposed in each figure refers to the purchase year of the vehicle under analysis.

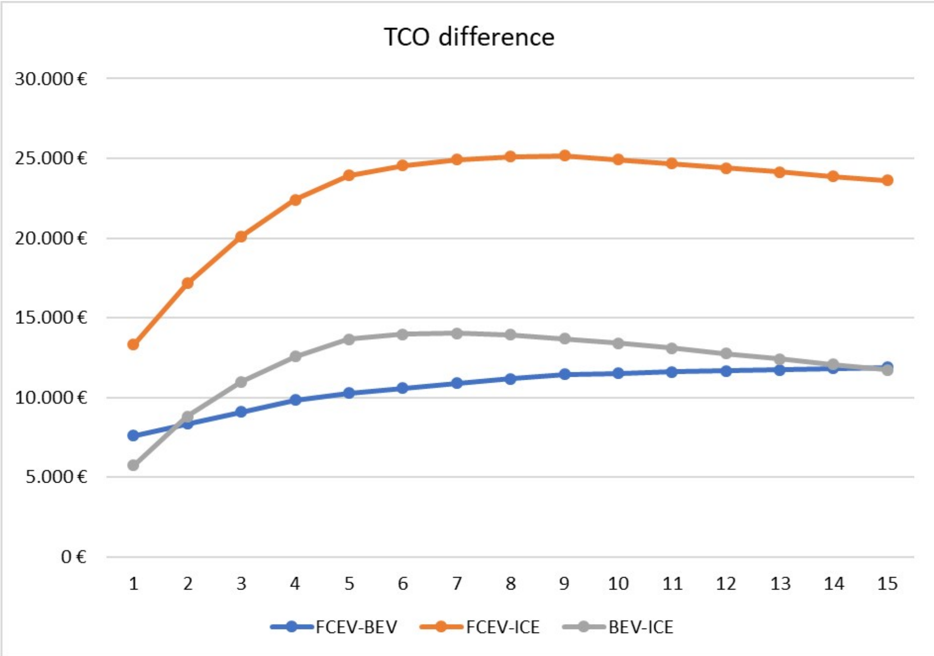


Figure 5.7: TCO difference - Medium segment..

5.3.1 FCEV results

The FCEV is the vehicle characterized by the highest number of parameters that are time-dependent in this analysis: fuel cell, hydrogen tank, battery, fuel cost and fuel consumption. The outcomes obtained (figure 5.8) confirm that, as expected, the technology shows from 2020 to 2050 a huge decrease of approximately 42% in the retail price and 40% in TCO. The main driver of this cost decrease is the fuel cell, which alone allows decreasing costs by more than 11.000 € .
Considering the year-by-year variation is possible to observe how the maximum decrease occurs in the period 2020-2025, in the following periods the trend progressively decreases, showing a reduction in the TCO of only some hundred euros between 2035 and 2050. For this reason, finally, it is possible to consider the year 2035 as the one that allows the FC technology to reach its maximum maturity.

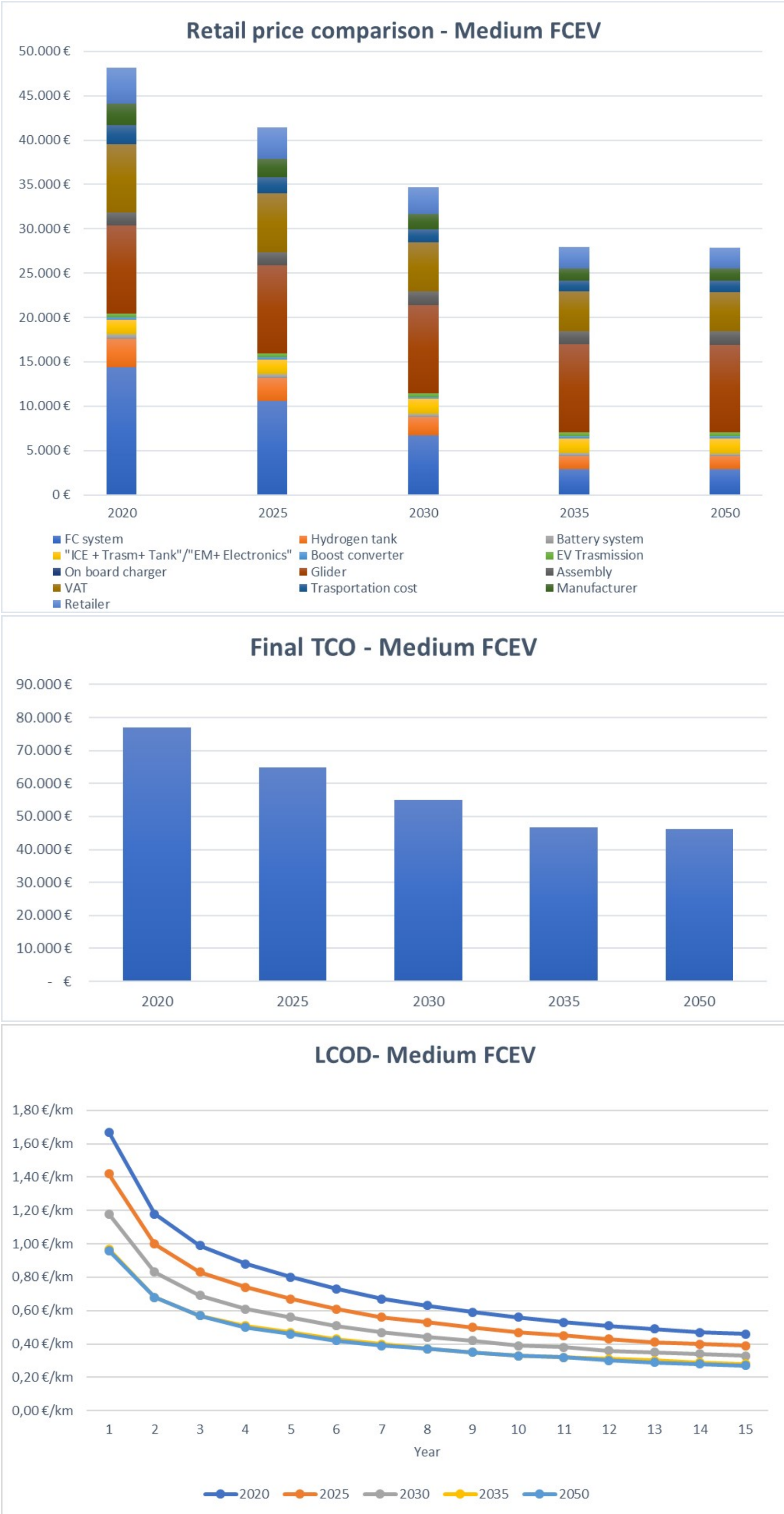


Figure 5.8: Medium FCEV parameters forecast.

5.3.2 BEV results

Figure 5.9 represents the results related to the BEV technology. Also in this case it is possible to see an important decrease in both the retail price (35%) and the total cost of ownership (29%) due to the decrease in the cost of the battery pack, unique time-dependent parameter together with the fuel consumption of the vehicle, also if it is important to remember that their diminution lead also to a fall

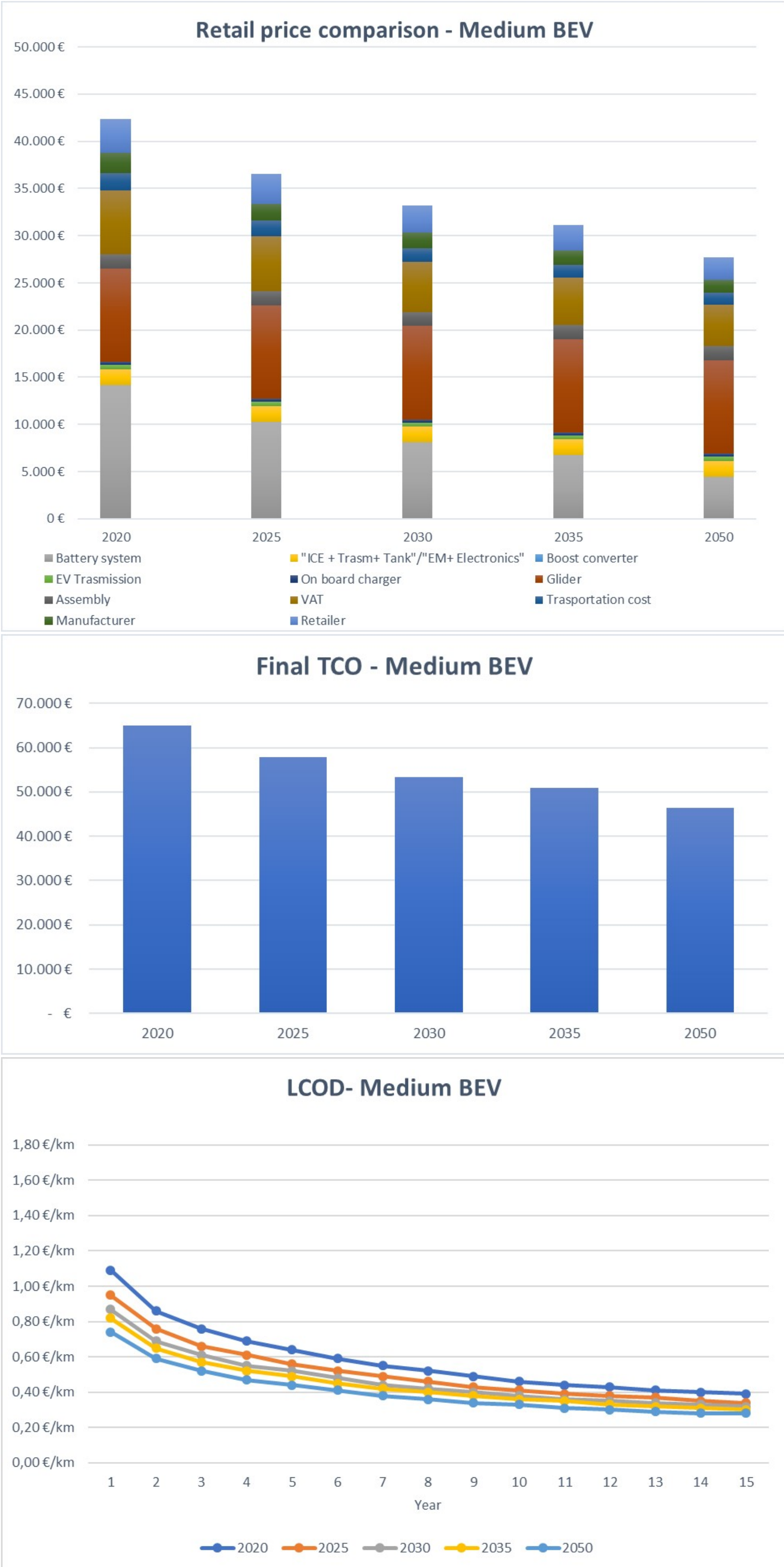


Figure 5.9: Medium BEV parameters forecast.

in taxation and external cost like the retailer cost calculated as a percentage of the total manufacturing cost. This time, the trend is almost constant over the time window leading to a minimum for the BEV cost in 2050.

5.3.3 ICEV results

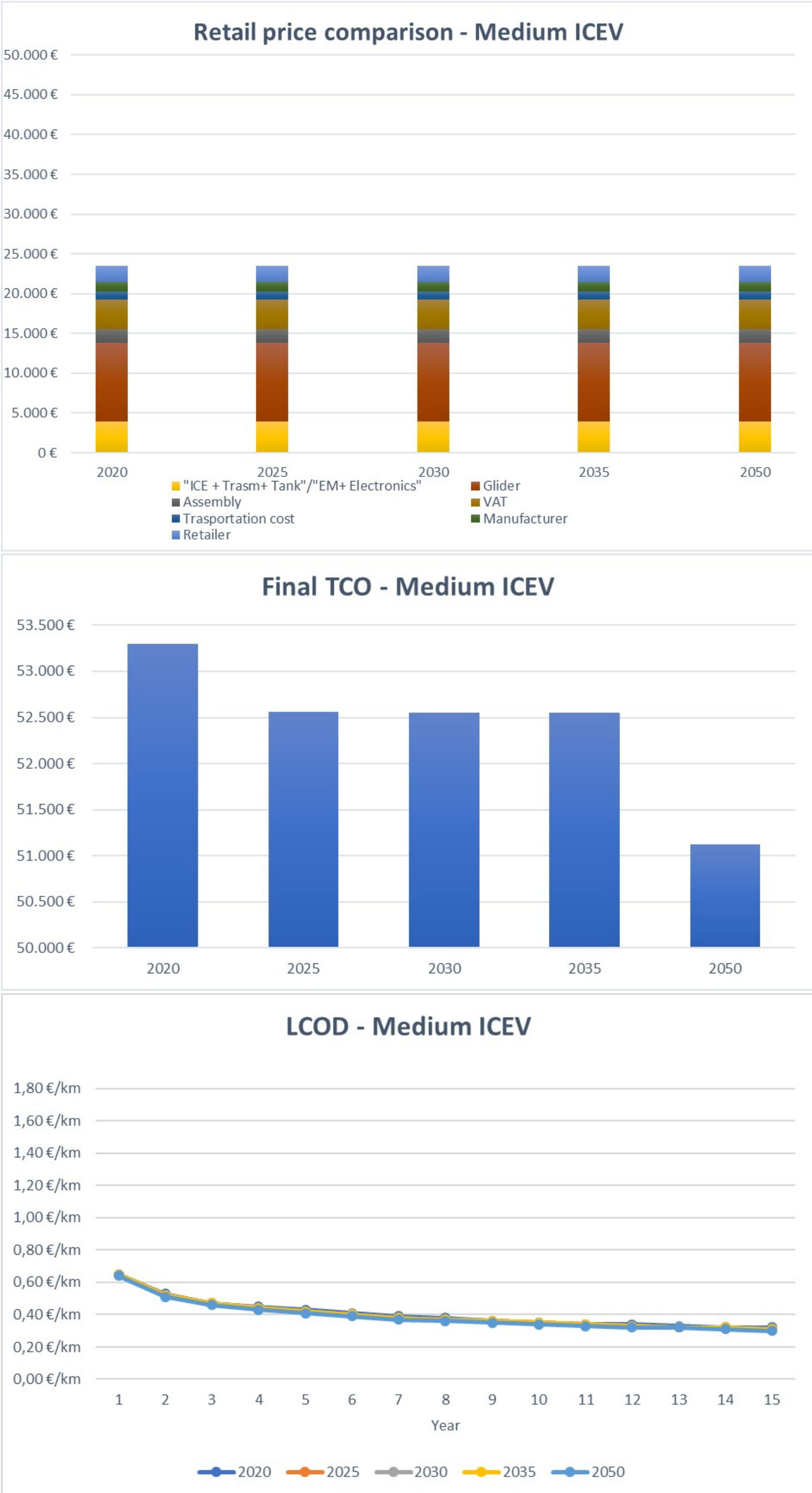


Figure 5.10: Medium ICEV parameters forecast.

Finally, figure 5.10 displays the outcomes of the forecast of the retail price, TCO and LCOD of the ICEVs. In this case, as expected, the results are completely different with respect to the other two technology, indeed only an improvement in the consumption performances of the vehicles is supposed in this study because of the high level of readiness of the technology. This hypothesis results in a constant retail price over the years and a slight reduction (4%) in the TCO for the vehicles purchased in 2050.

5.3.4 Comparison between technologies

Once analysed one by one the single technologies, it is possible to move on to the comparison between them, in order to understand if and when the decrease in costs found for zero-emission cars is such as to allow more convenience compared to the internal combustion engine.
The parameters taken into consideration are the retail price, the TCO and the evolution of the LCOD, the latter is used to identify the year in which the trend reverses, while the first is fundamental being not only the largest expense but also the first one that is faced up, so a large difference between the prices of two vehicles can discourage the buyer even if at the end of ownership the total costs of the two vehicles have a different relationship to their purchase price.

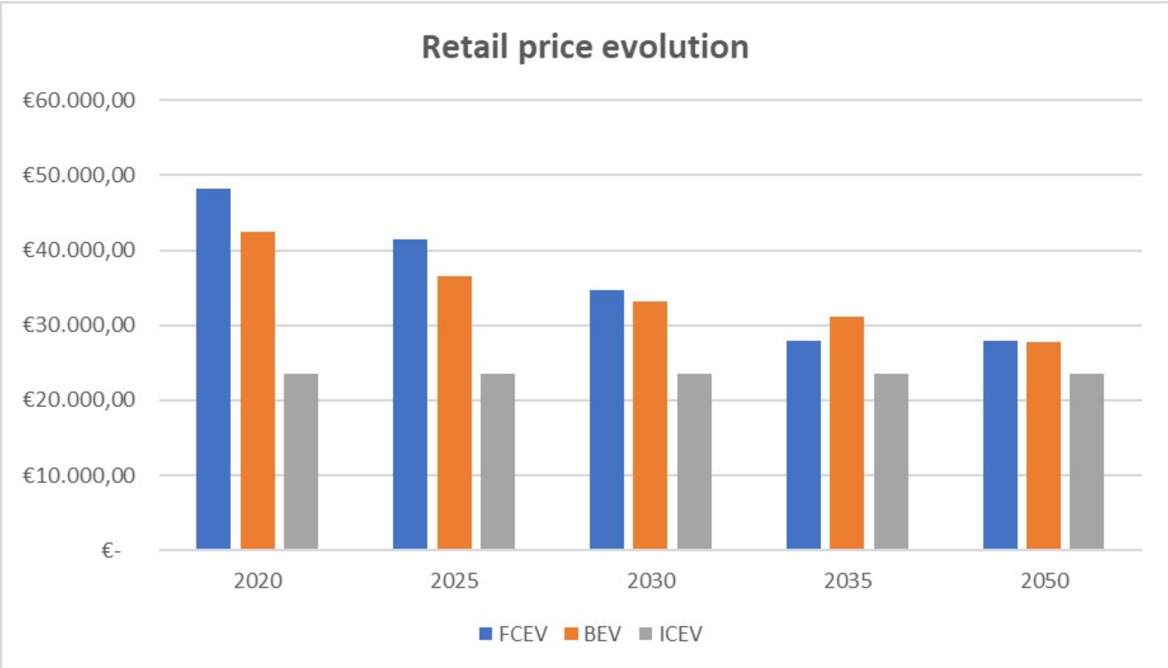


Figure 5.11: Retail price evolution. - Medium segment

Comparing the evolution of the different retail prices (figure 5.11) it is possible to see how, despite the huge diminution in the zero-emission EVs cost, the ICEV keeps being the cheapest technology in the market also if the prices of the three vehicles are quite similar and there is no longer a difference that would clearly disadvantage one technology over another, in particular regarding the comparison between the prices of BEV and FCEV, which are almost identical in 2050. As already highlighted, FCEVs reach their maximum potential already in 2035, overcoming momentarily the BEVs, which decrease in cost continues up to 2050.
Additionally, by analyzing the curves representing the LCOD and the TCO it is possible to see how the trends of the three vehicles are getting closer and closer going forward over the years. The main highlights can be resumed:

1. Already at the end of the lifetime of a vehicle purchased in 2030, the operating costs of the different vehicles are comparable.

2. The FCEVs are cheaper to own than the BEVs starting the fourth year of life for a vehicle bought in 2035.

3. FCEVs and BEVs overtake ICEVs starting respectively from the ninth and fourteenth year for a vehicle purchased in 2035.

4. The further decrease in battery cost expected by 2050 eventually leads to a very similar trend for BEVs and FCEVs, which exceed ICEVs between the eighth and ninth year of lifetime and then settle as the most affordable technologies in the end of the timeframe.

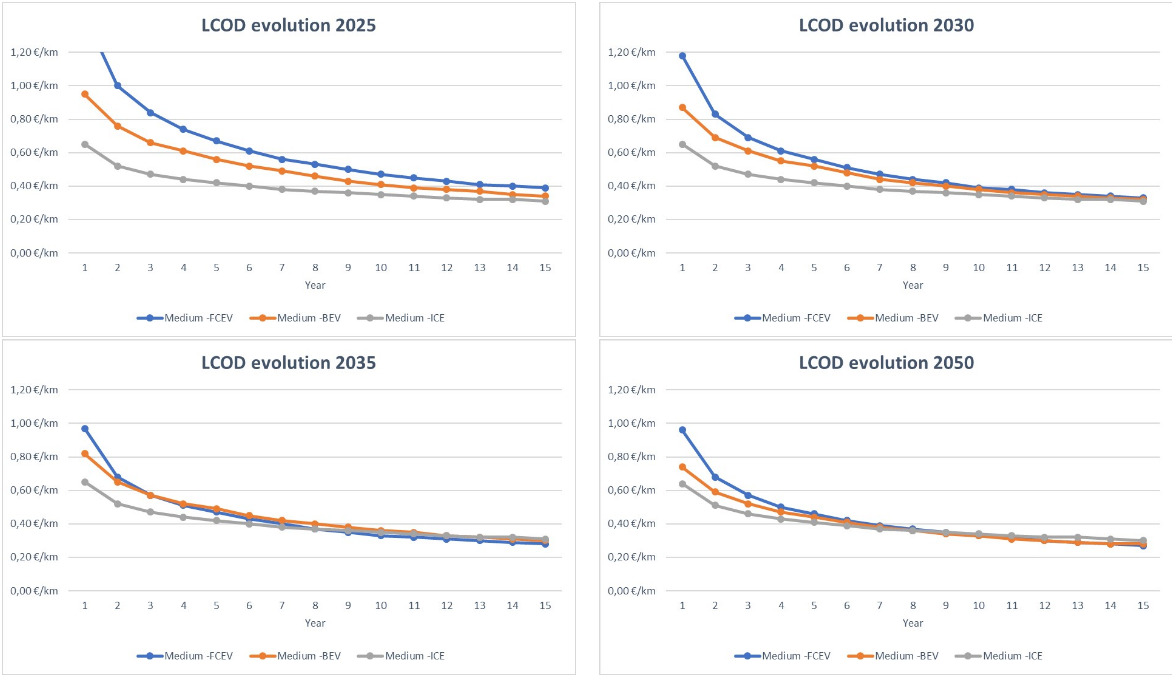


Figure 5.12: LCDO evolution - Medium segment.

It is really important to highlight the importance of the decrease in the cost of hydrogen in order to achieve cost parity as well as the fact that the volatility of the costs of diesel and electricity can significantly change the results. These possibilities will be analyzed in the sensitivity analysis, performed in the next section.

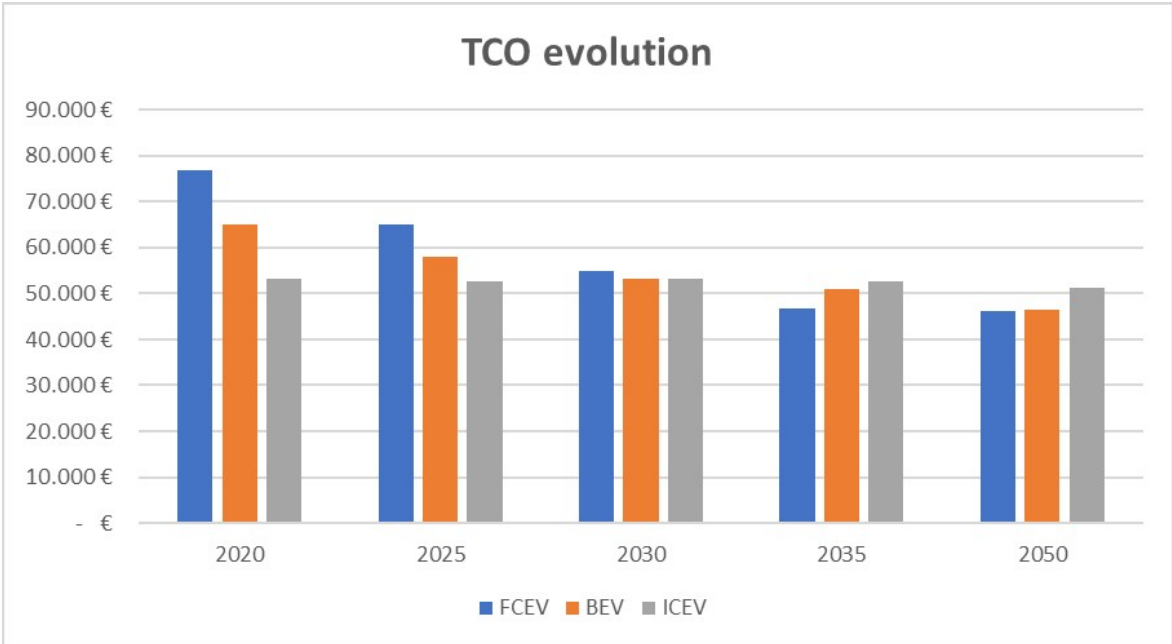


Figure 5.13: TCO evolution - Medium segment.

5.4 Sensitivity analysis

The general high grade of uncertainty that characterizes the TCO analysis makes fundamental the role of the sensitivity analysis to assess the most influential parameters and the reliability of the results. For this reason, two main steps have been carried out to give a complete view of the range of the results: firstly each parameter subjected to uncertainty has been varied singularly, electing in this phase the most influential parameters of the study, secondly, two other scenarios in addition to the base case have been created combining several hypotheses on the parameters previously tested, with the aim of giving an upper and a lower bounds to the future perspectives of the hydrogen light duty mobility.

5.4.1 Parameters comparison

Regarding the first step, all the parameters have been varied from the "Base case" scenario to a "High cost" scenario, characterized by higher prices, and a "Low cost" scenario, on the contrary, characterized by lower prices. For the fuel cell and hydrogen tank, the costs of the components vary by + 20% in the high-cost scenario and decrease to the high production rate price for the low-cost scenario. All the other costs regarding the powertrain and the O&M have been varied in a range of more or less 20% unless the markup coefficient (the parameter that merges transportation, manufacturer and retailer costs), that has been varied in a range of 10%. Regarding the total annual mileage, it has been chosen to use an asymmetrical interval, using a value of 18.000 km as the upper limit and a value of 10.000 km as the lower one. Finally, the discount rate has been varied to 1% in the "High cost" scenario and to 5% in the "Low cost" one. All the considerations just done are resumed in the table 5.3, while on the figures 5.14 and 5.14 is possible to observe all the effects of the listed parameters on retail price, for the parameters that make up the vehicle's powertrain, and TCO, for the parameters referred to the operation and maintenance of the vehicle. For the sensitivity analysis on the retail price, the results are referred to as a medium segment FCEV, with the exception of the analysis on the battery where the outcomes are associated with a medium BEV. As regards the sensitivity analysis on TCO, the data concerning a medium size vehicle for each technology are reported.

	High	Base	Low
Fuel cell (Eur/kW)	201,5	167,9	41,5
Hydrogen tank (Eur/kWh)	21,7	18,1	12,9
Battery	20%	0%	-20%
Glider	20%	0%	-20%
Motor	20%	0%	-20%
Markup coefficient	10%	0%	-10%
Fuel cost	20%	0%	-20%
O&M	20%	0%	-20%
Mileage	18.000	13.045	10.000
Discount rate	1%	3%	5%

Table 5.3: Sensitivity analysis - parameters variation.

The sensitivity analysis on the costs of the powertrain components shows how the correct assessment of the cost (and of the production rate) of the fuel cell is crucial for the FCEV price estimation, having a 43% difference between the high-cost scenario and the low-cost one. The same observation can be done regarding the BEVs that show a price that is really sensitive to the battery cost, as expected. On the other side, the influence on the powertrain cost of components such as the motor and the hydrogen tank is negligible for the final outcome. Finally, a different observation can be done about the glider cost and the markup coefficient, indeed they respectively have an influence of +-6% and +-8% on the FCEVs cost estimation, which is also higher considering the other technologies. Viewing the high uncertainty on these last parameters, their wrong valuation can lead to an error in the estimation of the TCO but with different effects on the final outcomes. Regarding the glider cost, the independence of this parameter from the type of technology allows the uncertainty in their

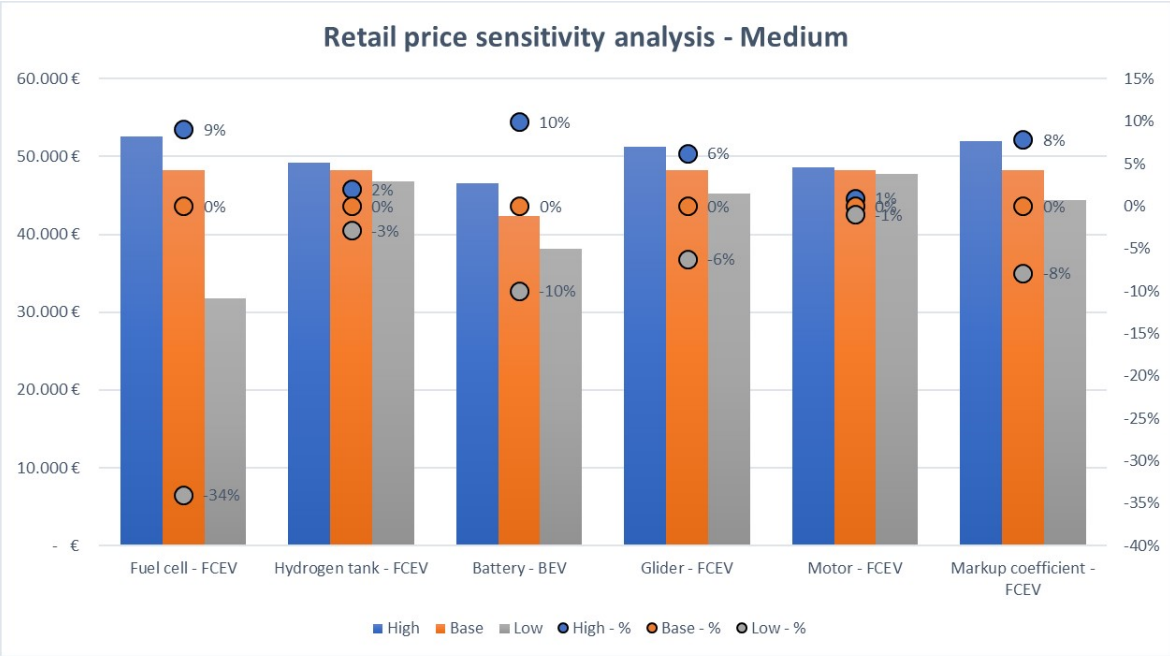


Figure 5.14: Sensitivity analysis - Powertrain components.

evaluation to have a limited role in the comparison between the different technologies. Looking at the markup coefficient, expressed as a percentage of the manufacturing cost, its wrong estimation affects the results also in absolute terms and therefore it can be considered in the future to improve the results of this analysis.

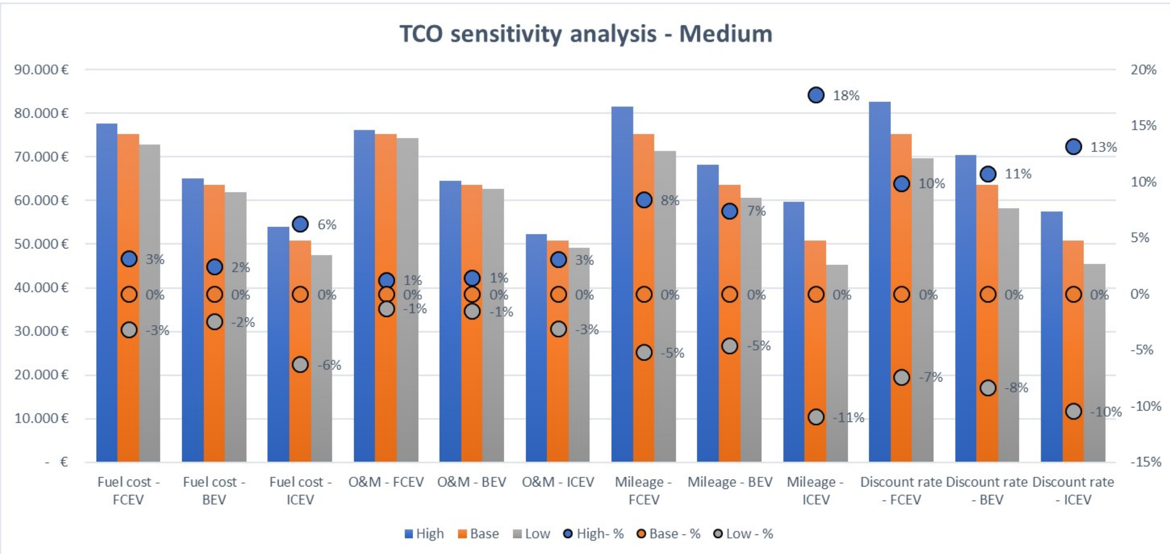


Figure 5.15: Sensitivity analysis - O&M parameters.

Subsequently, moving on to the analysis of the O&M parameters on the TCO results some important results can be highlighted:

1. Having the lowest retail price, the ICEVs are the most sensitive to the change in the O&M parameters costs;
2. The high uncertainty and variability of the prices of different fuels can lead to decisive errors in the comparison between technologies;

3. Mileage and discount rate are the terms that influence mostly the final results. The total mileage is really sensitive to the single owner habits and, for this reason, it is difficult to improve the consideration already done, while the discount rate is really variable in time and its estimation is really difficult in the long term. At the same time, the independency of these terms from the technology has a limited effect on the comparison between different vehicles;
4. The effect of the total maintenance on the final outcomes is limited;

5.4.2 New scenarios outcomes

Given the assumptions made in the previous subsection, two scenarios representing borderline cases were considered to see if the results undergo a qualitative as well as a quantitative change. The table 5.4 represents the scenarios taken into consideration.
In particular, Scenario 1 was created to simulate the possibility in which the forecasts on the hydrogen market are too optimistic and the events that led to the increase in the price of diesel end, lowering the average price of recent years.
On the other hand, Scenario 2 aims to assume the achievement of the maximum development rate for the market of hydrogen and battery-powered vehicles, maintaining constant the fuel prices assumed in the base case scenario. The results obtained are following reported.

	Scenario 1	Scenario 2
Fuel cell (Eur/kW)	High	Low
Hydrogen tank (Eur/kWh)	High	Low
Battery	Base	Low
Glider	Base	Base
Motor	Base	Base
Markup coefficient	Base	Base
Hydrogen cost	High	Base
Electricity cost	Base	Base
Diesel cost	Low	Base
O&M	Base	Base
Mileage	13.045	13.045
Discount rate	3%	3%

Table 5.4: Sensitivity analysis - Scenarios.

Scenario 1 - Pessimistic

In the first scenario it is possible to observe how, despite the trend of the retail prices of the three vehicles is unchanged with respect to the base scenario, the difference in price is larger during the entire duration of the analysis. The FCEVs remain the most expensive vehicles in 2050, spaced by almost 6.000 € from the ICEVs and nearly 2.000 € from the BEVs.

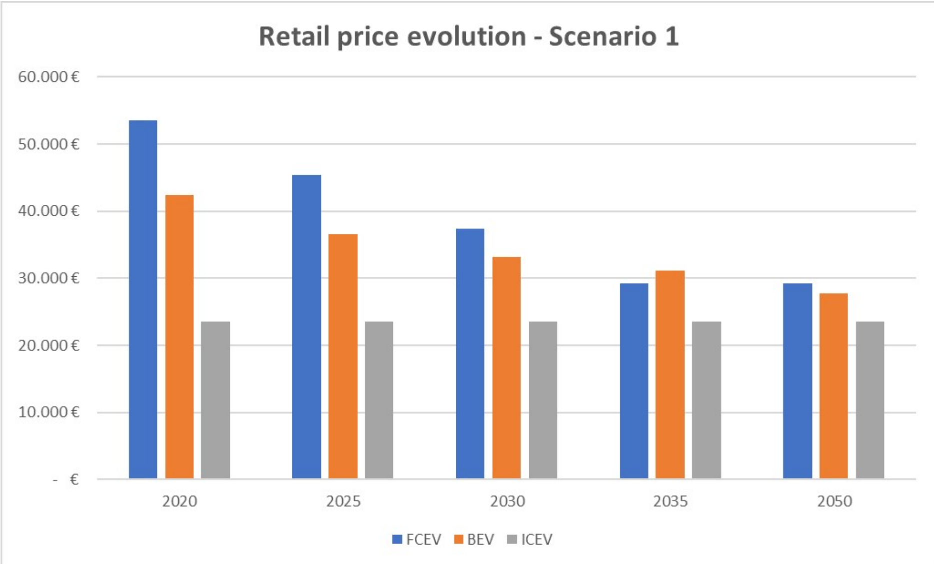


Figure 5.16: Retail price evolution - Scenario 1.

Looking at the effects on TCO and LCOD, we can see how the results remain qualitatively the same with respect to the reference case. The total cost at the end of the lifetime of the three technologies is comparable starting from the year of purchase 2035, but in this case, the FCEVs exceed the ICEVs only at the end of the lifetime both thanks to the higher costs of the fuel cells, tank and hydrogen, and to the lower cost of diesel, which leads to a decrease in the cost of ownership for the diesel vehicle. In 2050, BEVs rank as the cheapest vehicles with a TCO always lower than FCEVs over the lifetime and lower than ICEVs from the eleventh year.

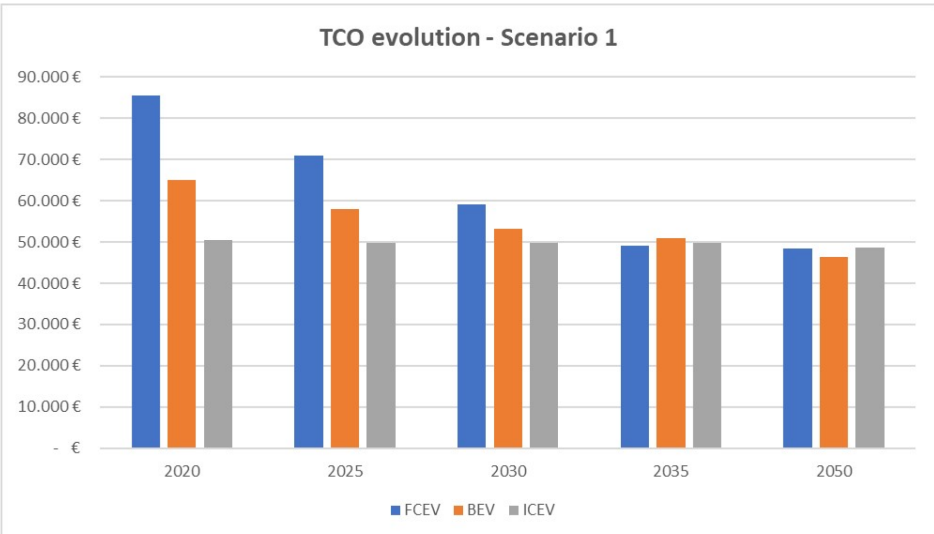


Figure 5.17: TCO evolution - Scenario 1.

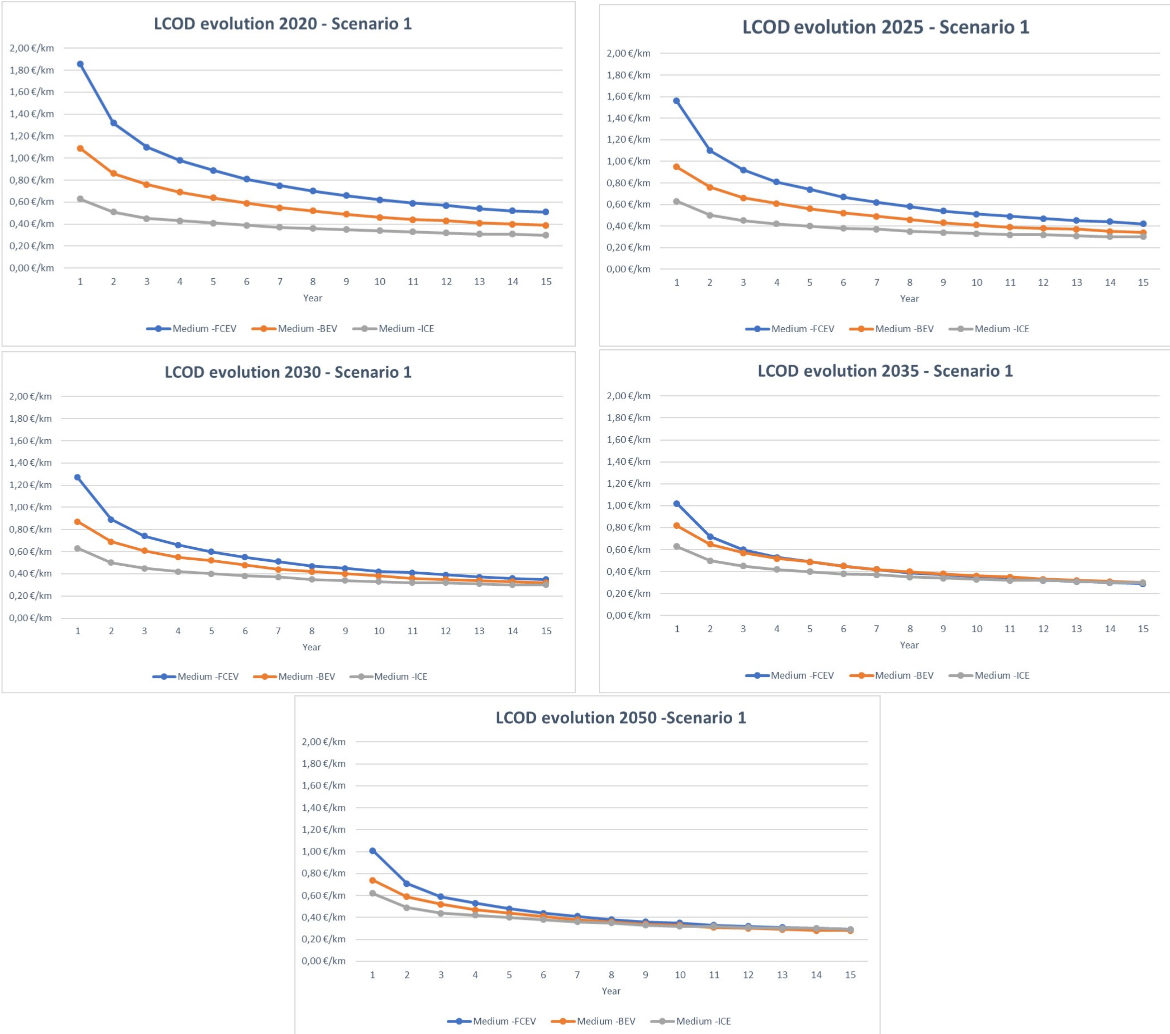


Figure 5.18: LCDO evolution -Scenario 1.

Scenario 2 - Optimistic

In the second scenario, the retail prices of the vehicles under analysis are characterized since the beginning by a much lower difference in price. The FCEVs reach a high degree of development since the year 2020 but the huge decrease in the price of the battery over the years makes the BEVs the cheapest zero-emission vehicles at the end of their lifetime. Also in this case the zero-emission vehicles are not capable of reaching the retail price of ICE technology.

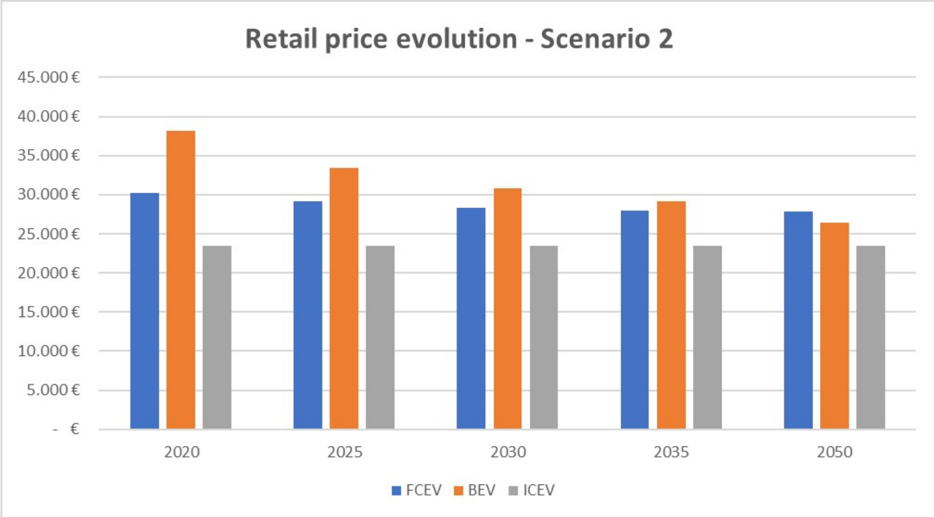


Figure 5.19: Retail price evolution - Scenario 2.

On the other side, looking at the TCO and LCOD evolution the FCEVs are really competitive since the beginning of the time window, overtaking the ICEVs already in 2025. In 2050 FCEVs and BEVs are the cheapest vehicles to own, with an LCOD of 27 c€/km compared to 30 c€/km of the ICEVs. It is important to remember that this scenario is really optimistic and it is more to be considered as an extreme case, assuming the maximum degree of advancement for zero-emission technologies.

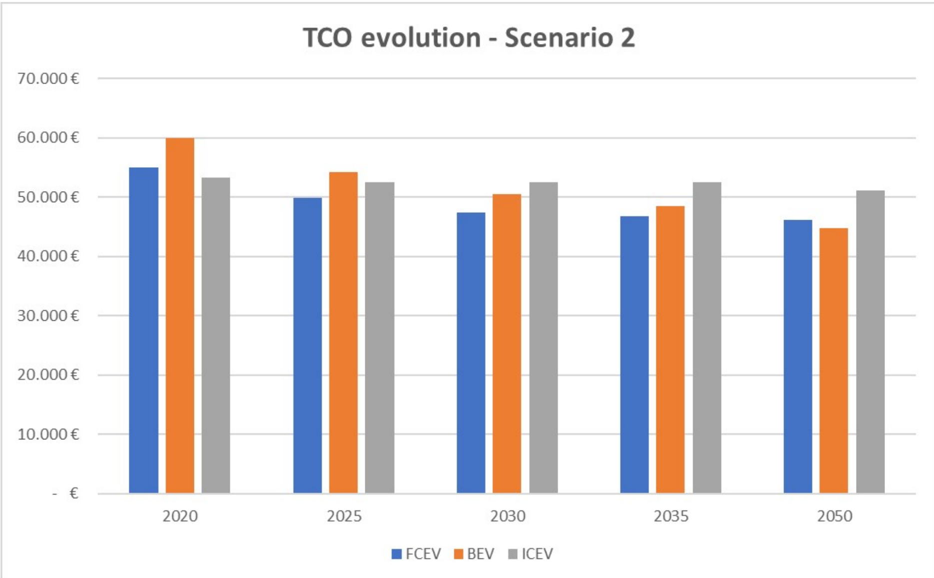


Figure 5.20: TCO evolution - Scenario 2.

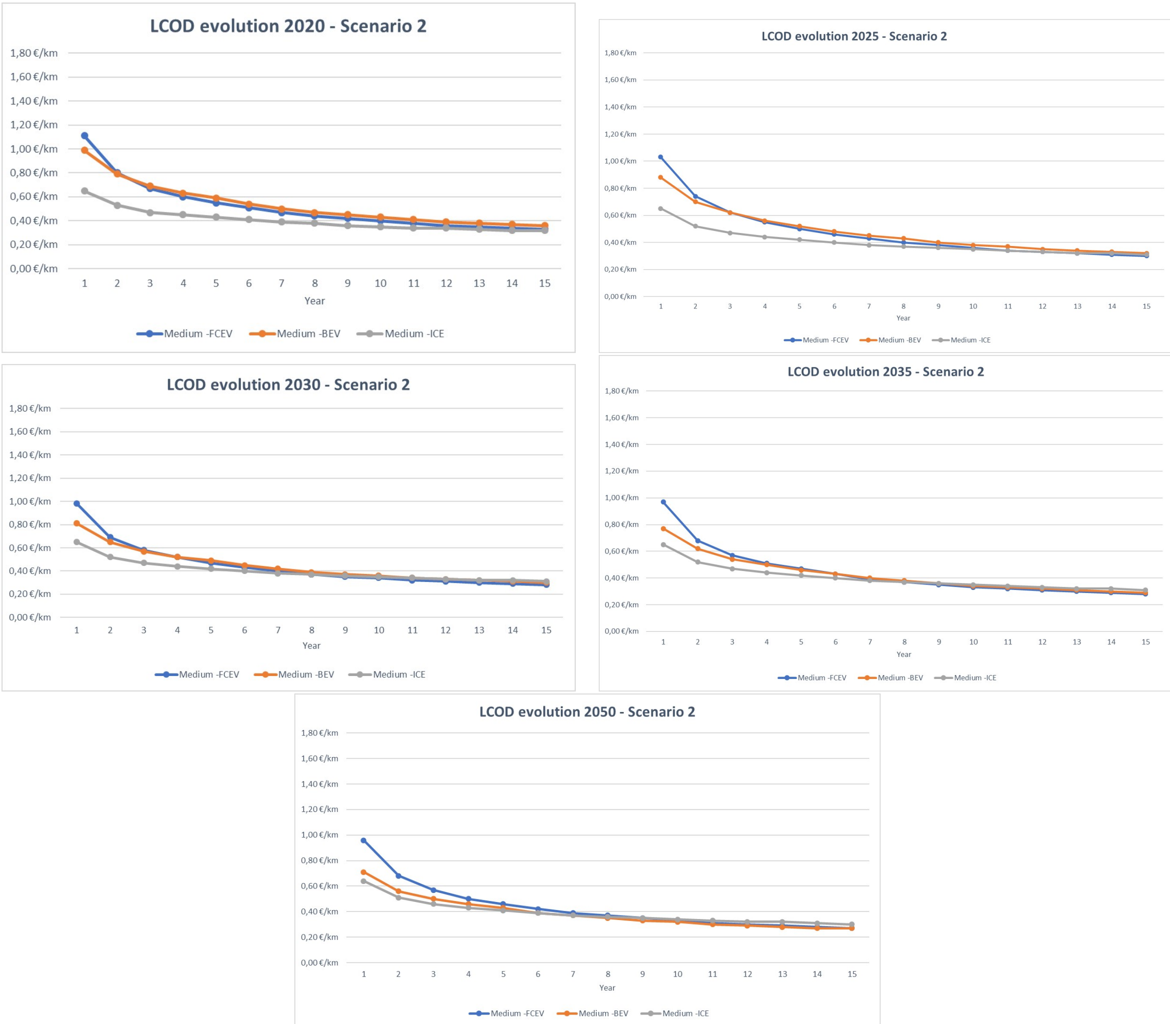


Figure 5.21: LCDO evolution -Scenario 2.

Conclusions and perspective

Retracing the main steps that have been gone through in this work it is now possible to highlight the main results that have been obtained, outlining which is the primary perspective for improving the tool and the methodology that has been defined.
After a brief introduction about context and scope that make useful the deepening of the evolution of hydrogen vehicles Total Cost of Ownership and its comparison with battery electric vehicles and internal combustion engine vehicles, the principal features of the powertrain architecture and its components has been presented, highlighting not only the technical characteristics but also their cost evolution from 2020 to 2050.
Following, the methodology to be used for the TCO estimation has been described. Firstly, a unique formulation for the TCO calculation has been illustrated; secondly, the single terms of the equation have been deepened, defining a quantitative formulation to apply and the boundary conditions for the problem of interest.
The penultimate step of the work was the presentation of the main features of the tool, showing the interface and characteristics of each of the sheets before passing to the analysis of the results. The last chapter of the work was focused on the result analysis. The first part of the chapter has been focused on the reliability analysis of the retail price estimation, about what the tool seems to calculate the price of the market vehicle with an error lower than 10%. Following, a base scenario has been studied. It highlights how FCEVs and BEVs have the potential to greatly reduce their production and operating costs, coming from 2035 to compete strongly with diesel technologies. This result is very important, as 2035 is the expected year for the ban of ICEVs from the market. Subsequently, given the great uncertainty that intrinsically characterizes the data used, a sensitivity analysis was carried out, defining the most influential parameters within the study. As a result, the importance of the correct estimate of the cost of fuel cell, battery, glider and fuel for the calculation of the TCO was highlighted.
In light of this consideration, two further scenarios have been defined with the aim of setting an upper and lower limit to the reliability of the analysis. In this regard, in the first scenario, a decrease in the price of diesel was assumed, together with higher prices for zero-emission technologies. In this case, the result obtained highlights how, even if with a less evident trend, the intrinsic decrease in the costs of fuel cells, tanks and lithium batteries leads zero-emission technologies to compete starting from the last years of 2035 and from 2050 in the more competitive way.
In the second scenario, however, the possibility of a large development rate for fuel cells, hydrogen tanks and batteries has been assumed. In this optimistic case, the technologies under analysis are comparable starting from 2025, leading to a really fast diffusion of FCEVs and BEVs in the market.
As said the results obtained are subjected to uncertainty due to: the lack of information regarding the costs of the glider, sales and distribution and the uncertainty about the cost evolution of fuel cells, batteries and fuels. The glider and the strategies to transport and sell the vehicles are subject to the influence of the procedures and business model of the single manufacturers and, for this reason, direct contact with them would be crucial for the improvement of the results obtained. Regarding the fuel cells, batteries and fuels price evolution, their dependence on factors not only of a technological nature but also of a social, political and strategic nature (the spread of incentives, the development of infrastructures, the emergence of conflicts, investments in research) makes the study of these components intrinsically uncertain and for this reason, the development of the tool reported in this work, allows a continuous updating of the data, to gradually improve the results obtained.

Appendices

As mentioned in the previous chapter, the appendix shows all the figures concerning the small, SUV and Pickup segments. They were not presented in the results chapter as they show results qualitatively equal to those shown by the medium segment. In each subsection, the retail price composition, the annuity and the evolution of Retail price and TCO are shown, together with a table containing the highlights referring to the LCOD evolution.

Small

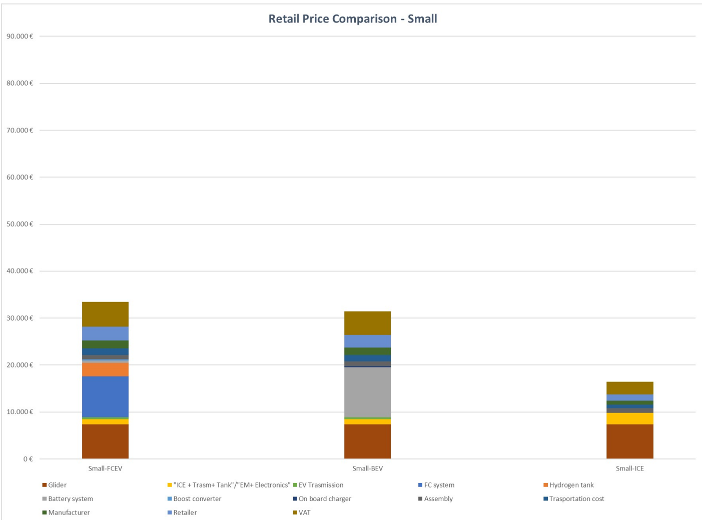


Figure 7.1: Retail price - Small segment.

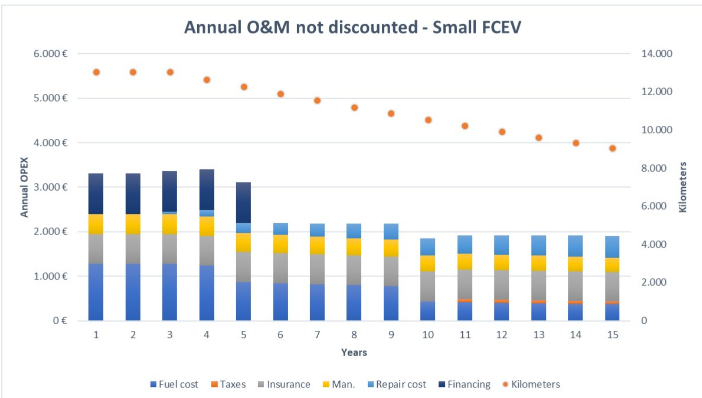


Figure 7.2: Annuity - Small FCEV.

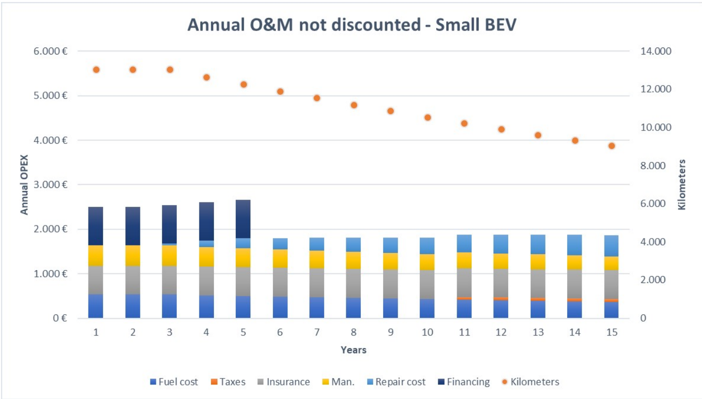


Figure 7.3: Annuity - Small BEV.

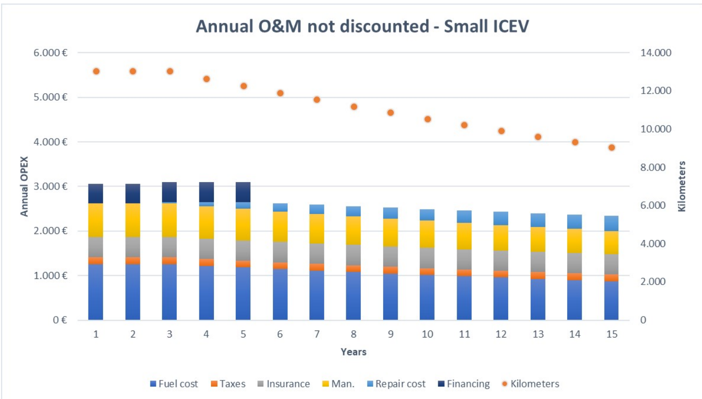


Figure 7.4: Annuity - Small ICEV.

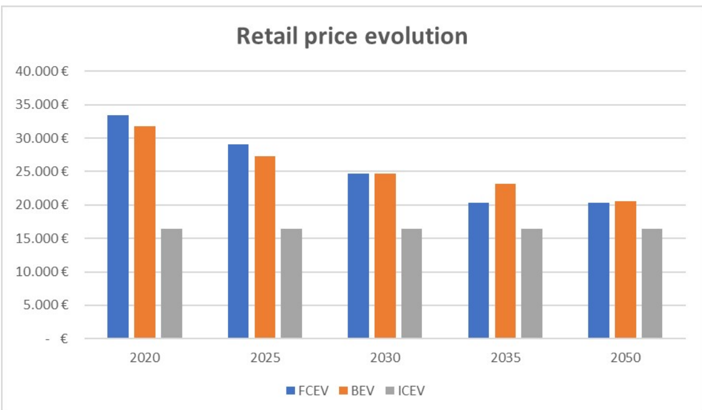


Figure 7.5: Retail price evolution - Small.

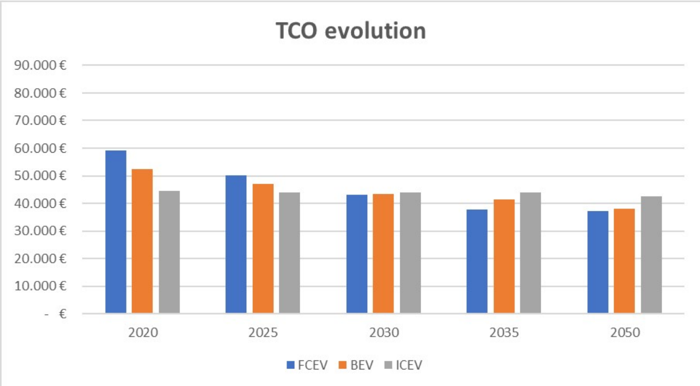


Figure 7.6: TCO evolution - Small.

Small	
Year	Highlights
2030	• All the technologies have the same LCOD at the end of lifetime;
2035	• FCEVs overcome BEVs starting from the third year; • FCEVs overcome ICEVs starting from the eighth year; • BEVs overcome ICEVs starting from the twelfth year;
2050	• BEVs and FCEVs overcome ICEVs starting from the ninth year; • FCEVs have the lowest LCOD at the end of lifetime;

Table 7.1: Small segment LCOD evolution highlights.

SUV

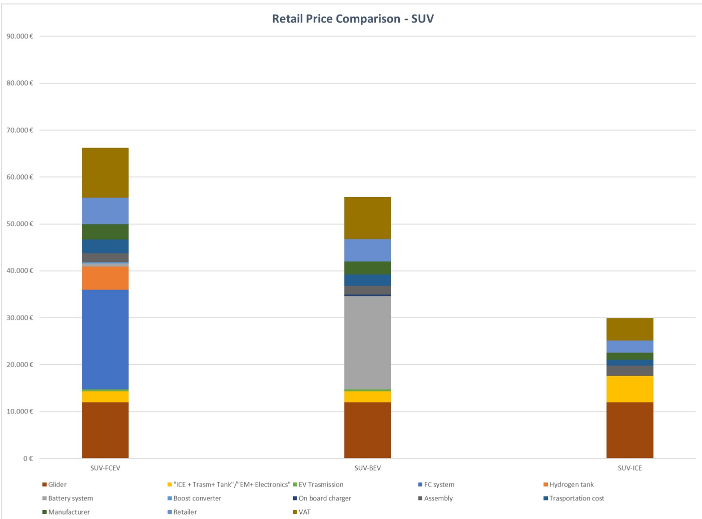


Figure 7.7: Retail price - SUV segment.

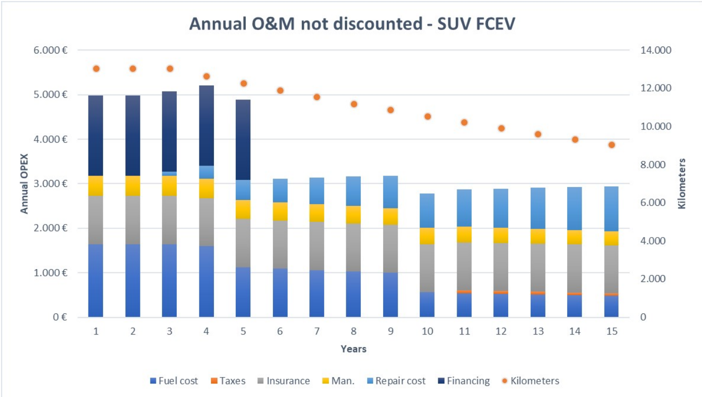


Figure 7.8: Annuity - SUV FCEV.

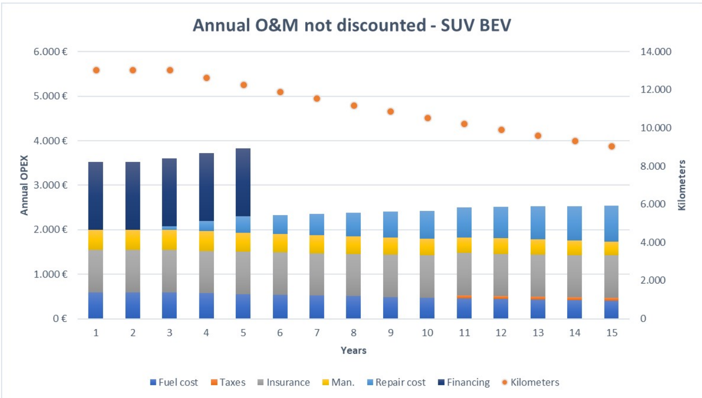


Figure 7.9: Annuity - SUV BEV.

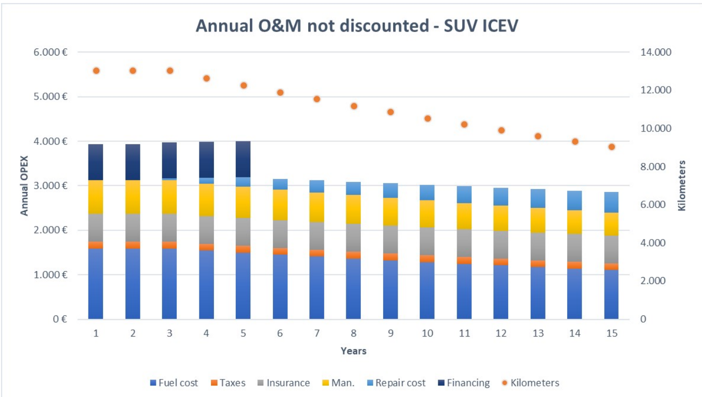


Figure 7.10: Annuity - SUV ICEV.

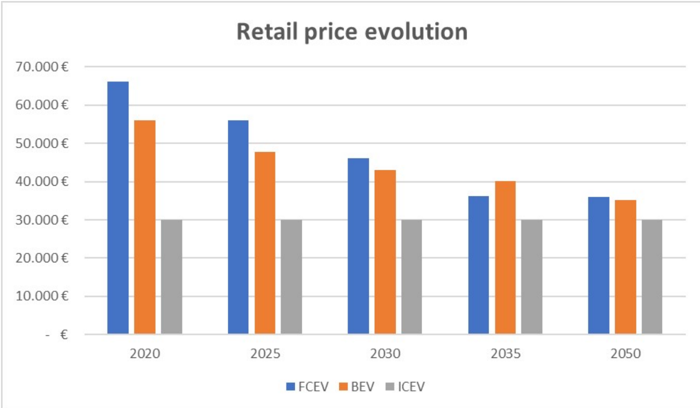


Figure 7.11: Retail price evolution - SUV.

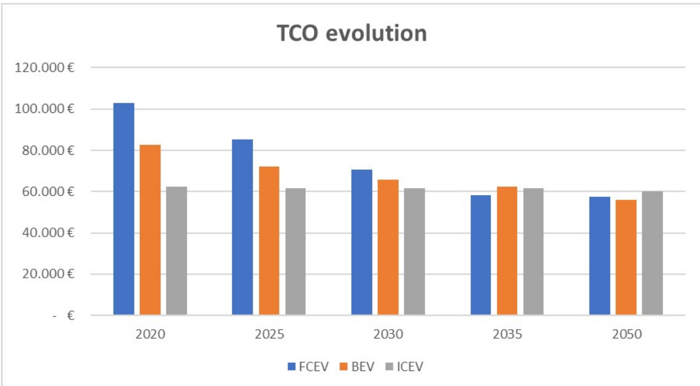


Figure 7.12: TCO evolution - SUV.

SUV	
Year	Highlights
2035	• FCEVs overcome BEVs starting from the fourth year; • FCEVs overcome ICEVs starting from the eleventh year; • BEVs and ICEVs have the same LCOD at the end of their lifetime;
2050	• BEVs overcome ICEVs starting from the eleventh year; • FCEVs overcome ICEVs starting from the thirteenth year; • BEVs are the cheapest vehicles at the end of lifetime;

Table 7.2: SUV segment LCOD evolution highlights.

Pickup

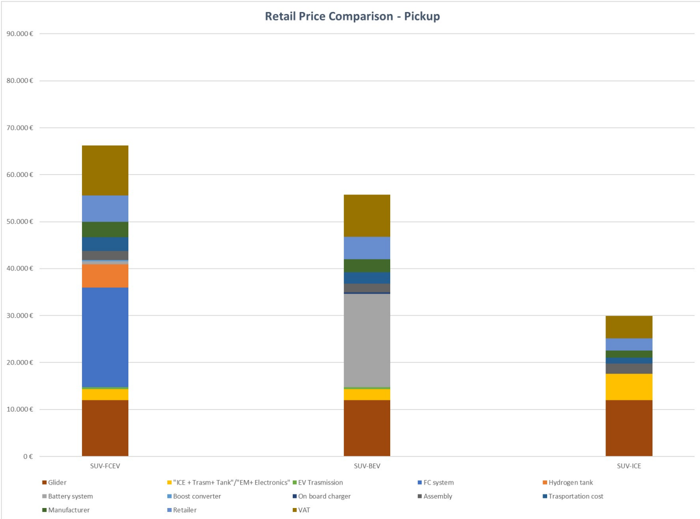


Figure 7.13: Retail price - Pickup segment.

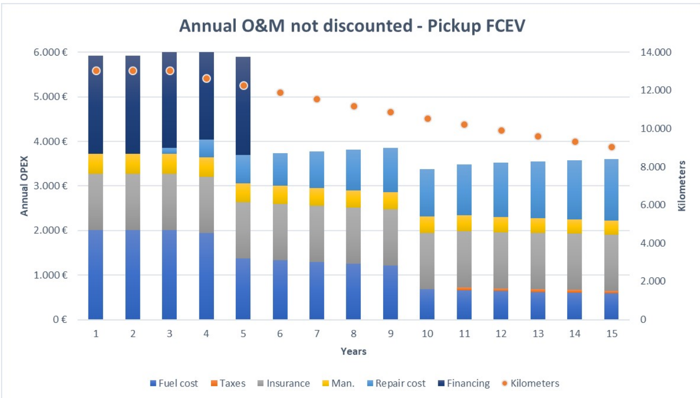


Figure 7.14: Annuity - Pickup FCEV.

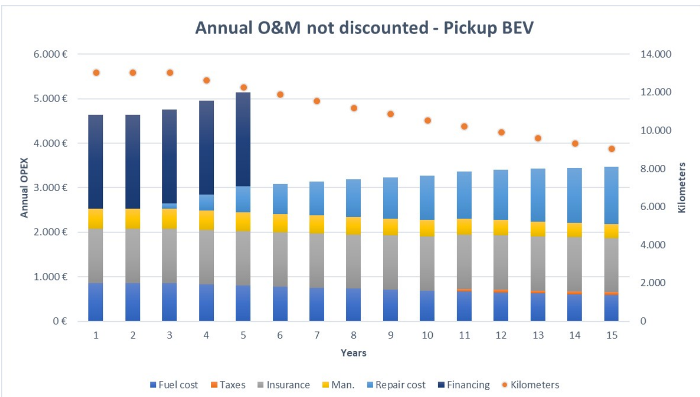


Figure 7.15: Annuity - Pickup BEV.

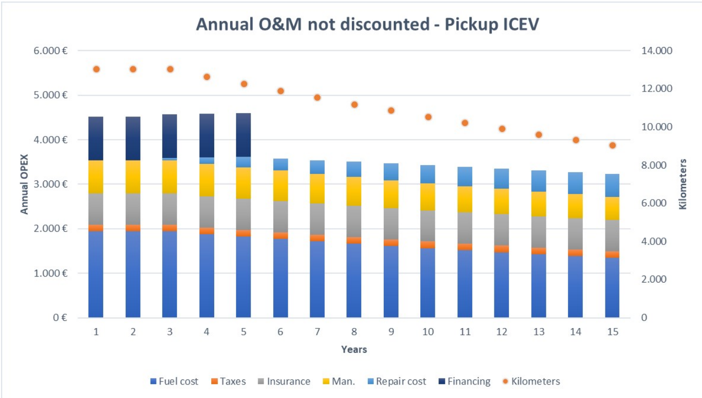


Figure 7.16: Annuity - Pickup ICEV.

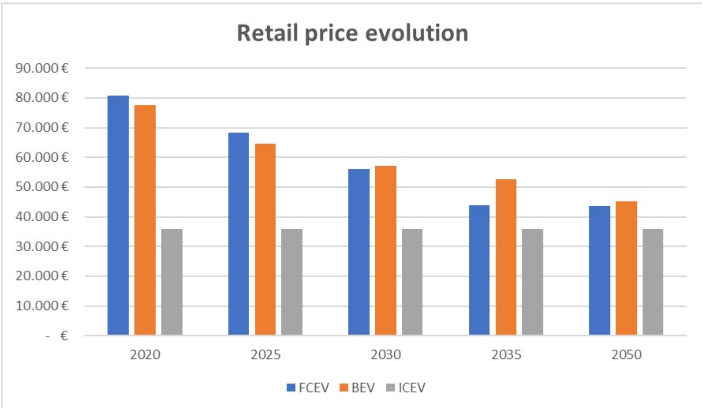


Figure 7.17: Retail price evolution - Pickup.

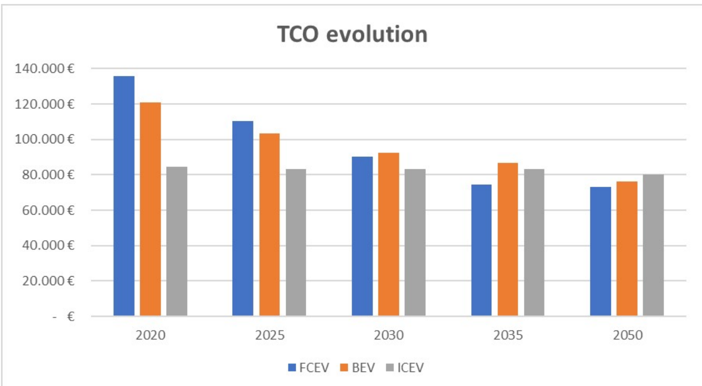


Figure 7.18: TCO evolution - Pickup.

Pickup	
Year	Highlights
2030	• FCEVs overcome BEVs starting from the twelfth year;
2035	• FCEVs overcome BEVs starting from the second year; • FCEVs overcome ICEVs starting from the ninth year; • ICEVs remain cheaper than BEVs at the end of lifetime;
2050	• FCEVs overcome ICEVs starting from the tenth year; • BEVs overcome ICEVs starting from the eleventh year; • FCEVs have the lowest LCOD at the end of lifetime;

Table 7.3: Pickup segment LCOD evolution highlights.

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