POLITECNICO DI TORINO

Master's Degree
Energy and Nuclear Engineering
Renewable energy systems

Comparative analysis of Total Cost of Ownership for H2-ICE, H2-Fuel Cell, and Battery Drivetrain technologies

Study on Finnish heavy-duty road transport

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Abstract

Climate change is a critical global phenomenon that is developing in several local environment emergencies in recent years. Thanks to an increased sensibility and concern regarding this subject, we are witnessing the adoption of different strategies and goals for the reduction of emissions and mitigation of environmental impact.
The road transport sector is one of the major contributors to greenhouse gas (GHG) emissions, as it is still largely reliant on traditional powertrains solutions. While some progresses have been observed in the passenger car sector, heavy-duty transport remains mainly founded on diesel internal combustion engines.

This Master of Science thesis aims to evaluate and compare from economic perspective three possible solutions for the decarbonization of heavy-duty freight transport:

- Battery electric trucks
- Fuel cell electric trucks
- Hydrogen fueled internal combustion engine trucks

The analysis is based on the Total Cost of Ownership method, that allows to consider cost elements of the vehicles throughout their entire usage period. Consequently, various cost components will be evaluated, regarding both initial expenses (CAPEX) and operational costs (OPEX); for each of these elements, a detailed description of the methodology used for its estimation is provided, as well as a final quantitative assumption, based on the current economic scenario.
The background of this study is the Finnish market and road network: indeed, high competitiveness of Finnish electricity market, as well as its geographical characteristics, create a very favorable environment for the development of alternative powertrain vehicles. Today and probably in the next future, it is one the countries with greatest potential to make these trucks economically competitive with traditional ones.

The objectives of this thesis are twofold:

- Suggest the most suitable solution for heavy-duty truck powertrain choice, according to the specific needs of industries or transport companies: to ensure the most comprehensive analysis, different case

studies have been considered, with several sensitivity analysis regarding possible changes in the assumed parameters

- Provide readers with a methodology for the definition of the Total Cost of Ownership of vehicles with alternative powertrains, giving the possibility of adapting this study to other specific needs applying minor modifications

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Acronyms

AC	Alternating Current
AFIR	Alternative Fuel Infrastructure Regulation
APR	Annual Percentage Rate
BET	Battery Electric Truck
BEV	Battery Electric Vehicle
BMS	Battery Management System
CCUS	Carbon Capture Utilization and Storage
CNG	Compressed Natural Gas
CNG-ICET	Compressed Natural Gas Internal Combustion Engine Truck
CO2	Carbon Dioxide
D-ICET	Diesel-fueled Internal Combustion Engine Truck
DC	Direct Current
dge	Diesel-Gallon Equivalent
DOE	(US) Department Of Energy
DOT	(US) Department Of Transportation
EDV	Electric-Drive Vehicle
EU	European Union
FC	Fuel Cell
FCET	Fuel Cell Electric Truck
FCEV	Fuel Cell Electric Vehicle
GDP	Gross Domestic Product
GHG	Green-House Gases

GVW	Gross Vehicle Weight
H2	Hydrogen
H2ICET	Hydrogen-fueled Internal Combustion Engine Truck
H2ICEV	Hydrogen-fueled Internal Combustion Engine Vehicle
HCT	High-Capacity Transport
HDV	Heavy Duty Vehicle
HEV	Hybrid Electric Vehicle
HGV	Heavy Goods Vehicle
HSS	Hydrogen Storage System
HV	High Voltage
HVAC	Heating Ventilation and Air Conditioning
ICE	Internal Combustion Engine
LCOD	Levelized Cost Of Driving
LCOT	Levelized Cost Of Transport
LDV	Light Duty Vehicle
LEV	Low Emissions Vehicle
LHV	Long and Heavy Vehicle
LNG	Liquefied Natural Gas
LNG-ICET	Liquefied Natural Gas Internal Combustion Engine Truck
M&R	Maintenance and Repair
MDV	Medium-Duty Vehicle
NCV	Net Calorific Value
PEMFC	Proton Exchange Membrane Fuel-Cell
PTC	Positive Temperature Coefficient
PTO	Power-Take-Off
SUV	Sport Utility Vehicle

TCO	Total Cost of Ownership
US	United States
VAT	Value-Added Tax
ZET	Zero Emissions Truck
ZEV	Zero Emissions Vehicle

1. Introduction

Increasing sensibility on climate change has led many countries, during last years, to introduce policies aiming to reduce pollutant emissions and mitigate impact on the environment.

Among many other important effects, one of the main ones has been the diffusion of low- or zero-emissions vehicles on the market, represented in the largest share by battery electric vehicles, with some minor examples of fuel-cell electric vehicles. Unfortunately, this gradual change in the vehicle market has not reached the heavy-duty vehicle segment yet, due to both technical and economic uncertainties, which make difficult the choice among the different possible powertrains for a specific need.

1.1 Global context overview

In 2015, Paris Agreement, negotiated and ratified by 196 parties at COP21, set the renewed commitment for the reduction of emissions and mitigation of climate change at global level. Long-term goal of the treaty is to keep the temperature rise, due to global warming, below 2°C above pre-industrial levels, with the aim to limit the increase to maximum 1.5°C [1]: according to many studies, this would have substantial beneficial effects on climate change. To achieve this target, it is necessary to reduce emissions as soon as possible, with the goal to reach global carbon neutrality by the middle of XXI century, and the suggestion to cut emission at least of 50% within 2030.

Regrettably, although COP21 and other commitment agreements, global CO2 emissions are still increasing in last years: the rate of growth has significantly decreased, and developed economies like EU and US have begun to experience reductions in their annual emissions, but the growth of countries as China, India, and several African countries, both in terms of economy and population, has had a harmful impact on global pollution.

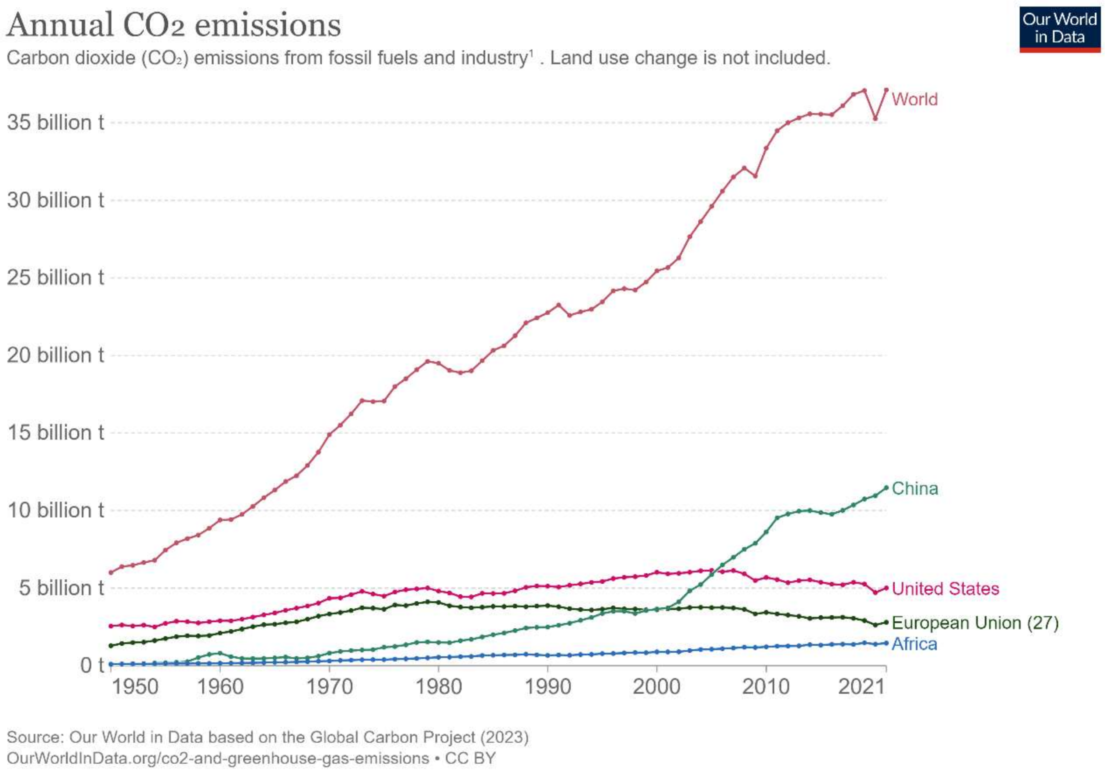

Figure 1.1 - *CO2 emissions* [2]

Transport sector is one of the main contributors to global CO2 emissions: in 2018, it impacted for more than 25% of the overall greenhouse emissions [3], and it is the second most important contributors, behind energy production. Transport sector was also responsible of the use of more than 65% of the total end use oil in the world, and road transport alone for about 49% [4]. Emissions connected to transport have continued increasing in the last decades: this growth is mainly connected to generic economic development, as both freight and people movements become more frequent and capillary, developing in domestic or international transport and contributing to GDP increase.

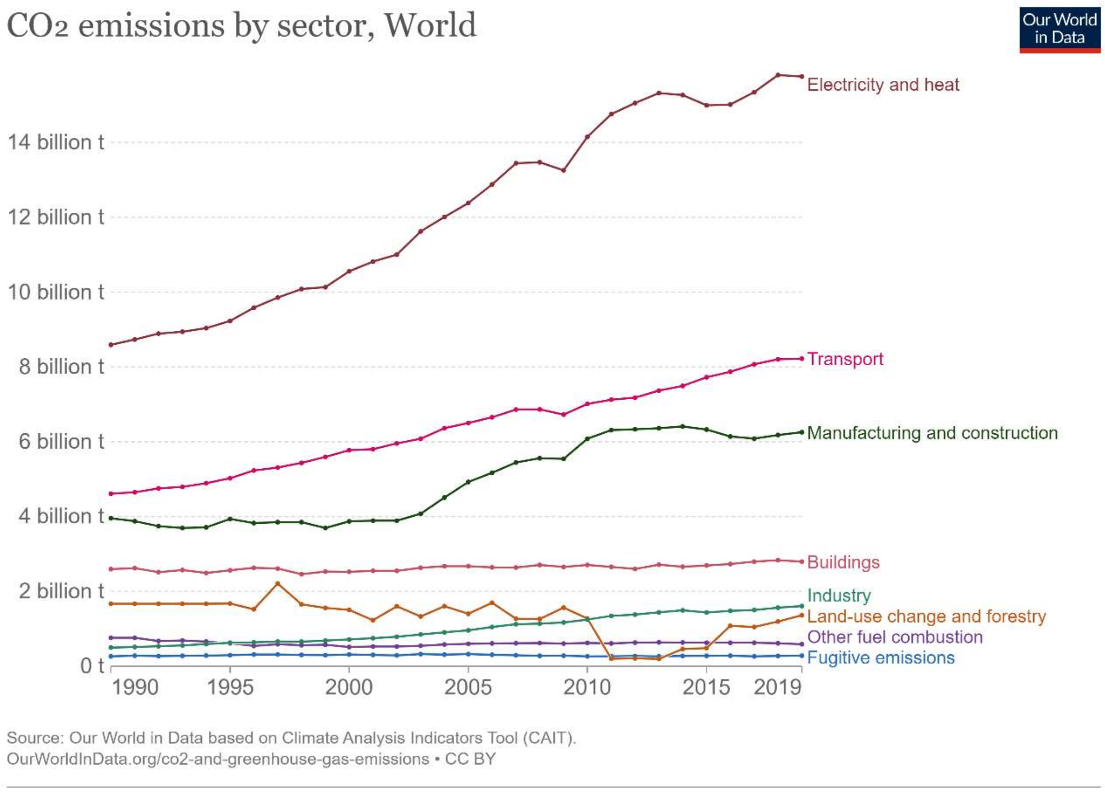

Figure 1.2 - *CO2 emissions by sector* [5]

Within transport sector, road transport is by far the largest contributors to GHG emissions, representing 74% of the sector CO2 production [5], well above the contribution of aviation and shipping.

In the context of politics aiming to mitigate effect of global warming, and in particular reducing impact of road transport sector, low- and zero-emissions vehicles are starting to spread in the market. One important consideration, before proceeding in discussions about ZEVs, is that, in this context, emissions are considered following a tank-to-wheel approach: basically, pollutants are entirely quantified basing on what the vehicle directly emits, without considering the "fuel" production process. Hence, an electric vehicle will be deemed carbon-neutral, without taking into account possible emissions connected to the powerplants necessary for the electricity, or the ones due to the process of hydrogen production. Evidently, aiming to a carbon-neutral impact on environment, hydrogen and electricity production should not be based on fossil resources and instead rely on low-footprint sources.

At the moment, most diffused type of ZEV is represented by battery electric vehicles, that during last years have increased their market share, especially in those countries with well-developed economies. Diffusion of these vehicles has been enhanced by an improvement of their technical aspects (as efficiency and driving range) and a decrease of their prices, that has brought them also to more economic segments of the market.

Beside BEVs, another example of ZEV is represented by fuel cell electric vehicles, typically fueled with hydrogen, but they still represent an extremely small share of overall vehicles, mainly due to the limited refueling infrastructure and the high current cost of hydrogen.

Currently, these solutions still represent a very low share of the market, as in most of countries traditional internal combustion engines (mainly fueled by gasoline or diesel) are still the most used solutions, due to a well-developed refueling infrastructure and generally lower costs of the vehicles. For these reasons, the shift to less environmental impacting solutions will probably require many years to be completed, needing large investments in incentives for costumers and infrastructure. Although these difficulties, virtuous examples like Norway, where in 2019 more than 40% of the total new vehicles registrations was represented by electric vehicles, show that this revolution is possible.

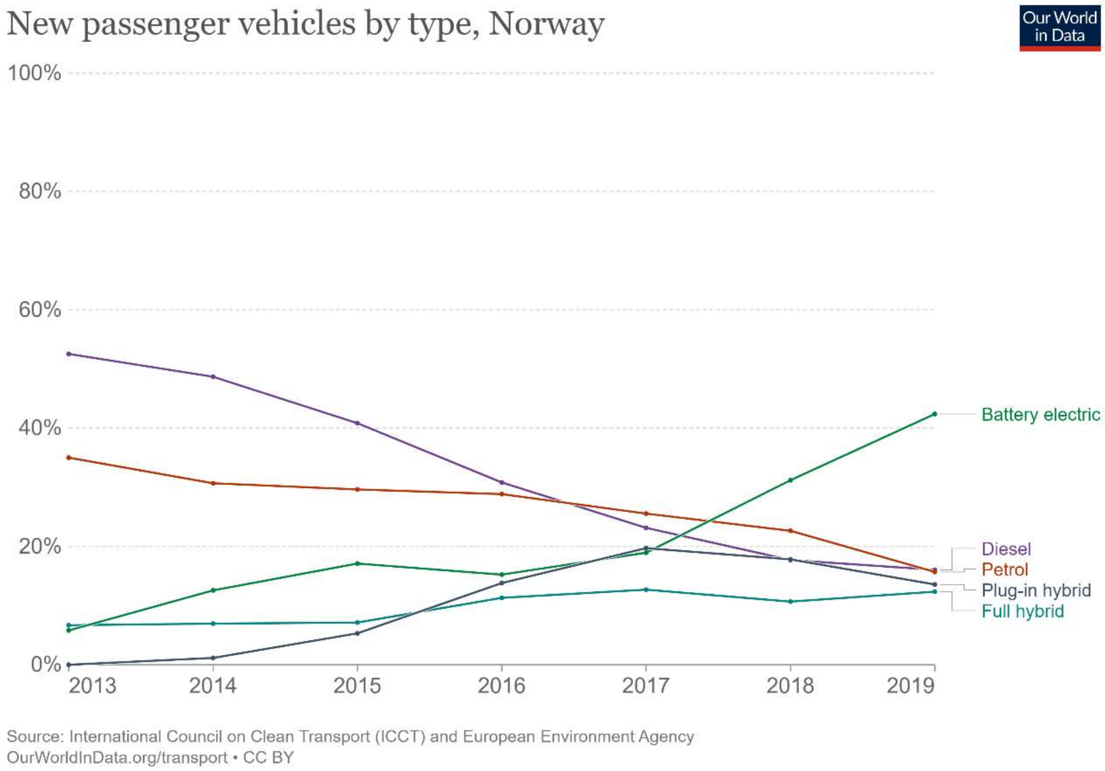

Figure 1.3 - *Registration of new vehicles by type, Norway* [6]

While in the passenger cars context the path for the transition toward alternative powertrains seems defined, with BEVs that represent the leader solution due to their efficiency and relatively low costs, the situation concerning heavy-duty vehicles is still far from be defined.

At present day, trucks segment is still largely based on diesel and, in minor share, gasoline in every country in the world; some alternative solutions, with a lower carbon intensity, as compressed or liquefied natural gas, have been tested and today they represent a small share of the market. In the fully carbon neutral scenario described by Paris Agreement, the decarbonization of heavy-duty vehicles is necessary, and this transition, to be effective, must start as soon as possible.

During past years, while the passenger cars segment gradually explored the possibility of BEVs, HDVs have been left behind, due to both technical and economic reasons:

- The high driving range required by a truck as well as the power rate due to its weight could not be satisfied by the batteries used up to some years ago, due to their low energy and power density that would have resulted in an extremely large and heavy battery pack
- Recharging spots were few and with too low power rates, so the infrastructure was not considered reliable for an entirely electric fleet
- High costs of the vehicles could end up in a less convenient solution compared to traditional powertrains

To overcome these limits of BETs, the possibilities provided by hydrogen were investigated, analyzing two different uses: fuel cell electric and hydrogen fueled internal combustion engine trucks. The great advantage of these powertrains is the overcome of issues related to driving range: even with current gravimetric densities[1], a 700-bar hydrogen tank could store a large amount of hydrogen with a total weight comparable to the one of a diesel engine. A second advantage of the H2ICET solution concerns the “low” retail costs of the vehicles, mainly due to the similarities with current internal combustion engine trucks, especially CNG solutions.

Unfortunately, the issues connected to the recharging stations that limited the BETs use were even more dramatic analyzing the hydrogen situations, due to the lack of a defined infrastructure network.

Fortunately, some of the technical limitations that hindered the widespread adoption of these powertrains in previous years have been mitigated, if not

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[1] Gravimetric density is defined as the ratio between the mass of stored hydrogen and the mass of the entire storage system

entirely overcome, through technological advancements and these solutions are progressively becoming more interesting.

Due to these reasons, and to promising future improvements to the infrastructure that will be described in following chapter, it seems reasonable to start analyzing the economic feasibility of these vehicles, comparing their costs and limitations in order to find the best choice depending on different needs.

1.2 European and Finnish context overview

According to 2015's Paris Agreement, European Union is committed to promote laws and politics aiming to reduce its climate impact, with the purpose to maintain global warming below +2°C. In this context, European Commission has approved, in 2020, a set of policy initiatives aggregated in a document called European Green Deal: final goal of this plan is to make the European Union climate neutral by 2050 [7]. To define a path helping to reach the final target, European Climate Law legislated that by 2030, greenhouse gas emissions should be at least 55% lower compared to 1990 levels [8]. The two documents define a series of investments, initiatives and taxes in different sectors, as construction, biodiversity, energy, transport and food, aiming to achieve neutrality and promote virtuous development.

Transport sector is probably one of the fields where the transition toward carbon neutral technologies will be more critical, but also more important.

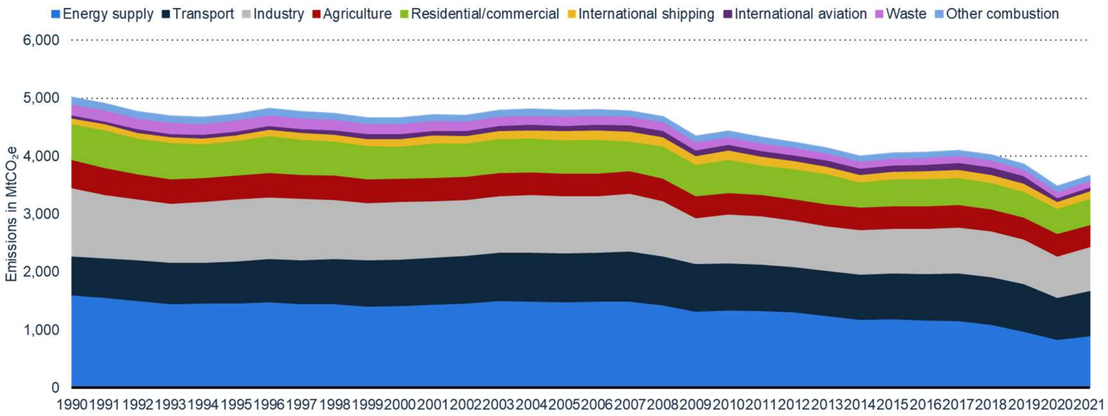

Figure 1.4 - *EU emissions by sector* [9]

Unlike most of other sectors, for which emissions have seen a gradual decrease during the years, resulting in a total reduction of about -1.4 Gton CO2eq from 1990 levels (about -30%) [10], GHG emissions connected to transport sector are increasing, with 2021 that has seen a contribution from transport sector of 32% of overall CO2 emissions [9] (see Figure 1.4).
Road transport accounts for about 71% of the total transport emissions, and 52% can be connected to passenger cars and light-duty vehicles, while heavy-duty road transport claims about 19% [10].
Road traffic, and especially freight transport, is the backbone of European trading: in 2022, 77% of all the freight transported over land were carried by trucks [11], which represent an essential part to the functioning of European logistic.
Unfortunately, this sector is still strongly related to fossil fuel use: in 2021, almost 300,000 new trucks were registered in EU, but of these, just about 0.5% is considered a ZEV, mostly BET [12].

Data regarding Finland are not more positive: on an entire fleet of about 172,000 operating trucks in 2022, only 25 are BET [13]; in 2021, transport sector emitted more than 21% of the total CO2eq of the country. Passenger cars show slightly more optimistic data: more than 10% of newly registered cars in 2021 was BEV, with Finland at third place in EU, behind Sweden and Denmark [14].

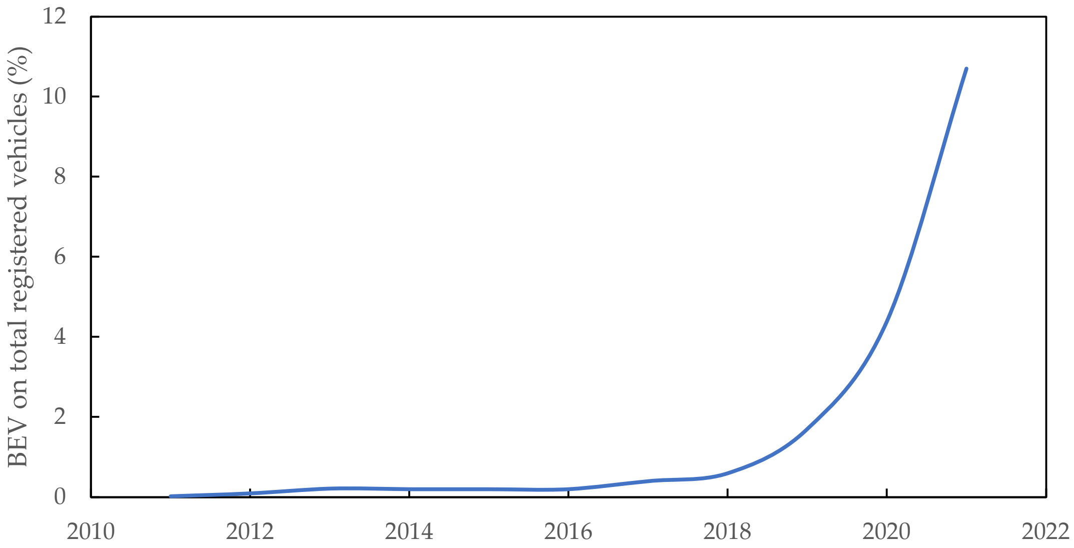

Figure 1.5 - *BEV/Total registered vehicles* [14]

To achieve the ambitious goals aiming to prevent global warming, a transition toward zero-emission vehicles is fundamental, and in particular it is needed a fast enhance to the decarbonization of heavy-duty vehicle fleets. Among the low- and zero-emission possibilities for trucks powertrains, the most promising ones, as mentioned above, seem to be:

- Battery electric trucks
- Fuel cell electric trucks
- Hydrogen fueled internal combustion engine trucks

For sake of completeness, it must be added that these are not the unique solutions that are under analysis during these years: among the others, two other possibilities must be mentioned:

- Use of biofuels in internal combustion engines: these fuels could guarantee, in some scenarios the carbon-neutrality or even the carbon-negativity of a vehicle (on a well-to-wheel approach); unfortunately, there is still an open debate about the sustainability of biofuels concerning the land impact and their economic viability
- Use of catenary: trucks could be charged during driving through an overhead connection to electric grid, with the possibility of using a very small battery also on long-haul vehicles; the disadvantage is that this technology is strongly dependent on the development of a specific infrastructure, that, according to most of the studies [15], could have extremely high costs

For these reasons, in this document only the three above-mentioned solutions will be analyzed.

Today, besides some technical limitations that will be discussed in following paragraphs, the most significant obstacle to the widespread adoption of these technologies is the need for a capillary infrastructure, capable to fulfill the basic needs of a large fleet of hydrogen or electric trucks.

In recent years, the availability of charging stations for electric cars has increased throughout Europe, creating a connection with the growing popularity of electric vehicles. As the infrastructure becomes more reliable and extensive, more people are inclined to purchase battery electric vehicles (BEVs), which in turn encourages further expansion of the charging network etc.… in a virtuous cycle of cause and effect. In 2023, thanks also to private chargers installed directly by BEVs owners in their houses, the recharging network for electric passenger cars can be considered at least acceptable for the current share of battery cars. As an example, in the city of Helsinki, there are currently 51 public charging stations for cars, each one with a number of charging points that can go from one to some tens [16].

Unfortunately, not every charging station designed for car use can operate on trucks: the discriminating variable is typically the power output of the charging points, that must be higher for heavy duty vehicles applications. Typical rated power of standard chargers is in the range 3-50 kW, and most of them usually are 11 or 22 kW; these specifics are not sufficient to recharge a truck battery in a reasonable time, due to its larger size, and high-power chargers are needed.

For large BET chargers, typically three levels are identified [17]:

- Up to 100 kW: for overnight charging, used in private depots or in public areas
- Up to 350 kW: fast charging during operation period
- About 1 MW: ultra-fast public charging

Currently, in Finland, there are less than 100 public charging stations equipped with 100+ kW chargers, and less than 10 considering 350+ kW power [16].

Regarding hydrogen refueling network, the infrastructure still has a drastically lower level of penetration, due to the extremely low diffusivity of FCEV and H2ICEV on the roads (but also the reverse relation of effect-cause can be considered true).

In Europe, in 2023, there are 174 operating hydrogen refueling stations, most of them providing hydrogen at 700 bar, and 92 are located in Germany [18], [19]; some other private refueling points are present in some cities, mainly used for urban bus fleets. In Finland, today, there are no public refueling stations operating.

As obvious, the current infrastructure for hydrogen refueling is absolutely not sufficient for a FCET or H2ICET large fleet operating in the country; situation of electric chargers, even if less critical, must be improved too.

With this goal, in March 2023, European Commission, Parliament and Council of Ministers have reached the final agreement on EU Alternative Fuel Infrastructure Regulation (AFIR), that requires from every Member State [20]:

- Installation of fast recharging stations every 60 km in the core corridors of the Trans-European Transport Network[1] (TEN-T) within 2025, with a minimum installed aggregated power that should reach 600 kW by 2027

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[1] Core TEN-T: it comprehends not only roads, but also railways, inland waterways and short sea shipping routes. It links the major cities and nodes in Europe to foster efficient transportation of people and goods [121]

- Same requirement for every smaller road (comprehensive TEN-T[1]) by 2030 (installation) and 2035 (600 kW power)
- 15% of the entire TEN-T (core and comprehensive) must be equipped with fast-charging stations for trucks and buses every 120 km by 2025, and 100% must be reached within 2030 (with chargers every 60 km of the core TEN-T), with at least two 350 kW recharging points in each station
- Installation of one hydrogen refueling station at 700 bar every 200 km of the core TEN-T and in each urban node withing 2030 (minimum capacity of 1 ton/day)

If these targets will be achieved in short time, there is a strong probability that truck fleets operating in Europe could switch to ZEVs without particular logistic issues. Of course, some more detailed analysis on the supply chain behind the refueling and recharging infrastructure should be done, in order to enable them to operate in the proper way, with proper forecasts about demand distribution and the best positions for the network nodes, but this is not the objective of this document.

Finland is expected to be a particularly favorable environment for the implementations of AFIR objectives and the diffusion of ZET fleets.

During last years, Finland has moved its energy supply drastically toward renewable sources (with a significant increase of wind power in recent years) and nuclear energy, as visible in Figure 1.6.

This transition has brought two important benefits:

- Decrease of the carbon intensity: Finnish average carbon intensity of the entire power sector is about 131 gCO2/kWh, the third lowest in Europe, with obvious beneficial effects on environment and pollution [21]
- Decrease of electricity prices: in 2022, average price for non-household consumers was about 10.35 cent€/kWh, which is the cheapest in the EU [22]

These low prices of electricity are extremely positive for the diffusion of BETs, meaning that the lower "fuel" costs compared to traditional diesel are likely to compensate the higher initial investment for the truck.

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[1] Comprehensive TEN-T: it connects all regions of the EU to the core network [121]

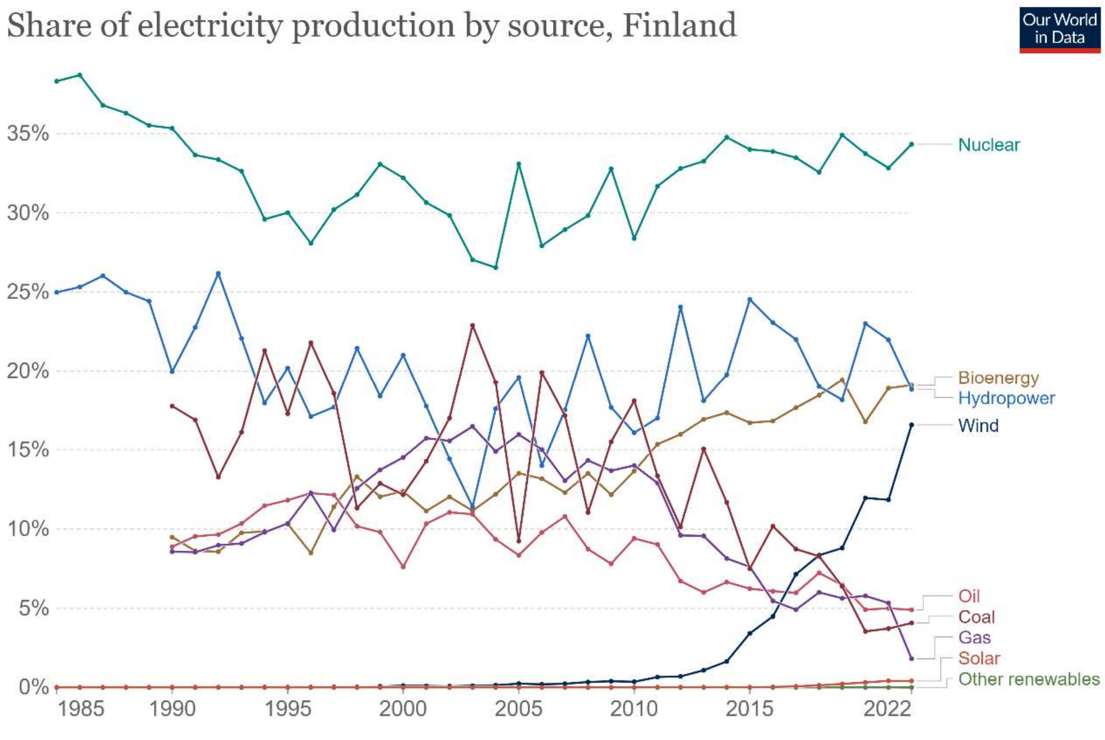

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Figure 1.6 - *Electricity production by source* [23]

Moreover, these low electricity prices should also have good impact on the hydrogen price: it is worth to remember that, following a policy aiming to reduce impact on environment, the hydrogen used in the vehicles should come from water electrolysis, exploiting electricity produced by sources with low carbon-intensity. Considering this, it is clear that a low electricity price would mean a low hydrogen production cost, and, consequently, a low hydrogen price.
Unfortunately, current scenario is really different: in 2020, about 145,000 tons of hydrogen were produced in Finland, but less than 1% came from water electrolysis, while the rest is produced through steam reforming [24]. To promote a "cleaner" hydrogen production, dozens of new investment projects have been launched in recent years, also with important public investment aids, and most of them are now in preliminary planning phase [25]. Thanks to these actions, Finnish government is confident to be able to produce green hydrogen necessary to completely fulfill internal demand, and become a net exporter in some years, due to its competitive price.

This promising premises represent the main reasons that have led the choice of Finland as the background of this economic analysis, confident that this country will be one of the first in EU where a transition toward a new mobility will be technically and economically feasible but hoping that it will not remain a unique example in the long term.

1.3 State of the art of technologies

Considering both technical characteristics and potentialities of Finland, most promising solutions for substituting current fleets with ZEVs are:

- Battery electric truck
- Fuel cell electric truck
- Hydrogen-fueled internal combustion engine truck

Technology of battery electric vehicle is, among the three mentioned above, the most studied and of common use. In passenger cars sector, but also on small motorcycles, BEVs are becoming every year more popular, due to their high efficiency and low maintenance costs compared to traditional vehicles; also purchase cost of the vehicle, that was significantly higher than ICEVs in the past, taking BEVs generally to the segment of luxury cars, is decreased: this is mainly due to the costs of batteries, that have seen a reduction of almost 90% in less than 15 years [26].

Most common technology for batteries in electric vehicle is lithium-ion, that guarantees good power- and energy-density, and their properties have been improved in the years, giving the possibility of overcoming the limited driving range of first models. Currently, specific energy of a vehicle battery pack is in the order of 0.125-0.250 kWh/kg [27], [28], allowing to reach in passenger cars capacity up to 100 kWh and (declared) driving range of 650 km, as current Tesla Model S [29], [30].

Even with recent development, the battery technical specifics are still the Achille's heel of BET, especially for long-haul applications: while on urban routes the electric powertrain allows to reach efficiencies significantly higher than diesel equivalent vehicles, and, due to the limited daily mileage, the size of the battery can be relatively limited, on long distances limits of the batteries are not totally overcome yet. Firstly, it must be considered that, at high average speeds as in a typical highway, the difference in driving efficiency between internal combustion engines and electric powertrains is not so impacting as it is for urban routes, due to the increase in efficiency of ICEs at high loads (more detailed analysis will be provided in Fuel economy evaluation chapter (2.2.1)). Secondly, it is worth remembering that, although specific energy of li-ion batteries is increased in recent years, it is still drastically lower than the one of liquid fuels (e.g., diesel specific energy is about 12.67 kWh/kg). These two disadvantages prevent use of BETs in some specific applications, for example on extremely long routes, or at least they impose to consider some measures to overcome them.

Currently, the BET with higher energy capacity results to be the Tesla Semi, delivered to some first costumers at beginning of 2023: it is a 37-t truck (full load), equipped with 900 kWh battery pack that should allow a (declared) driving range of 800 km [31].

Assuming the case of a 76-t truck with a daily mileage of 720 km, operating in Finnish cold weather, it is calculated, according to the model that will be presented in Fuel economy evaluation chapter (2.2.1), that a 1200 kWh battery should be necessary, even with the assumption of using the 45 minutes mandatory break of the driver for partially recharge the vehicle. At present day, no vehicle have such a large battery, and even if there was, it must be remembered that it would weight about 7000~9000 kg, with a consequent loss of payload (and other technical issues regarding the weight distribution on the tractor). A possible solution would be increasing the break of the driver during the day, but this is something that must be considered in the operation planning. In any case, this kind of technical limitations affect very few cases, and in most of applications it is possible to conclude that, with a properly developed charging network, BEVs could fulfill most of the needs.

Fuel cell electric vehicles are still drastically less diffused, both in passenger cars and trucks segments; they could be fueled with different mixtures, but generally hydrogen is used (from this point and in the rest of the document, concerning FCEVs it will always be assumed they are fueled with pure hydrogen). Main advantage of this technology is that it uses an electric powertrain, with its high efficiency, and a fuel, that allows to have a higher energy density than batteries and shorter refueling time; main disadvantages are a higher price of the vehicles and a lower energy efficiency (due to the fuel cell compared to the battery). In a tank-to-wheel approach, FCEV are considered among the zero-emissions vehicles, since the only by-product of the fuel cell is water.

Today, the most used fuel cell technology in transport application is PEM, following the example of passenger car models (among all, Toyota Mirai [32]), but different other possibilities were tested during the years, as direct methanol, phosphoric acid, molten carbonate, solid oxide and reformed methanol.

The fuel cell system is usually supported by a battery, and the interaction between the two is extremely important, because it determines the operation strategy of the vehicle and, consequently, the sizing of the components; typically, FC can operate as [33]:

- Load follower: FC has a large size, battery is relatively small and it is just used to cover peaks of power demand
- Range-extender: the powertrain relies mainly on the battery, and the FC is only used to extend the driving range and to recharge the battery when needed

In this document, the assumed FCETs will be designed to operate with FC in load following mode, with a large FC system and a small size battery.

Another variable that must be considered is the onboard hydrogen storage system (HSS): today, three main options are available:

- Liquid hydrogen
- 350 bar compressed hydrogen
- 700 bar compressed hydrogen

Liquid hydrogen storage system represents the best solution in term of energy density and specific energy, as hydrogen reaches higher density than in the gaseous form; however, to be maintained liquid, it must be kept at -253°C and the liquefaction process is extremely expensive in energy and economic terms. Plants operating with liquid hydrogen are extremely scarce in Europe today, and in future plans for the development of the infrastructure (described in European and Finnish context overview chapter (1.2)), refueling stations are generally not assumed to operate with it.

350 bar compression is the common standard for hydrogen storage in bus applications and some trucks are designed according to it too. The main disadvantage of this storage system is that the energy density is limited by the "low" compression rate: in long-haul trucks, needing high quantity of stored hydrogen, this could cause a loss of maximum payload due to volume limitations of the vehicle; for completeness, if must be added that in Finland, due to limits on dimensions different than in the rest of Europe, the maximum payload is usually reached on a weight basis, so this disadvantage of 350-bar storage could be almost negligible. On the other hand, a lower compression would mean less energy spent by the refueling station for the delivery.

700 bar compression is the most used solution considering passenger cars, but also newer projects in HDV field start using it: it allows to reach higher energy and gravimetric densities, resulting in higher payload capacity; in contrast, the

tank and the storage system are more expensive compared to the 350-bar case (about +10% €/kg [34]).

Other storage solutions, as metal hydrides, zeolites or ammonia, are generally considered not suitable for vehicle applications, as their gravimetric density is too low.

Considering the three possibilities, it has been decided to assume a 700-bar storage system in all the case studies, as it seems to be the most promising for future developments, taking into account both the vehicles and the refueling infrastructure.

As a last consideration, it is worth remembering that one the main advantage of FCEVs on BEVs is the higher flexibility they guarantee: for a total recharge, a BET will need, depending on the capacity of its battery and the deliverable power of the charging spot, a stop between one and several hours; on the opposite, refueling of a hydrogen storage in a proper station would require no more than some minutes, a time similar to a traditional diesel refueling.

The technology of hydrogen-fueled internal combustion engine vehicles is the least widely adopted among the three solutions studied in this document: the primary reason for this is the declining interest in H2ICEVs, with a preference for zero-emission technologies such as BEVs and FCEVs.

Indeed, first consideration that must be done on H2ICEs is that they cannot be considered as zero-emission powertrains: although hydrogen combustion has purely water as byproduct, trace amounts of CO2 (mainly from lubricant oil) and NOx (similar to or even higher than traditional gasoline or diesel engines due to high combustion temperature) are emitted by the engine; although this is surely a disadvantage, studies indicate that strategies such as exhaust gas recirculation can significantly reduce NOx emissions, and the CO2 emissions are low enough to consider H2ICEVs as a possibility in the decarbonization transition [35], [36].

Other cons compared to electric powertrain are the lower efficiency of combustion engines, particularly marked at low loads, and the higher maintenance costs.

On the other hand, first important advantage of this solution lies in its simplicity: being based on the well-established technology of combustion engine, final prices of the vehicles will be drastically lower compared to BEVs and FCEVs, especially in recent years, when batteries and FCs are still being improved and developed. In particular, it is worth mentioning the great similarity between H2ICEs and compressed natural gas engines in terms of components and combustion strategies. This similarity allows the experience gained in the production of CNG trucks to be leveraged in the development of H2ICEVs, resulting in relatively low costs; these similarities between the two types of trucks will be largely exploited in this document for the evaluation of the costs of components.

The second advantage of H2ICEs over FCs (and in particular to PEMFCs) is that the requirements on hydrogen purity are significantly less stringent: while this may not be a significant factor in a future scenario with widespread refueling infrastructure, it should be considered in the coming years when standards and networks are not yet well-defined. Lastly, some studies highlight that H2ICEs do not rely on rare raw materials such as lithium, cobalt, nickel, or platinum, which are necessary for the production of batteries or fuel cells: this fact not only has an impact on manufacturing costs, but also have potential benefits during the end-of-life stage of components, considering their disposal and recycling [36].

For these reasons, H2ICEVs are being regarded as a viable option for the decarbonization of truck fleets, at least in the short term, and they will be evaluated in this document.

Regarding considerations on hydrogen storage systems, they remain the same as in FCEVs case, described above, and same assumptions have been taken.

These three technologies have been evaluated as the most suitable for decarbonization of HDV fleets, in particular in the Finnish context, for both technical and economic reasons.

In following chapters, a more detailed economic analysis will be proposed, in order to find the best solutions depending on specific case studies.

1.4 Economic analysis

To operate the economic comparison object of this review, the Total Cost of Ownership (TCO) of each considered vehicle will be calculated.

This type of analysis is largely used in economic studies referred to vehicles, as it is considered a simple way to summarize many parameters in a single final result, with the possibility of comparing different kind of vehicles or powertrains.

Aim of the TCO evaluation is to calculate the final cost of an asset, in this case a vehicle, on its entire lifetime; for this reason, both initial purchase price and operational costs are considered, assuming parameters representing the duty-cycle of the good, its possible lifetime, external constraints…

This method is particularly useful when used on vehicles with important differences concerning capital and operational expenses. As it will be described in following sections, these vehicles have largely different purchase costs between each other, but this disparity is counterbalanced by the operational costs: TCO provides a methodology to compare the final costs on their operational periods.

In literature, TCOs are largely used to evaluate vehicles related costs on their lifetime, and comparison between different powertrains are not infrequent; for this reason, part of the contents presented in this document will be taken from past studies, assuming some methodologies and models that are not original of this analysis.

Y. Ruf *et al.* [37] in the report for Roland-Berger provides important ideas considering applications of HDVs on specific European routes, analyzing the competitiveness in terms of TCO of different powertrains, as diesel engines, hydrogen fueled fuel cells, battery electric vehicles or others. Descriptions of duty-cycles of the trucks in each case study are largely detailed, and this approach has been used as an example for the definition of the case studies that will be used in this thesis and that will be described in following sections. Key findings of this report are that in near future, diesel trucks will remain more convenient than alternative powertrain, but with future scenarios, after 2030, assuming a development of the technologies and consequently a decrease of purchase costs, FCEVs will probably become cheaper, on the entire lifetime, than diesel vehicles for all types of duty cycles; BEVs should become convenient over FCEVs and diesel for short urban routes, while on longer routes, hydrogen powertrains are expected to be a better solution.

Rout *et al.* [38] describes a detailed approach for the calculation of TCO for HDVs considering different powertrains, providing important hints on the definition of the main parameters needed for the analysis. Differently from Roland-Berger study, this report enlightened that BEVs could become the cheaper solution for trucks even in current scenario, while FCEVs have the potential to become more convenient than diesel in a future scenario with the assumption of large development of electrolyzers, but will probably remain more expensive than BEVs unless strong policies encouraging hydrogen use were introduced.

ICCT [39], [40] provides two studies of the TCOs of heavy-duty vehicles for long-haul applications in European scenario: beyond a general evaluation of the initial and operational costs of the vehicles, it analyzes costs specific for different countries, taking into account fuel costs, incentives, taxes… of each context, arriving to a final comparison between FCEVs, BEVs and diesel vehicles. Unfortunately, among the considered countries, Finland is not present. Outcomes of these studies is that BEVs will probably become convenient over diesel solutions in most of European countries within 2030, even assuming a "current development" scenario. Considering FCEVs, at current prices of hydrogen, they will remain more expensive than diesel also in next years; in a sensitivity analysis, authors demonstrate that break-even condition is reached in most of countries within 2030 if the price of hydrogen is assumed to reach 3 €/kg. Many other studies use the TCO analysis applied to vehicles, providing evaluations for different segments, from passenger cars to heavy-duty vehicles, and this methodology cannot be considered original of this study.

Nevertheless, difference between the presented results should suggest how difficult this kind of evaluations are, especially when they are referred on developing technologies, for which both initial and operation costs are not well defined yet. Final result is based on cost assumptions that could be badly predicted, giving numbers that will be revealed as not consistent in next years: this gives the need of providing the readers not only of the results, but the entire methodology, so that it could be changed in a second moment in order to satisfy different needs.

Remembering that parameters will probably be evaluated with some degrees of uncertainty that cannot be avoided in a developing scenario, sensitivity analysis will be presented together with the results, in order to provide some evaluations on possible corrections of the assumed parameters.

An important consideration that must be presented at this point is that, while BEVs and FCEVs are observed in many studies as examples of "alternative" powertrain, hydrogen fueled internal combustion engine vehicles are not considered in almost anyone the reviewed documents. For this reason, evaluations regarding this kind of powertrain will be more difficult, due to lack of literature on this field.

The need for a total comparison that involved the three mentioned powertrain technologies is the main driving motivation of the study here reported, with the aim to provide model that could be applied to future business cases.

Beyond that, Finland is considered to represent a good opportunity for the development of alternative vehicles, due to the particular combination of costs of electricity and road-traffic needs. This has oriented the choice of this analysis to this context, assuming parameters specific for the needs (and the constrains) of this specific country.

As it will be demonstrated, different powertrains are convenient for different uses and in different scenarios, and not a single best solution will be identified: general idea that the report aim to highlight is that each case can have its best possibility, and giving a methodology for future studies based on specific needs is the major objective of this document.

2. Model definition

Limits of some economic studies regarding vehicles is that they focus only on purchase and fuel costs: these can be among the largest cost components of a vehicle but they are not completely representative of the costs over the entire lifetime. Especially on longer analysis windows (15-20 year), recurring costs such as maintenance, insurance, midlife overhaul costs can have a not negligible impact on the total costs of a vehicle.

The Total Cost of Ownership (TCO) is an economic indicator, used to estimate the total expenses associated with the purchasing and usage of an equipment.

The aim of conducting a TCO analysis is to offer a comprehensive perspective on the costs associated with a particular tool throughout its entire lifespan; one notable advantage of TCO analysis is its ability to summarize in a unique result all the cost related not only to the initial price, but also the operational expenses, enabling meaningful comparisons between different equipment options, facilitating informed decision-making.

Use of TCO is largely diffused in comparing vehicles or even fleets: it can help in the choice among different vehicles classes, fleet dimensions or, as in this case, different powertrains.

Accuracy of the results of analysis of this type is based on the correct identification of the main vehicle costs of ownership and on their precise estimation. Main costs of a vehicle are typically related to purchase and fuel expenses, but other parameters are also important to be considered, as maintenance, depreciation, taxes…

Objective of this document is to provide a comparison between different powertrain solutions for HDV, considering battery electric powertrain, fuel cell based powertrain and hydrogen-fueled internal combustion engine: to do this, all the main sources of cost for the vehicles will be considered, with major attention on the ones that are not common to the three technologies, because they will be the basis for a correct choices among these possibilities.

TCO model

Vehicle purchase cost		
	Retail price	Price of the vehicle, evaluated basing on components teardown
	Financing	Evaluation of interest rates and type of financing
	Depreciation	Evaluation of the depreciation rate, using models from literature
Fuel cost and infrastructure		
	Fuel economy evaluation	Fuel economy of the vehicles evaluated from literature
	Fuel price assumptions	Assumptions on "fuel" prices, with possible scenarios
Insurance cost		Insurance costs evaluated on weight classes
Maintenance and repair costs		
	Maintenance and repair	Maintenance costs based on annual mileage
	Midlife	Midlife overhaul costs (battery replacement, FC substitution...)
Taxes and fees		
	Vehicle registration taxes	Registration taxes according to Finnish legislation
	Annual fees	Evaluation of due annual fees according to weight classes and use
Road tolls		Road tolls evaluated on the different case studies
Other costs related to HDV		
	Payload reduction	Payload reduction due to additional weight of alternative powertrain
	Drivers cost	Drivers cost based on annual driving hours
	Additional time for recharging	Additional time for recharging of BEV

Table 2.1 - *TCO components*

First-user perspective is assumed for this model, so the vehicle is considered to be new at the beginning of the considered period, while it will be resold on second-hand market at the end of its useful life (assumptions on duration of this period will be discussed in section Assumed cases definition section (3.2)).

Beyond "standard" cost components, as purchase price, fuel, maintenance, insurance… vehicles considered in this analysis are exposed to costs connected to their commercial activity; this fact not only contributes to strongly increase some parameters (e.g., annual mileage will be much higher than a typical passenger car), but introduces some additional ones, as driver cost or payload capacity.

In Table 2.1, main sources of costs are reported, which will be discussed in detail in following sections. These parameters will be studied related as much as possible to Finnish context: as it will be described in the detailed analysis, for some of them it will be relatively easy (as taxes and tolls), while for others, data are too scarce for an analysis specific for a single country (as maintenance and purchase costs).

As it will be explained, some of these parameters are common or at least similar to traditional powertrains, while other will be specific for the considered technologies: these ones are usually the most difficult to evaluate, as they are referred to alternative fueled vehicles that are not well diffused on the market, and quantitative evaluations on these costs are still extremely scarce.

Evaluations of most of the cost components are based on current scenario, assuming numbers referred to today market, but some considerations about future trends will be exposed in final sections through sensitivity analysis.

Regarding TCO evaluations for vehicles, it is usually reported in aggregate terms, summing up costs on the entire span of the analysis timeframe, or on a per-kilometer (or per-mile) basis, as a levelized cost of driving (LCOD) [41].

Considering that this study is referred to commercial vehicles, in particular trucks whose main use is freight transportation, particular focus should be given to the costs related to this transport capability. To properly describe these costs, final results will be reported on a $cent€/km/t$ basis: this unit of measure of freight transport reflects the costs of transporting one ton payload on one kilometer of the route [42]. This unit allows to fastly represent possible changes in the payload capacity, due to the different powertrains: for example, as it will be discussed in more detail in following sections, BEVs can observe a decrease of the payload due to the weight of the batteries, in order to maintain the entire truck below the weight limits imposed by legislation; this payload reduction would simply be considered in the results as an increase of the unit cost.

Cost expressed in this way will be called in this document Levelized Cost Of Transport (LCOT).

Another possibility for reporting the LCOT could have been the use of a unit of measure based on freight volume ($cent€/km/m^3$). The choice of an analysis based on mass has been taken considering that Finnish limits on trucks dimensions (that will be discussed in detail in Heavy-duty traffic in Finland (3.1)) are stricter on weight basis than on volume basis: for this reason, many trucks travelling at full-load in terms of weight are not completely charged in terms of volume. Considering that limits for the rest of Europe are different, the choice of a volume-based analysis could be the best one for other countries.

TCO as aggregate term is calculated as:

$$TCO = \sum_{i=1}^{N} \frac{C_i}{(1+d)^i} \qquad 1$$

Where:

- i = considered year
- N = final year of the analysis
- C_i = total cash flow of the year, in €
- d = discount rate

To express the results on a per-ton-kilometer basis, it is sufficient to amortize the costs over the kilometres driven in each year, or "discount" the miles along the costs [41], [43].

Global equation for the calculation of levelized cost of transport is:

$$LCOT = \frac{TCO}{\sum_{i=1}^{N} \frac{VKT_i \cdot TF_i}{(1+d)^i}} = \frac{\sum_{i=1}^{N} \frac{C_i}{(1+d)^i}}{\sum_{i=1}^{N} \frac{VKT_i \cdot TF_i}{(1+d)^i}} \qquad 2$$

Where:

- VKT_i = vehicle kilometers traveled in year i, in km
- TF_i = transported freight in year i, in t

As observable in the equation, not only the cash flow, but also the kilometers traveled in a certain year are discounted through the discount rate d. Reason of this operation is that the lifetime cost is a function of the cost per ton-km in year

i, and this annual cost value must be discounted, in order to evaluate it with a lower weight [41]. Another way of seeing this is that if only the cash flow was discounted, the corresponding costs per ton-km would decrease over the years: this is not the focus of a discounted cash flow analysis, as their unit costs must be mainteined constant, and only their weight has to become lower in the years.
As a qualitative example, TCO and LCOT of a typical 4x2 diesel tractor are here reported:

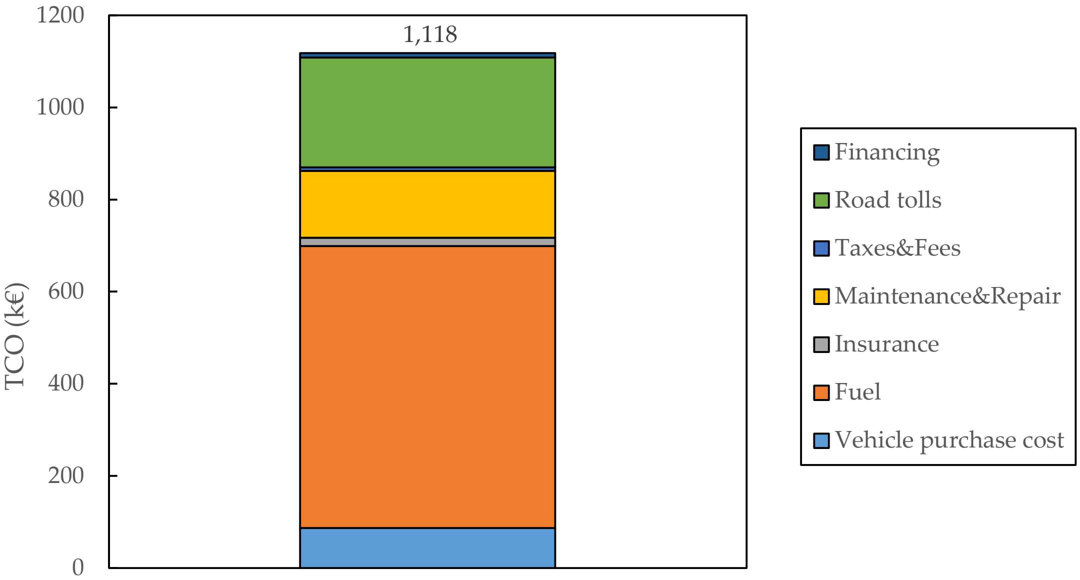

Figure 2.1 - *TCO of diesel tractor*

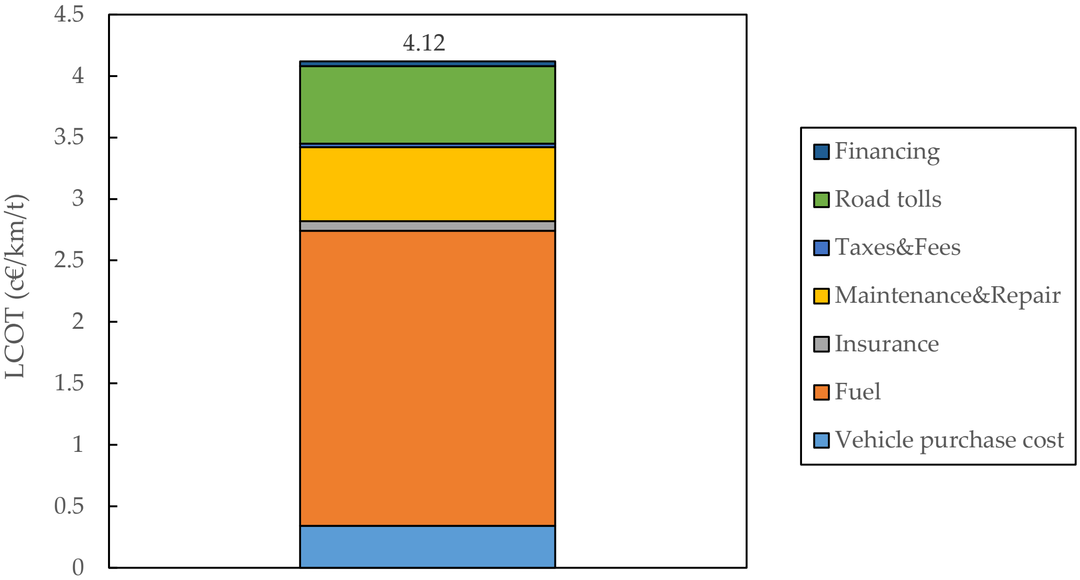

Figure 2.2 - *LCOT of diesel tractor*

As it can be observed, fuel costs represent by far the most impacting cost component on the lifetime of the vehicle; maintenance and repair, road toll and vehicle purchase costs are also remarkable, while other components, even if not negligible, have a minor impact on the total.

In following sections, main cost components and parameters are discussed in detail for the model.

2.1 Vehicle purchase cost

2.1.1 Vehicle retail price evaluation

This category includes all the costs related to the purchase of the vehicle: final result should represent the amount that the buyer pays to the producer, so it excludes registration taxes or other fees (that are considered in Vehicle registration taxes (2.5.1)).
It is fundamental to notice that, while it can be relatively trivial to define retail price for goods that are quite diffuse on the market, for example diesel trucks, this is not true for vehicles that are really scarce in current fleets, and their price is not well defined by market dynamics. Dimensions of market of innovative types of vehicles, as BEVs, FCEVs and H2ICEVs, are today extremely reduced and this prevents the definition of precise prices, that are still strongly connected to the particular case they are applied to; for this reason, literature on this topic is not abundant, and provided numbers can be quite conflicting.
In general, it is possible to state that current costs of vehicles with modern powertrains will be generally higher than the correspondent costs of well-known technologies, as diesel engines, due to research costs, lack of standardization of components, few manufacturers... In the next future, they will probably become cheaper, due to improvement of technologies, scale-up economy, second-hand market presence…
In this context, it is possible to think about the market profile of BEV in the LDV market: some years ago, average prices were considerably higher, due to the novelty of the technology and the market type (almost a monopoly controlled by Tesla); today, prices have decreased, and diffusion of BEVs in low-cost segment is spreading. Beyond that, diffusion of BEVs in the LDV market has surely

enhanced the possibility for a definition of electric powertrains also in HDVs, considering the decrease in battery and other components cost in the past years. Hydrogen technologies are drastically less diffused at present day, especially in road transport, but they will certainly increase in the future, with a probable exchange of technologies and skills with sectors different from HDVs, as aerospace and railway systems.

Lastly, it should be noted that market of BEVs and FCEVs is today strongly impacted by the presence of national incentives given by many European countries (and also extra-EU): as a result, sellers tend to inflate prices of their goods, leading to prices that are not fully justified by materials and manufacturing costs.

Vehicle purchase cost is generally one of the most impacting factors on the TCO of every kind of vehicles and powertrain.

Many reports defining TCO for vehicles assume retail price of the trucks with top-down approach, assuming estimations from previous literature or shifting prices of well-known powertrains (diesel ones) to advanced powertrains with some hypothetical conversion factor. This approach can give effective results if it is based on consistent previous studies, but in fact it provides numbers that are quite difficult to verify in a critical approach.

To avoid this problem, in this report it has been chosen to follow, as long as it is feasible, a reverse methodology: basing on M. Kuhn *et al*. [28] approach, retail price for innovative powertrains is evaluated following a bottom-up methodology. With this procedure, the final price is calculated starting from estimations of cost of components (according to the powertrain technology), summing them up and eventually considering a Retail Price Equivalent multiplier, representing indirect manufacturing costs.

The main advantage of this break-down is that it considers each component on its own, with a more precise control on uncertainty of prices (that cannot be avoided, considering we are dealing with components that are not yet diffused on market), allowing a second control on the consistency of each assumption, instead of just having the overall price.

According to M. Kuhn *et al*. [28], overview of the major elements (and principal sources of cost) of HDVs is reported.

Here, components common to the three technologies (and also to diesel trucks) are enumerated:

- cab
- electrical and wiring harness

- air brakes
- heating, ventilation and air conditioning (HVAC) systems
- cooling modules
- chassis and driveline

Cost of these components is relatively easy to determine, as they are all part of the well-defined market of diesel trucks.
Then, components peculiar to BEV are considered:

- Battery pack system: it includes
    - Battery cells: their cost is mainly dependent on energy capacity. More than 50% of this cost is due to material costs, and it generally accounts for about 80% of the cost of the entire battery system
    - Battery management system
    - Other battery sub-systems: including HV management systems, internal cooling systems, mechanical supports…
- High Voltage components: responsible of power control during charging and driving modes, include
    - DC/DC converter
    - On-board Charger
    - HV distribution system
- Battery and electronics thermal management:
    - Chiller/Heat exchanger
    - HV and LV pumps
    - HV PTC heater
- Electric HVAC systems: they utilize high voltage components to replace engine driven air conditioning and heating
    - HV PTC heater
    - HV air compressor
- Electric drive unit: providing mechanical power to the wheels,
    - Inverter
    - Electric motor
    - Gearbox/transmission
- Electric air brake compressor system
    - Electric steering pump system

For all these components, costs are mainly related to power capacity of the system (kW), with exception of battery pack system, whose cost is related to energy capacity (kWh).

Considering components characteristic of FCEV:

- Fuel Cell system: including:
    - Fuel Cell stack
    - Balance of Plant
    - Fuel cell boost converter
- Hydrogen Storage System
    - Hydrogen tanks
    - Balance of plant
    - Structure
- Battery pack system: needed also for FCEV, although energy capacity needed is lower than BEV, as it is not the main energy storage feeding the powertrain; it includes
    - Battery cells
    - Battery management system
    - Other battery sub-systems: including HV management systems, internal cooling systems, mechanical supports…
- High Voltage components: responsible of power control during charging and driving modes, they include
    - DC/DC converter
    - On-board Charger
    - HV distribution system
- Battery and electronics thermal management:
    - Chiller/Heat exchanger
    - HV and LV pumps
    - HV PTC heater
- Electric HVAC systems: they utilize high voltage components to replace engine driven air conditioning and heating
    - HV PTC heater
    - HV air compressor
- Electric drive unit: providing mechanical power to the wheels,
    - Inverter
    - Electric motor
    - Gearbox/transmission
- Electric air brake compressor system
- Electric steering pump system

As before, main cost driver of these components is the power capacity, with the exceptions of hydrogen storage system and of battery, whose cost is energy capacity dependent.

Unfortunately, M. Kuhn *et al*. [28] does not provide the same study applied to H2ICEVs, and, as today, no other document provides anything similar applied to this technology. In fact, in literature review phase, it has been observed that data regarding the purchase cost of these trucks are extremely rare, and the few provided data that have been found are not fully verifiable.

For this reason, it has been decided to assume, for the engine components, the same costs that are generally reported for CNG trucks (as the engine components are extremely similar), adding some specific consideration regarding the hydrogen tank.

A bottom-up approach for CNG vehicles purchase cost evaluation is provided by B. Noll *et al*. [44], although with a lower degree of detail than M. Kuhn *et al*. study.

According to this report, main components peculiar to CNG (and, for purpose of this study, H2ICE) vehicles are:

- Internal Combustion Engine: in this category, all the engine components are included: although a more detailed teardown could be more interesting, considering that CNG trucks are relatively diffused also today, estimation of cost of this component has been evaluated quite reliable
- Aftertreatment Unit: considering that emissions from hydrogen combustion are limited compared to the natural gas, some reports assume that cost of this unit could be reduced in H2ICEVs with respect to the one of CNG vehicles, but this decrease is not considered in this document, in order to avoid possible underestimation of the prices, being literature on this topic almost absent
- Transmission: data on this topic should be quite precise, as they are derived from traditional diesel powertrain, and it is not specific for CNG
- Tank: due to the different pressure levels commonly used, tanks for CNG and H2 are different; cost of this component is evaluated basing on M. Kuhn *et al*. [28] document, since the tank is the same considering both FCEVs and H2ICEVs

Once identified all the components participating in defining the powertrains costs and assumed costs for each one of them, they are summed up, obtaining the total Direct Costs. These costs represent the production cost of the powertrains.

Final purchase cost is not only defined by Direct Costs, but it is needed to also include the Indirect Costs (consisting of assembly labor costs and other manufacturing costs) and Net Income of the producer of the powertrain.

For the assumption of the three costs (Direct, Indirect and Net Income) determining the total retail cost, the direct cost is multiplied by a Retail Price

Equivalent factor RPE. M. Kuhn *et al.* [28] assumed this factor basing on observations on the truck market of different powertrains.

$$TPC = DirectCosts + IndirectCosts + NetIncome = RPE \cdot DirectCosts \qquad 3$$

Final result of this multiplication represents the total retail cost.

Unit costs of the components as provided by M. Kuhn *et al.* [28] and B. Noll *et al.* [44] are reported in Table 2.2[1]. Both the documents provide three different estimations of most of these costs, representing the uncertainties in their evaluations, but for sake of simplicity, just the average value will be reported here, while some considerations on possible changes in the component prices will be introduced in following sections, regarding some sensitivity analysis.

Component	**Cost**			**Unit**	**Reference**
	BEV	**FCEV**	**H2ICEV**		
Cab, cooling modules, chassis&driveline	19,150-23,730	19,150-23,730	19,150-23,730	€	[28]
Electrical&Wires, HVAC, air brakes	6,380-7,910	6,380-7,910	6,380-7,910	€	[28]
Battery pack system	230	545	x	€/kWh	[28], [45]
On Board Charger	65	60	x	€/kW	[28]
DC/DC converter	82	82	x	€/kW	[28]
HV distribution system	25	23	x	€/kW	[28]
Battery and Electronics Thermal Management	19	8	x	€/kW	[28]
Electric HVAC system	132	132	x	€/kW	[28]
Electric drive unit	75	75	x	€/kW	[28]
Electric air brake compressor	1360	1360	x	€/kW	[28]
Electric steering pump	273	273	x	€/kW	[28]
Fuel Cell system	x	230-1135	x	€/kW	[28], [44]
Hydrogen storage system	x	1435	1435	€/kg	[28]
Internal Combustion Engine	x	x	55	€/kW	[44]
Aftertreatment Unit	x	x	0.71	€/ton	[44]
Transmission	x	x	5320	€	[44]

Table 2.2 - *Unit cost of components*

---

[1] For costs provided in USD [$], here and in the entire document, exchange rate 1 EUR[€]=1.10 USD[$] is assumed [122]

Costs reported in Table 2.2 are referred to typical tractors, assuming net weight of the single tractor about 8 ton and powertrain size about 350 kW.

Regarding the components indicated as "Cab, cooling modules, chassis&driveline" and "Electrical&Wires, HVAC, air brakes", the costs reported are dependent on the type of cabin: the lower one is referred to a day-cab truck, the higher one to a sleeper-cab truck.

Values reported in table have been assumed consistent for every component size, and no scale factor has been assumed. This evaluation has been taken considering that on components that do not rely on a well-established manufacturing process (as batteries or FCs) unit costs are not efficiently scaled up depending on their size, due to the lack of production standards.

Unit cost of components are also provided by F. Unterlohner *et al.* [46] in its TCO evaluations, and they are coherent with the ones reported above.

Regarding the fuel cell system, some additional comments need to be included, since prices reported in literature are extremely vary, due to the substantial absence of a defined market for this type of component.

This is a particularly critical point, as fuel cell cost can represent an important cost component for the final retail price, and different assumptions have an enormous impact on the purchase cost of the truck.

Some costs provided by reviewed reports are here reported:

	[€/kW]	**Reference**
Kuhn et al. (2021)	1135	[28]
Unterlohner et al. (2021)	811	[47]
Y. Ruf *et al.* (2020)	430	[42]
Noll et al. (2021)	230	[44]
Hunter et al. (2021)	180	[48]
Burke et al. (2020)	160	[49]
Armstrong et al. (2019)	130	[50]

Table 2.3 - *Fuel cell prices from literature*

Some of the documents mentioned above also suggest the possibility of a decrease of the unit costs due to future development of the technology and the market, assuming possible costs for future years (e.g., 2030 or 2050), but these assumptions are not considered in this paragraph.

ICCT [51] provides a detailed literature review about current fuel cell price, including some of the documents mentioned in table above, arriving to conclude that an average unit cost can be assumed equal to 430 €/kW. This price has been considered acceptable for this study, but some sensitivity analysis will be added in the Results section.

2.1.2 Vehicle financing

Generally, new vehicle purchases are financed by some kind of loan; according to A. Burnham *et al.* [41], 87% of new vehicles in US are financed, by banks or by financing companies.

For this reason, it was assumed that the considered vehicles are bought through a loan by the owner company.

In this case, the purchase cost of the vehicle is not considered as a single payment on the first year, but as a recursive expense for the entire duration of the loan.

Assuming the financing of the vehicle requires to determine a proper interest rate for the loan; this can vary generally according to the credit tier of the company and the duration of the loan. Interest rate is usually expressed as Annual Percentage Rate (APR), which represents the overall annualized cost indicator of a loan: it includes interest, fees and other charges that borrowers will have to pay [52].

Interest rates can be fixed or variable: the second is not precisely defined by the contract, but it changes with the prime rate, based on the European Central Bank funds rate. Fixed interest rate results to be the most common choice among companies.

Given an APR, it is possible to calculate which is the net monthly due payment for the company, with a simplified approach comparing to a detailed consideration of all the fees and one-time costs.

The monthly due interests are calculated with:

$$interest_{mon} = RB \cdot \left(\frac{APR}{12}\right) \tag{4}$$

Where the Remaining Balance RB represents the amount that is still due to the loan creditor calculated based on the initial borrowed amount.

The interests and the balances are calculated in order to maintain the total monthly payments constant during the entire period of the loan.

The monthly payments are then summed up on yearly bases, and will be considered as a repeated cost on the TCO analysis, with the proper considerations due to the discounted cash flow analysis (see Discount rate paragraph (2.8)).

Not every TCO analysis consider the financing of the vehicle and the consequent loan costs, so the literature review results to be quite limited; nevertheless, some findings are here reported:

- A. Burnham *et al* [41] reports a statistical analysis on the loan conditions generally applied for vehicles financing in the US: for commercial vehicles, APR can vary from 2% up to 13% for lowest credit tiers (data from 2020). Although this important differences among data, depending on the type of debtor, the vehicle, the state and other factors, average APR is defined as about 6%, with an average duration of the loan of 63 months.
- ICCT in its studies [39], [40] assumes 2% of interest rate with a loan duration of 5 years, but no external references are provided.
- A. Alonso-Villar *et al.* [53] assumes an interest rate of 6.2% for a 5-years loan, basing on statistics provided by tradingeconomics.com [54] (data referred to 2021)

According to central bank of Finland (Suomen Pankki), average interest rates for small and medium corporate loans (respectively below 250,000 € and 1,000,000 €) in Finland are respectively equal to 5.12% and 4.76% in 2022 [55]. It is important to notice that these interests have sharply increased in that year, while in the previous 5 years interest rates for small loans had never reached 4% and medium ones had always been below 3%. The majority (57%) of these corporate loans have generally a maturity below 5 years.

2.1.3 Vehicle depreciation

Depreciation is assumed to be the loss of value of a vehicle during the years of utilization. Resale price at the end of the considered lifetime for the first owner represents a net income for the owner, and it will be surely lower than the purchase cost at the beginning of the study: determining a consistent depreciation model is fundamental to evaluate which could be the selling price. Each year vehicle is assumed to lose part of its value, and this loss at year m can be represented by equation [41]

$$Net\ vehicle\ cost = \sum_{n=1}^{m} vehicle_{cost_n} = \sum_{n=1}^{m} (RV_{n-1} - RV_n) \quad 5$$

If we are just interested in discounting actual cash flows, net vehicle ownership cost equation can be simplified in:

$$Net\ vehicle\ cost = C - RV_m \quad 6$$

Where C is the purchase cost and RV_m is the residual value at year m, when the vehicle is resold.

Depreciation is one of the largest factors affecting the TCO, especially if the ownership period is assumed to be short (order of few years) [56]. In case of leasing of the vehicle (more usual for LDVs), depreciation rate is already considered inside the lease price, so it has not to be separately added. Nevertheless, effect of revenues from the reselling of the vehicle is quite mitigated by the high interest rates that are usually assumed for HDV market: an income after 8 or 12 years from the beginning of the analysis is drastically less impacting than the same expense at the first years. In any case, an approximation as precise as possible of the reselling price helps increasing the reliability level of the analysis.

Evaluating price of a second-hand vehicle is not trivial, as many factors incur (model, model year, mileage, location, possible damages, travel history…) and to define a model to include in some ways all these variables for a generic vehicle is even more difficult.

Considering "innovative technologies" as the ones discussed in this study, definition of these variables is particularly problematic, as studies on their deterioration during time are still limited. Studies regarding LDV do not totally agree on depreciation rate of BEV with respect to standard engines: in 2016, Zhou *et al.* [57] analyzed residual value across different powertrains and they found that plug-in electric vehicles depreciations were comparable to HEVs and ICEVs in the early years but higher on older vehicles; in another study, Z. Guo and Y. Zhou [58] found that BEV Tesla Model S maintains value better than any other vehicle type evaluated.

Data regarding HDVs' depreciation are quite limited: A. Burnham *et al* [41] analyzed data from Commercial Truck Trader and TruckPaper.com [59] to define a model of resale value basing on age and mileage of the vehicles.

Different truck segments were taken into account, while it's important to remark that almost all the vehicles considered are diesel ICEVs (with a few CNG vehicles). Collected data come from the listing price of each vehicle, so assumed numbers do not reflect the exact transaction price, but in any case, they have been considered quite representative for the second-hand market.

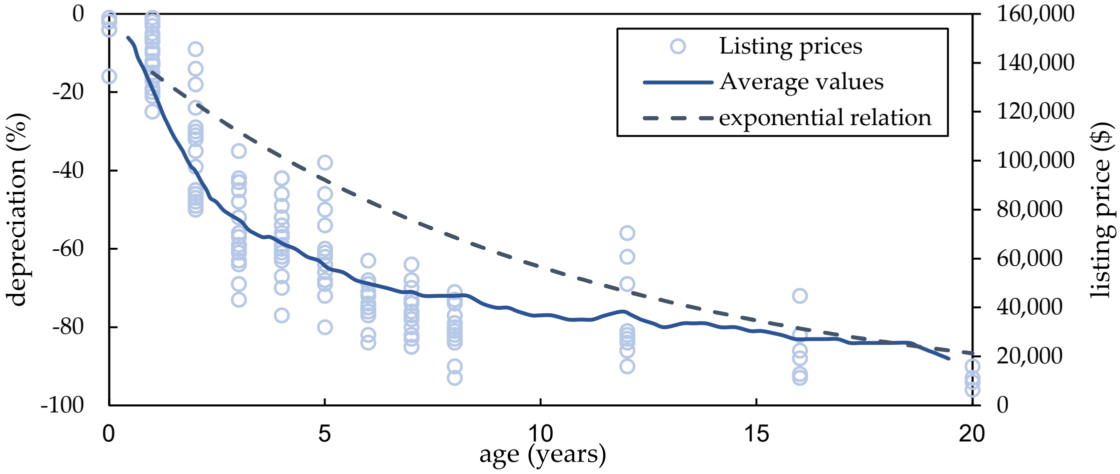

Figure 2.3 - *Residual value per age* [41]

A regression model was defined basing on the observed prices, and an exponential function dependent on cumulative mileage and age was elaborated for each truck segment.
Residual value was evaluated as [41]:

$$RV(a,m) = C \cdot \exp(A \cdot a + M \cdot m) \qquad 7$$

Where

- a = age, in years
- m = cumulative mileage, in thousands of miles
- C = retail price estimated at year 0 with no travelled miles, in €
- $exp(A)$ =percentage price retention from the previous year
- $exp(M)$ = percentage price retention from the previous 1000 miles

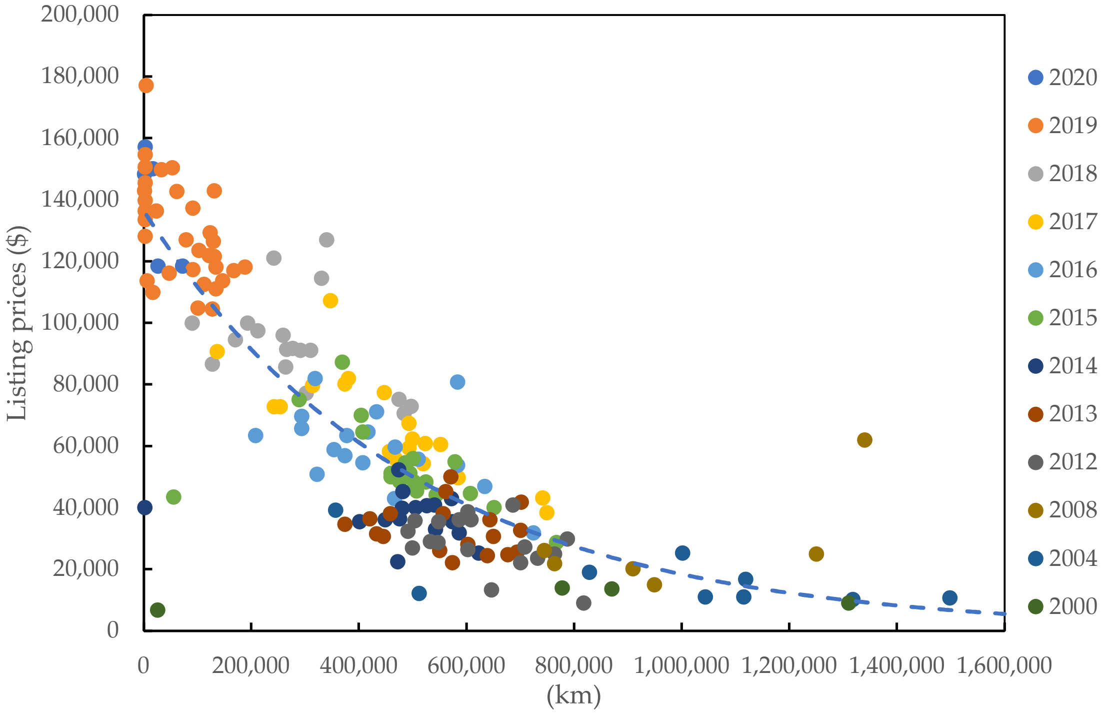

Figure 2.4 - *Residual value of class 8 sleeper* [41]

In this way, depreciation of the vehicles is evaluated at end of life as

$$Dep = C \cdot (1 - \exp(A \cdot a + M \cdot s)) \qquad 8$$

With s total travelled miles during lifetime.
A and M parameters are evaluated on basis of the truck segment, and results provided by the report are here mentioned:

	Sleeper-cab truck	Day-cab truck
exp(A)	0.9071	0.9113
exp(M)	0.9990	0.9991

Table 2.4 - *Depreciation coefficients*

It is worthy to mention that these coefficients were evaluated on basis of the US second-hand market, but for the purpose of this analysis, it has been assumed that differences with the Finnish context are not so impacting on this field.
Other studies, as F. Kleiner and H. E. Friedrich [60], assumed model describing depreciation rate based only on travelled mileage, ignoring the age of the vehicle. On the other hand, it makes hypothesis of a scaling factor addressed to

alternative drivetrains, representing influence of infrastructure density (lack of recharging points and refueling stations decreases the value of a vehicle of a given technology) and technology maturity (real and perceived reliability of a technology influences the resale value of a vehicle).

This factor has a strong influence on the resale value of new technologies as FCEVs and H2ICEVs, making their values to drop down faster than standard ICEV ones.

In this study, effect of this factor is not included, as it has been considered that infrastructure density, that could represent a not negligible issue at present day will be strongly improved in next years, also considering many incentives and EU directives in this field. Assuming that this study could be assumed useful to define TCO for trucks starting in 2023, the reselling on second-hand market is assumed to be at least after 8 years of use, and by that time, hydrogen and electric infrastructure should be developed enough for truck fleets that this difference with traditional ICEVs could be easily ignored.

As previously mentioned, the provided equation has been developed on basis of the diesel second-hand trucks market. Unfortunately, it seems impossible, today, to validate this model on a real market that involves HDV based on alternative powertrains, since they are almost absent on current fleets.

To have a general idea on how this market could develop, the only option is to observe market of used passenger cars: advantage of this market is that BEV have also today a non-negligible share of the market, and some evaluation can be done also considering this technology (unfortunately, FCEVs and H2ICEVs are almost unknown also for these segments of vehicles, so second-hand market is not developed yet).

With a similar approach to the one previously described A. Burnham *et al.* [41] defined a function describing the loss of values of vehicles in function of their age, differentiating according to vehicle segments and powertrains.

Important result related to the topic of this study is that new models of BEVs maintain higher residual values with respect to the corresponding ICEVs. This suggests that also this kind of alternative powertrain has finally reached a development level able to make these vehicles competitive with traditional technologies.

This is surely due to technology improvements, that have increased capacity of batteries, efficiency, reliability, recharging time… All these factors have competed in increasing durability of vehicles, maintaining high its value, and increasing confidence of buyers in these new powertrains.

After these observations, it seems reasonable to expect a similar trend also for HDVs: after a possible phase of development of the technology and its market, it

is probable that depreciation rate of electric HDVs will be at least similar to the one of ICEVs, and a more optimistic approach could also suggest that their value preservation could even be longer than traditional powertrains.
Same result is presented by ElementEnergy [61]: considering passenger cars, BEVs present a slower depreciation during the years with respect to ICEVs, and this phenomenon is even more remarked for large cars. This factor is more influent on longer period, considering for example second and third owner, but it is beyond the aim of this analysis.

After these considerations, it has been decided that the model provided by A. Burnham *et al.* [41], even considering that is based on American diesel-fueled trucks market, should provide a trustful approximation of the residual values of the vehicles object of this study.

2.2 Fuel cost and infrastructure

Fuel cost represents one of the major cost elements in the TCO of most of the vehicles, considering both passenger cars and heavy-duty vehicles. For the seconds, which usually see really high mileages on their lifetime, fuel can become the largest of all the cost components on the total life of the vehicle.
The two drivers of the fuel cost evaluation are the fuel economy of the vehicle and the fuel price.

2.2.1 Fuel economy evaluation

Fuel economy analyses the cost components of the TCO connected to the energy needed to make the vehicle properly work for a certain distance, considering the specific source of energy, electricity or hydrogen.
It is strongly related to the powertrain type, so it is particularly important to define a fuel economy evaluation in this study, considering that the comparison is dealing with different powertrain technologies. Beyond that, fuel economy depends also on the size class of the vehicle, payload, the type of travel and road, the technical quality of the vehicle, driving-mode…

Basing on these many factors, precise evaluation of the fuel economy of a vehicle can be quite problematic, as it requires to assume several details on the vocation of the truck.
Regarding traditional powertrain technologies, as diesel ICEs, observations and literature could be detailed enough to provide some definitive figures with a high degree of precision, taking into account many of the main elements affecting it. Dealing with alternative powertrains, these data are still very scarce, so the evaluation of the fuel economy has to be partially based on manufacturers declarations and laboratory observations, which are often slightly different from real cases.
Furthermore, literature regarding LDVs is generally more exhaustive: BEV technology is already quite diffused among passenger cars, and some examples of FCEVs are also present (e.g., Toyota Mirai); for HDVs these technologies are completely new, so literature based on real studies is almost absent.

Fuel consumption is traditionally presented in diesel-gallon equivalent per km [dge/km] or in kWh per km [kWh/km], while for hydrogen-based powertrains sometimes the mass consume per km is reported [kg/km or $kg/100km$]: considering that this report is dealing with electricity and hydrogen energy, it has been chosen to use kWh/km for every powertrain. In some cases, also observations on efficiency will be done, defined as the inverse of fuel consumption [km/kWh].
Regarding passenger cars, literature generally agrees on the observation that electric powertrains (especially BEVs) have drastically lower consumptions than ICEVs (assuming diesel, gasoline, and CNG data, that are currently the most common on the market).
This is mainly due to the higher efficiency of electric powertrains at partial loads, that drastically reduces consumes on routes with frequent start and stops.
A. Burnham *et al.* [41] collected a large amount of data (more than a thousand of vehicles) regarding fuel economy of different powertrains, and main results for SUV segment are here reported in Figure 2.5:

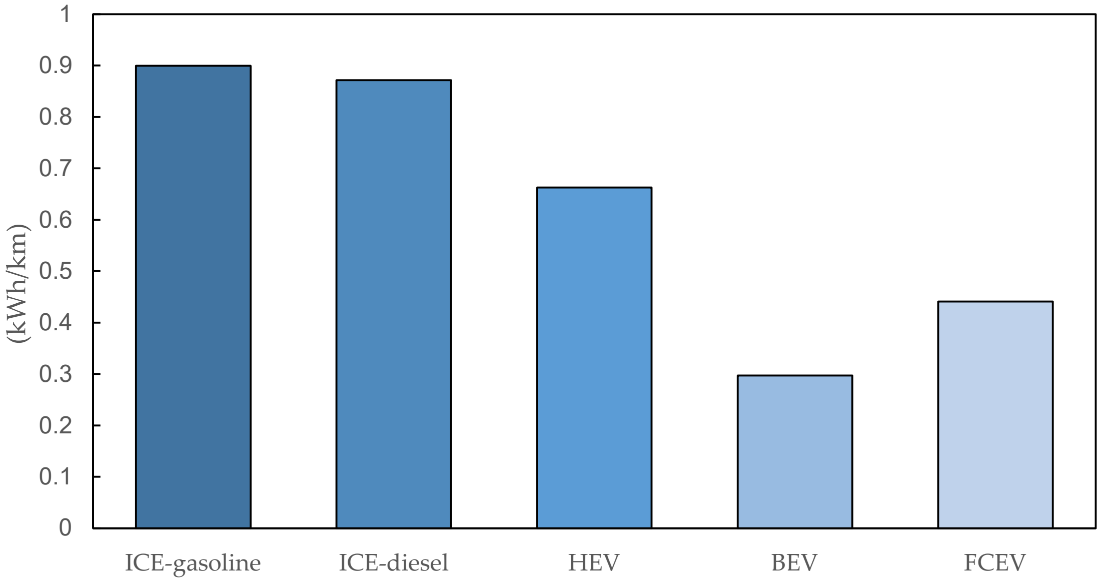

Figure 2.5 - *Fuel economy for SUVs [40]*

Reported data are aggregated, so they represent an average value of different types of vehicles (belonging to the SUV category) and driving modes.

As observable, fuel economy of BEV is almost one third of the traditional powertrains, while FCEVs have higher consumptions than BEVs, but still has about half of the ICEVs consumes.

Main driving parameters in the definition of the fuel economy are the weight of the vehicle (heavier vehicles generally have higher consumes) and the most frequent types of routes (urban routes are generally the most consuming, followed by highways and rural routes, as observable in Figure 2.6); in particular, on urban routes and in general for journeys including many stops, electric vehicles result to have efficiencies drastically higher than internal combustion powertrains.

Regarding HDVs, first consideration is that data, being scarcer than for passenger cars, have higher degree of uncertainty.

Main observation done by A. Burnham *et al.* [41] is that difference in the consumptions between powertrains is less remarked for HDVs than it was for LDVs. This is mainly because trucks travel for a larger share of their time at relatively high speeds, on extra-urban roads or highways, where the efficiencies of electric and ICE powertrains are not so different as they are for low load operation of the engine. Furthermore, in many cases the battery represents an additional weight for the vehicle, contributing to increase the energy consumptions calculated on a payload basis (some more detailed considerations will follow in section Payload reduction (2.7.1)).

Considering HDVs, two different parameters have to be included in the weight evaluation: the weight class of the vehicle and the payload conditions. Indeed, while for passenger cars, the actual weight of the vehicle is usually similar to the nominal one, since most of the weight is due to the vehicle itself, a tractor trailer operating at maximum capacity can reach a weight that is more than twice the one of the vehicle with an empty trailer [41].

American Department Of Transport published a report [62], referred to diesel trucks, analyzing different driving cycles with three payloads conditions of a 32 t truck (21 t as maximum payload), and results are reported in Figure 2.6[1]:

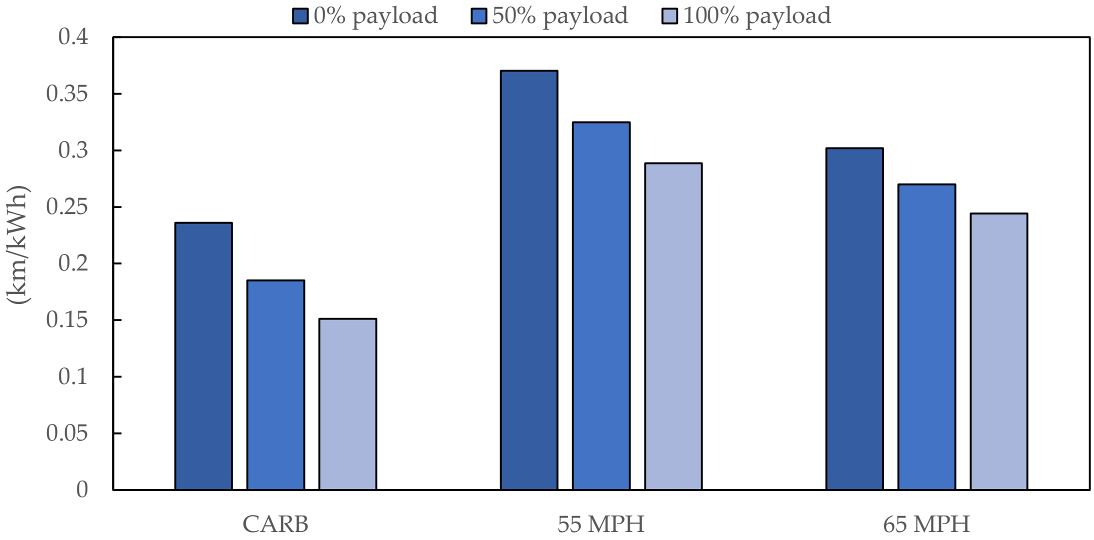

Figure 2.6 - *Fuel efficiency for long-haul diesel truck [61]*

It's observable that fuel efficiency is largely impacted by payload: on urban route fuel efficiency of the empty vehicle (about 15 t) is about 50% higher than the one at full payload, when the weight of the vehicle is about the double. At constant velocity this difference is less remarked, as visible on the two cases with higher average speeds: due to the reduced number of start&stops, fuel efficiency difference between 0% payload and 100% payload is relatively low, although still absolutely not negligible.

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[1] CARB: duty cycle modeled by California Air Resources Board to simulate an urban stop&go route

Use of the vehicle has also a large impact: for urban or rural transport, with frequent brakes and low speeds, electric engine results remarkably more efficient, due to both the engine itself and the regenerative braking system, while for highway routes, where speeds are high and constant for long periods, efficiencies are higher for all powertrains, with decreased differences between the technologies.

In addition to "standard travel" fuel consumption, HDV are characterized by two more consumption fractions: idling and power-take-off. Idling consists in those moments when the vehicle engine is running, but the truck isn't moving: examples are stops in traffic, loading time, drive-through lines, use of heating or air conditioning… Power-take-off (PTO) is referred to the time needed to "warm-up" the engine before the vehicle starts moving.

Regarding diesel trucks, NREL has evaluated impact of idling and PTO can represent each up to 10% of the total energy use of a utility truck [63]; for sleeper-cab trucks, this share can be even higher, as they have hoteling periods: average sleeper truck can have 1800 h of hoteling each year, with consumes of 3.5 liter/hour [41] (in cold weather regions, as Finland, even higher consumes are possible) of diesel for climate control of the cabin and other needs.

Both idling and PTO should become less impacting on the overall consumption in the case of electric powertrain: the extremely high efficiency of BEV at partial load could make idling really low consuming, while the fast switch on of electric powertrain should make PTO extremely fast.

As previously mentioned, real cases observations are still very limited for BETs and FCETs, but in literature some assumptions, based on laboratory tests and manufacturers declarations, are provided:

Author	Fuel economy [kWh/km]		Type of vehicle	Reference
	BEV	FCEV		
CARB (2021)	1.15	1.89	Day-cab truck	[64]
CARB (2021)	1.37	1.88	Sleeper-cab truck	[64]
Rout et al. (2022)	1	3.43	Long-haul truck	[38]
ICCT (2021)	1.38	2.76	42t tractor, combined payload[1]	[39], [40]
Mareev et al (2017)	1.59	x	40t long-haul truck	[65]
NREL (2021)	1.68	2.11	37t long-haul truck	[48]
T&E (2020)	1.44	2.53	40t tractor, used for regional delivery	[66]
T&E (2020)	1.15	1.95	40t tractor, used for long-haul journeys	[66]
Y. Ruf *et al.* [42]	1	x	26t rigid	[42]
Y. Ruf *et al.* [42]	1.4	x	47t tractor	[42]
Y. Ruf *et al.* [42]	x	1.66	34t rigid or tractor	[42]
Y. Ruf *et al.* [42]	x	3	64t rigid or tractor	[42]

Table 2.5 - *Fuel economies in literature*

As observable from reported data, fuel economy is not exactly defined, due to two main reasons:

- Lack of data from real cases, due to the low diffusivity of these technologies
- Strong bond between the average consumes and the conditions of use of the vehicle (roads, payload, driving-mode…), that would require much effort and time for a comprehensive literature

Y. Ruf *et al*. [42] also provides some hydrogen consumptions for FCETs evaluated on specific case studies located in different places around Europe: considering different applications with their own weight classes, duty cycle and external conditions, their consumptions were reported to be between 2 and 2.8 kWh/km.
Many of the cited reports also provide some assumptions on possible fuel economies based on future development of the technologies: these data are generally not considered in the major case studies of this thesis, but some evaluations on future scenarios will be provided in Results section.
In B. Noll *et al*. [44] the authors used data collected from previous literature to define an exponential function of energy consumption for FCETs and BETs basing on their powertrain and weight.

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[1] Combined payload is defined as 70% reference payload (19.3t) and 30% low payload (2.6t)

Equation is here reported:

$$EC\left[\frac{kWh}{km}\right] = a \cdot \ln(w) + b \qquad 9$$

Weight w is expressed in kg, while a and b parameters change depending on the considered powertrain technology (in this section, just BEVs and FCEVs will be considered):

Vehicle	**a**	**b**
BET	0.3814	-2.6735
FCET[1]	0.6570	-4.1059

Table 2.6 - *Coefficients for fuel economy calculation* [44]

The difference on the energy consumption depending on the type of route (and duty cycle), previously remarked referring to ICETs, is largely less relevant for BETs and FCETs. Due to the electric powertrain, in normal environmental conditions (effects of low temperature will be analyzed in next lines), start&stops and low load operation are not so impacting on the fuel economy, as they were for ICEV.

H. Jung *et al.* [67] reports several fuel economy evaluations applied to different models of electric passenger cars, differentiating between urban and highways use: results are spurious, as in some case highway case has better fuel economy, for some other test opposite results are achieved; in any case, the differences between the two duty cycles are reported to be very low, suggesting that fuel economies are quite constant for electric vehicles in any type of use.

Moreover, it can be assumed that "information" about the type of route and use of the vehicle is already included in the datum regarding the weight of the vehicle: heavy trucks are mainly used on long-haul routes, while lighter ones are more typical in urban traffic. So, considering that this equation is based on statistical observations, it can be assumed that the type of route and vehicle weight are intrinsically connected.

In conclusion, this model obtained by the above equation has been chosen as a starting point for the definition of fuel economy of the BETs and FCETs that will be considered in Case study section, with some additional considerations

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[1] Equation regarding FCET was defined in the original document to provide results in kg/km, but coefficients were changed to have a final result in kWh/km (assuming NCV_{H2}=33.3 kWh/kg)

regarding the effects that Finnish low temperatures can have on their consume, that will be described in following lines.

BEV and FCEV fuel economy dependency on temperature

Differently from ICEVs, electric vehicles suffer of a sharp decrease of their efficiency at low ambient temperatures, and this phenomenon has a strong impact on the driving range of the vehicle.
This is mainly due to the effect of different factors:

- Energy demand for cabin heating: since almost null waste heat is produced by the electric powertrain, the needed energy for the HVAC plant must be provided by the battery or the fuel cell; for this reason, an external heater is installed, to ensure the proper comfort to passengers also under cold ambient conditions. Alternative possibilities as heat pumps have been evaluated in recent studies, but they do not represent the "state of the art" yet (and they still report some issues at extremely low temperatures), so they will not be considered in this study
- For BEVs, limited capability to recuperate energy from braking at low temperature: battery management system (BMS) limits charging and discharging currents at low temperature to avoid Li plating of the battery, which would lead to permanent reduction of cell performances, increasing its internal impedance; effect of this control on currents is the limitation of restored power through regenerative braking
- For FCEV, main criticality concerning energy consumption is connected to cold starts, because electrical heating is needed for the recondition of the FC system after a long stop time

This dependency of fuel economy on external temperature can have dramatic effects on the driving range of a vehicle: J. Taggart [68], basing on observations of several Tesla Model S, showed that their driving range can decrease up to -45% at -10°C compared to standard ambient temperature of 20°C, while J.R.M. Delos Reyes *et al*. [69] found a decrease up to -70% of the driving range of a Nissan Leaf at -26°C; both of these document consider the combination of cabin heating and reduced regenerative braking.
Streinstraeter *et al*. [70] studies separately the two phenomena, basing on Tesla Model 3 and BMW i3. They show that cabin heating alone can represent up to 30% of the used energy for these passenger cars at -10°C, with the most impacting effects occurring during short trips, particularly critical due to the heat transients, when the car is switched up. Additional result of the study is that the heating

energy does not only depend on the outside temperature, but also on other weather conditions: sunny days can have lower heating needs due to solar radiation through the front glass, also if temperature is particularly low.

Concerning regenerative braking, the report shows that it does not directly depends on the outside temperature, but on the battery temperature: on the two considered cars, when the battery is below -5°C, regeneration is not present, while above 10°C it reaches the maximum level and it maintains constant. Recuperated energy can represent up to 40% of the total energy spent on a trip, while it can be almost null on short trips, when the traveling time is too short to enable the battery to heat up.

Unfortunately, M. Steinstraeter *et al.* [70], although being detailed, is based on passenger cars, so it is not completely suitable for the definition of a model for trucks.

H. Lohse-Busch *et al.* [71] proposes a similar study referred to FCEVs, analyzing performances of Toyota Mirai at -7°C on different duty cycles; results report that, beyond energy needs connected to HVAC, that are similar to the ones observed in Tesla Model S, the peaks in fuel consumptions are mainly caused by the starts of the vehicle: for this reasons, their effect is negligible if the vehicle operates without frequent starts&stops, while it can have impacts up to -18% of efficiency on short trips.

For both cases, BETs and FCETs, considering that, even if in urban conditions, a HDV should not be interested in very short trips, but it would probably be involved in routes where its powertrain has enough time for properly heating up, this second effect connected to regenerative braking and FC heat up has not been considered. This can be particularly justified considering longer routes (extra-urban or highways), where the truck is not supposed to have frequent stops which could cause the cooling of the FC system; moreover, also in "warm" conditions, the impact of regenerative braking can be considered really low as the use of brakes on this type of routes is relatively rare.

On the other hand, cabin heating has been considered non-negligible, both on urban and extra-urban routes, and its impact on fuel economy has been evaluated.

Despite a deep literature review, no detailed analysis regarding the energy need for truck cabin heating has been found, so it has been necessary to define an ad hoc simplified model in this study.

Firstly, an approximated heat transfer coefficient was defined for the cabin of the truck; being based on convection with air, the heat transfer through the walls of the cabin is dependent on the air speed and, consequently, on the vehicle speed.

For sake of completeness, it must be pointed out that the energy need due to the cabin heating is not only due to the heat transfer through the cabin walls, but also to the ventilation of the internal environment. For simplicity, the two parameters have been considered aggregated, and they have been indicated as energy connected to heat losses through the walls.

The heat transfer coefficient multiplied by the cabin area for a standard sleeper-cab truck in idling conditions is evaluated in literature in the range of 51~70 W/K [72], [73]: for this simplified model, 65 W/K was assumed; considering that this parameter is directly connected to the surface of the cabin, and that day-cabins are generally smaller, 50 W/K was assumed as reference value for day-cab trucks in idling conditions.

To define the change in the heat transfer coefficient due to the relative speed between vehicle and air, a rough correlation connecting heat transfer coefficient and vehicle velocity has been defined. This function is based on observations on heat transfer coefficients of passenger cars provided by K. Balanna and P. S. Kishore [74]: the values provided in this report, referred to passenger cars, have been just scaled up, to reach the above-mentioned reference values of 50 and 65 W/K at low vehicle speeds, maintaining the same pattern reported by the empirical observations on cars. The 20 km/h and 80 km/h values, not provided by the report, were found according to an interpolation basing on a relation of 0.7 order, as suggested by J. Nitz and W. H. Hucho [75].

Results are here represented:

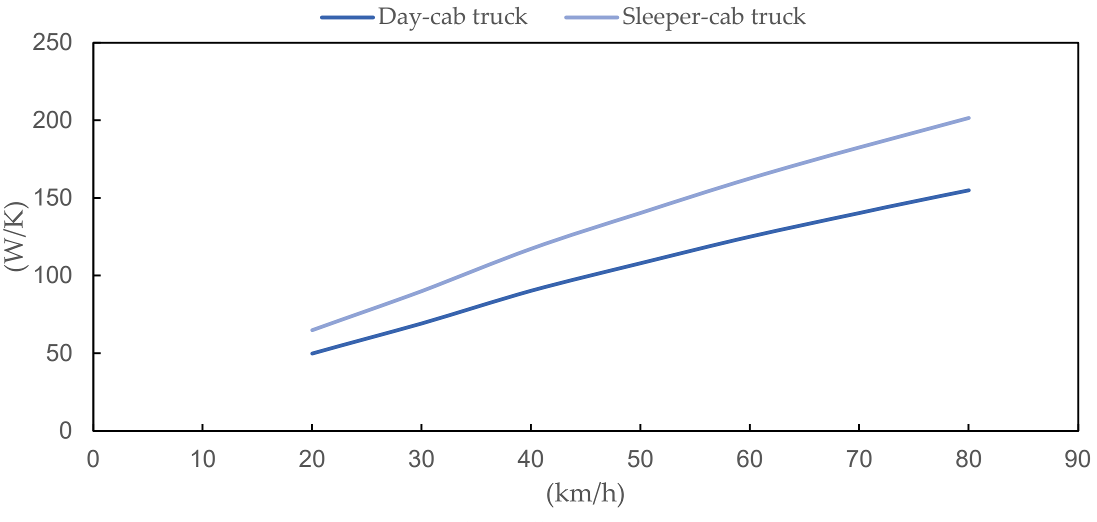

Figure 2.7 - *Heat transfer coefficients of truck cabins and velocity*

The final energy need for cabin heating is then evaluated approximating outside temperature of the considered routes on a monthly basis: this simplified model, despite being quite rough on the single journey, should be acceptable for an evaluation of average fuel economy on a yearly basis.

Fuel economy of H2ICEVs is by far the one for which literature is more incomplete.
At the present time, there are no H2ICEVs diffused on the market, neither considering passenger cars nor HDV, so the only available data regarding their efficiencies come from manufacturers' declarations and some laboratory tests, but the latter are very limited.
First consideration is that this technology, being a combustion engine, has important similarities with traditional ICEs as diesel or CNG ones. Main characteristic is that, differently from electric powertrains, for which the efficiency is almost constant for every power load, internal combustion engines have relatively low efficiencies at low loads, but it increases with the output power.
Plot regarding this different efficiency trends is provided by McKinsey [76]:

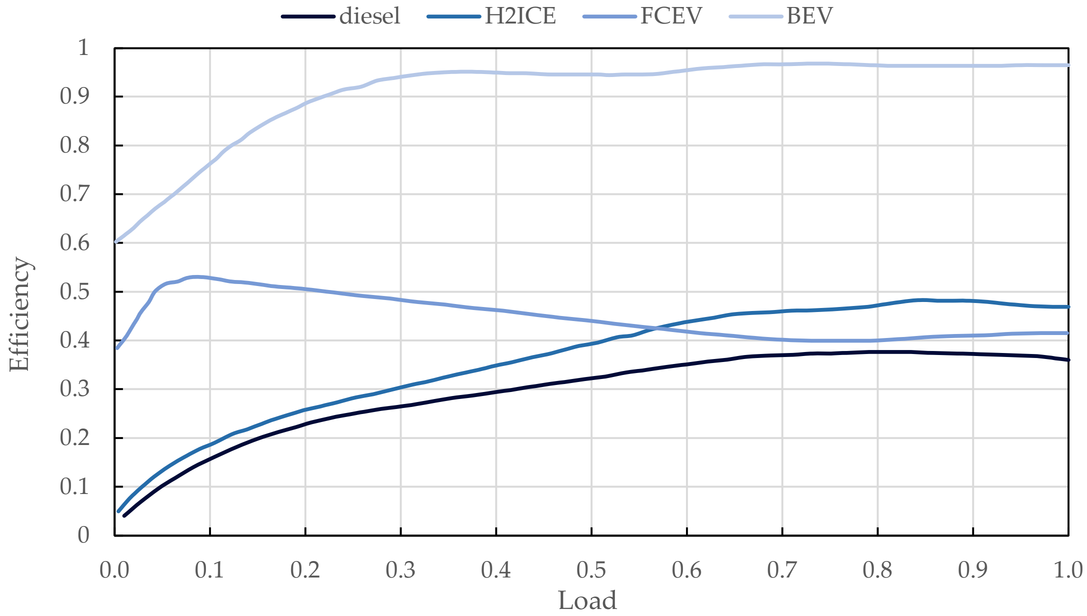

Figure 2.8 - *Efficiency and load* [76]

It is observable in the figure that BEV efficiency is about constant above 20-30% power load, while FCEV even observe a decrease of the efficiency when load becomes closer to 100%. Differently, H2ICEVs, as well as diesel vehicles, see their efficiency increasing with the load, and having its maximum at about full power.

Although the qualitative trend of the efficiency-load relationship has been considered reasonable, it is important to point out that, differently from McKinsey, H2ICEVs efficiency has been assumed as slightly lower (in energy terms) compared to the diesel one, as it has been decided to follow CNG model, as described in following lines, in a more conservative approach that it has been evaluated to be more reasonable in the next future, with the "first generation" H2ICEs.

This efficiency trend makes H2ICEVs generally more suitable to long-haul routes, where trucks travel for long time at high and constant speeds, while for urban applications electric drivetrain should be preferred.

Considering the extremely limited data regarding efficiency of H2ICEVs, as in previous sections, the similarity with CNG has been exploited: both the engine and the combustion process are reasonably similar in the two technologies, so some data can be taken directly from CNG trucks observations, that are, although not numerous, at least possible, due to the presence on the market of this powertrain.

According to W. Yaïci and H. Ribberink [77], average consumptions of CNG is generally about 10-15% higher than the ones of diesel trucks of the same category; the study suggests two main reasons for this reduced efficiency:

- Additional weight due to the storage tank and its auxiliary devices
- Relative nascence of the CNG-specific ICE technology

These two causes for the lower efficiency of CNG compared to diesel are obviously valid for H2ICEVs too.

This difference with diesel consumption is also stated by B. Noll *et al.* [44], that proposes, as before, the coefficients that should be used in Equation 9 to calculate fuel consumption given the vehicle weight:

Vehicle	**a**	**b**
CNG-ICE[1]	0.9091	-6.0915

Table 2.7 - *CNG coefficients* [44]

This equation is based on many observations and studies provided by previous literature, and results are quite coherent with the ones provided by W. Yaïci and H. Ribberink [77].

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[1] As before, coefficients were provided in the document in order to have a result expressed in kg/km, but they have been modified to give result in kWh/km (assuming NCV_{CNG}=13.1 kWh/kg)

Limit of this equation is that it does not consider the type of duty-cycle that the truck is operating in. As previously described, fuel economy of the vehicles is highly dependent on the type of route and the load of the engine: if this difference can be neglected for electric powertrains, that have an almost constant efficiency, this effect must be considered regarding internal combustion engines (fueled by CNG or H2). A partial adjustment to this assumption is that weight classes of the different vehicles are generally divided in different duty-cycles: small trucks are used mainly on urban routes, while on highways larger ones are preferred; this means that in the parameter of weight there could be already included an implicit information about the type of route.

Although this consideration, it has been judged necessary to analyze deeper in detail the different duty-cycles of the vehicles, conscious that they can have important influence on the fuel economy of ICE vehicles.

To include this parameter, measurements done by VTT and reported in P. Söderena *et al.* [78] were also considered. VTT used a chassis-dynamometer testing to evaluate, among other parameters (CO2 emissions, N2O emissions etc…), efficiency of powertrains in a 30-t and a 44-t CNG-fueled trucks.

Results are:

Vehicle	**Fuel economy [kWh/km]**
30t truck	5.14
44t truck	6.17

Table 2.8 - *CNG fuel economy* [78]

Tests have been done following a modelled route that includes both urban and extra-urban travel, with frequent start&stops; for sake of simplicity, considering that more than half of the time of the test was done in urban mode, the consumptions reported above are assumed as referred to a route that could be described as entirely urban.

For a complete model defining the fuel consumption of CNG and H2ICE trucks, the equation provided by B. Noll *et al*. [44] has been modified to fit with the data reported by VTT [78].

To simulate urban driving mode, an additional coefficient has been included to Equation 9, resulting in:

$$EC\left[\frac{kWh}{km}\right] = 1.6 \cdot (a \cdot \ln(w) + b) \qquad 10$$

Graphical relationship between energy consumption and vehicle weight is here represented:

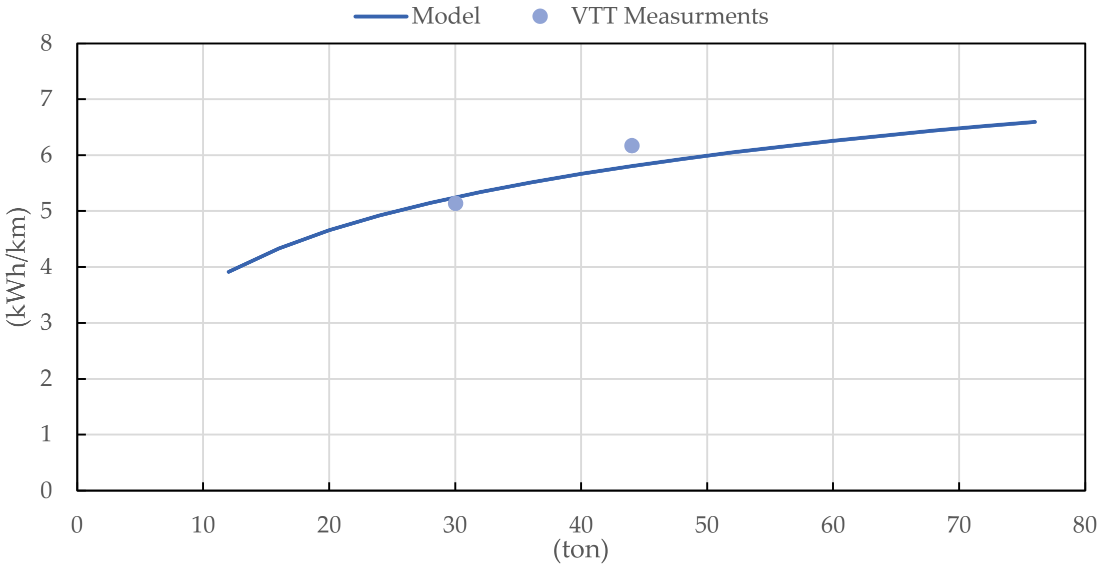

Figure 2.9 – *CNG urban consumption model*

For extra-urban and highway consumption, the "standard" Equation 9 without correction coefficient has been used, as suggested by B. Noll *et al*. [44].

Energy consumption for H2ICEVs is assumed exactly the same as CNG study, considering the two different equations (10 and 9) respectively for urban and extra-urban (rural or highway) routes.

Differently from BETs and FCETs cases, no specific considerations have to be done regarding the effects of low temperatures on fuel consumption. Indeed, in H2ICEVs, and in general any ICEVs, heating necessary for cabin comfort is provided directly by the engine, recuperating waste heat of the combustion, with very low effect on the cycle efficiency. Some observations even report that, at low outside temperatures, ICEVs could slightly increase their performances due to the minor effect of friction on the engine components, that is reduced in cold environment; in any case, this effect is really low, and in this thesis it has been considered negligible.

In a more exact model, it would have been reasonable also to assume a rate of decrease of the powertrain efficiency during the years of the vehicle. For sake of simplicity, considering that this parameter is just one of the several that the model includes, fuel economy is assumed as an average one on the entire lifespan of the trucks.

Energy storage dimensioning

Basing on the fuel economy evaluation, the dimensioning of battery and hydrogen tank is evaluated.

In every case, a worst case scenario for the fuel economy has been assumed: considering that fuel economy of FCEVs and BEVs is dependent on the outside temperature, this scenario is assumed as the entire travel occurs at -30°C; regarding the H2ICEVs cases, that is not dependent on outside temperature, an added +10% has been added to the standard fuel economy, to simulate an arbitrary worsening of the efficiency during the travel.

Then, the battery has been dimensioned considering a usable capacity equal to 90% of the nominal one, according to literature concerning last models [79]. The required driving range is assumed to be the needed daily mileage of each case study, plus 100 km as a "safety" residual charge.

Considering the hydrogen storages of FCETs and H2ICETs, the tanks have been dimensioned assuming 100% of usable capacity. The needed driving range is assumed as the daily mileage plus 200 km; this assumption, more conservative than the BET case, is due to the fact that hydrogen refueling stations will probably be less diffused than recharging spots, at least for some years, so a higher "safety factor" should be suggested.

Different model is assumed for in the case of long-haul applications: an intraday recharge/refueling has been assumed, so, in those cases, the needed driving ranges are consequently reduced, but the "safety mileages" are maintained.

2.2.2 Fuel price definition

Fuel price is one of the most impacting parameters in the TCO evaluation for trucks: in traditional powertrains (diesel or gasoline fueled), fuel costs are by far the largest component of the TCO; with alternative powertrains, due to their higher efficiency, the share of the fuel costs is slightly decreased, but in any case, it is still a critical one.

Unfortunately, while prices of traditional fuels usually see variations in a relatively small range, price of electricity and hydrogen can vary profoundly.

Indeed, the decarbonization transition imposes different policies that can impact on H2 and electricity prices, as incentives on renewable powerplants, tax cuts, public investments in hydrogen network… For this reason, it is particularly difficult to define a unique price for next years.

Regarding electricity, Finland can be considered quite ahead in the decarbonization transition: in 2022, less than 11% of the produced electricity derived from fossil sources. Even if electricity demand is expected to increase in next years, due to the electrification of many sectors, as transport, and new investments will be needed to complete the energy transition, the price of electricity is expected to maintain quite constant, or even to decrease thanks to the increasing production from wind plants [80].

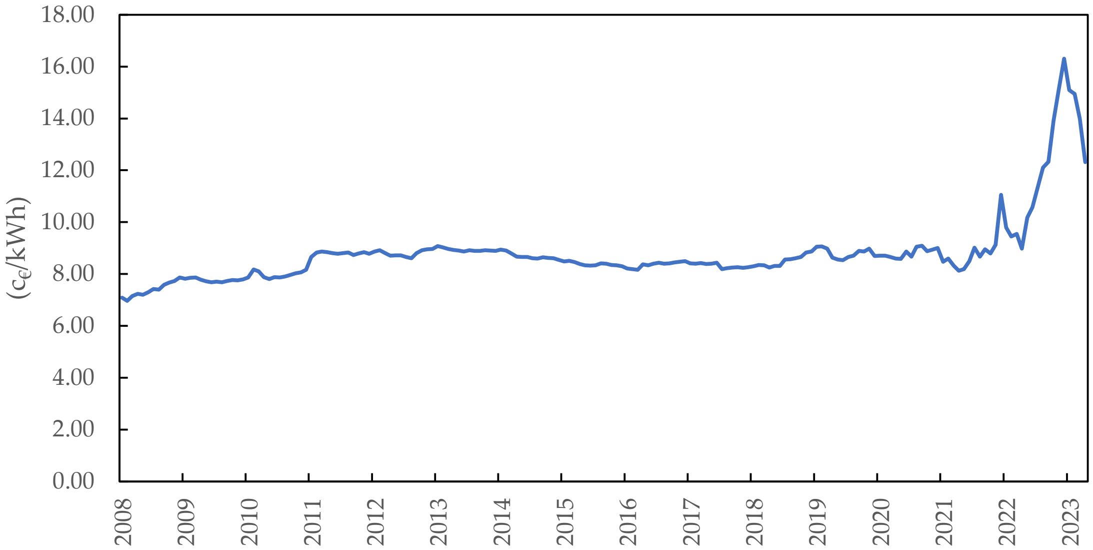

Figure 2.10 - *Electricity price for non-households in Finland*

At the same time, it must be mentioned that price of electricity in fast-charging facilities, used for intraday recharges, is significantly different from the average electricity price: according to K-Lataus (one of the major Finnish charging infrastructure operator), today price for high power charging is about 0.33 €/kWh [81].

Concerning hydrogen, at present day its production is still strongly based on fossil fuels and in particular on steam reforming: from purely economic point of view, this is the most convenient production method, as it allows to reach, today, final cost of hydrogen well below 2 €/kg (in Middle East, steam reforming without CCUS is reported to reach prices below 1 $/kg [82])

In a context of decarbonization transition, this is not a viable option, so the mass green hydrogen production is expected to shift, in next years, toward a large use of electrolyzers; in this way, hydrogen price will be strongly affected by electricity price.

Unfortunately, production cost, although it is the main cost component, is not the only parameter affecting hydrogen final price, since also transport, conditioning and refueling of the station [83] represent a non-negligible share; these parameters must be minimized, and they will surely decrease during the years, as the network is gradually improved, but at the moment, they represent roughly 50% of the final price.

Defining a unique price for electricity and hydrogen in future years can be at least challenging, if not even impossible, since many different factors can intervene modifying it: new investments, taxes, incentives, trading with other countries…

For this reason, a detailed sensitivity analysis will be provided concerning this variable.

2.3 Insurance costs

Insurance costs can represent an important share of the TCO of a vehicle, both considering LDVs and HDVs.

Cost of the insurance depends on many factors, including type of coverage, value of the vehicle, type of vehicle, where the vehicle usually operates, driver accidental history and age…[41].

Insurance annual premium is typically higher for HDVs than LDVs due to their higher value and, consequently, the more expensive potential damages.

ATRI, in A. Leslie and D. Murray [84], reports a statistical survey on annual insurance premium for freight trucks, basing on US data: average cost is 0.086 \$/mile, pointing out that costs can vary depending on the dimensions of the fleet, reporting average costs of 0.122 \$/mile for small fleets and 0.082 \$/mile for large fleets.

Most of the insurance premiums are based on the vehicle value: for this reason, many studies in literature reports assumptions of insurance annual costs as a percentage of retail price of the vehicle. E. den Boer *et al.* [85] assumes 1.5% as annual costs, while B. Noll *et al.* [44] assumes as annual insurance premium 2% of the vehicle retail price.

A. Burnham *et al.* [41] reports that an average insurance premium for a freight truck can be assumed between 5,000 and 7,500 $: considering that this evaluation is mainly based on diesel trucks (as they represent almost the total of current market), with a typical retail price below 150,000 $ [28], these assumptions correspond to 3.33% and 5% of the retail price.

Specifically for Finland, J. Laitila *et al.* [86] provides some estimations of insurance yearly costs for transport trucks: 5,500 € for a 124,200€ truck (4.4%) and 8,000 € for a 144,200 € truck (5.5%).

In general, no particular difference of annual premium is reported in literature depending on powertrain or fuel used: only E. den Boer *et al.* [85] reports that, in its assumption of the annual costs basing on the vehicle retail price, the percentage is slightly increased with respect to a traditional vehicle due to the newness of the considered technologies (BEVs and FCEVs).

For a more precise approach, it has been considered that the insurance premium is often based on the current evaluation of the value of the vehicle: for this reason, the premium usually decreases during the years, with increasing age and cumulated mileage. For this reason, in this report it has been chosen to assume as annual premium a fixed percentage of the residual value of the trucks; this residual value is evaluated each year following Equation 7 (see Vehicle depreciation section (2.1.3)).

Considering that all the three powertrains this document is dealing with (BEVs, FCEVs and H2ICEVs) can be considered new technologies, the percentage of the residual value has been assumed equal for all the types of trucks, and it has been chosen 5%.

2.4 Maintenance and Repair costs

2.4.1 Maintenance and Repair costs

Maintenance and Repair (M&R) includes all the set of actions aiming to decelerate the deterioration of the vehicle and its parts (maintenance), to restore the functionality of components (repair) and to evaluate the working status of the vehicle (inspection), including both labor and parts price.

It is possible to divide this kind of interventions in three main categories:

- Scheduled maintenance and inspection: it includes all the preventive replacement of vehicle components and other services at regular intervals, as prescribed by laws and manuals. In this category are included tire rotation, oil change, spark plug replacement, coolant inspection, brake fluid replacement, safety inspection, exhaust emissions inspection… [87]
- Unanticipated repairs: it includes all the operations on parts that do not have set replacement intervals, whose needs of maintenance are enlightened by inspections and diagnostic tests. Examples of this repairs are replacement of broken headlight bulbs, fix of exhaust system and in general every operation on broken components [87]
- Tire replacement, due to tire wear: it is often considered as an independent category as it can represent a significant portion of the overall M&R cost on the entire lifetime of the vehicle [87]

It is important to point out that in this section engine rebuilds, battery replacements and fuel cell stack refurbishments are not included, as they represent major costs peculiar of each drivetrain technology, so they will be discussed as a separate section, Midlife overhaul costs (2.4.2).

With fuel consumption and vehicle depreciation, M&R costs represent one of the most impacting categories on the operating costs.
Considering current literature, some studies have already been conducted on BEVs, partly basing on passenger cars and calculating projection of costs for HDVs; regarding FCEVs, numbers are not well defined yet, considering that market diffusion of this technology is still quite low; H2ICEVs represent the most critical point: diffusion of this technology is still almost null, and literature regarding this topic is very scarce.
In any case, numbers that can be assumed today for maintenance of BEVs, FCEVs and H2ICEVs are probably quite inflated with respect to a market stage when these technologies will be relatively diffused. This is mainly due to a lack of standardization of components and methodologies, that still requires deep research and development for a competitive market, as well as a scarcity of components on the market [42].
In any case, the majority of recent studies tend to concur on the fact that electric engines, particularly in the case of BEVs, are likely to have lower maintenance costs compared to diesel engines. This is primarily attributed to the inherent 'robustness' of electric powertrains in contrast to conventional transmissions. This trend has been widely observed in studies focused on light-duty vehicles (LDVs), although the precise quantification of these cost savings remains a topic of ongoing debate.

Regarding FCEVs, literature is quite various: some studies, considering that engine is basically an electric one, tend to consider maintenance cost of FCEVs similar to the ones of BEVs or slightly higher; others, considering that fuel cell technology is still not well known and their reliability relatively low, declare that maintenance costs of FCEVs could be more similar to diesel ICEVs than to BEVs.

In general, total M&R costs are calculated as

$$M\&R_{cost} = (cost_{component}[€] + cost_{labour}\left[\frac{€}{h}\right] \cdot time_{labour}[h]) \tag{11}$$

considering all maintenance, repair, and inspections.
Total cost can be then divided per the total mileage, or, rarely, per the mileage-payload $[ton \cdot km]$.
F. Kleiner and H. E. Friedrich [60] breaks down costs of maintenance, repair and inspection considering the main components of the vehicle, including in his study different kind of powertrains and vehicle categories.
Considering Maintenance, the study analyses 46 components and calculate total costs considering each of them, the needed labor and the frequency of needed maintenance, and dividing total result for the mileage:

$$C_{maintenance} = \frac{\sum_{c=1}^{46} f_c \cdot (C_c^{material} + C_c^{labour})}{M_{total}} \tag{12}$$

Similar approach is assumed for Repair costs, considering 24 main components:

$$C_{repair} = \frac{\sum_{c=1}^{24} f_c \cdot (C_c^{material} + C_c^{labour})}{M_{total}} \tag{13}$$

F. Kleiner and H. E. Friedrich [60] provides results for different powertrain technologies (including BEVs and FCEVs, unfortunately H2ICEVs are not considered, but CNG trucks are) and two truck-segments: long-haul tractor trailer with gross weight 40 ton and rigid urban truck of 12 ton.
Results, calculated on a $€/km$ basis, are here reported (to provide a reference value, also diesel trucks costs are reported):

M&R cost [€/km]	D-ICET	CNG-ICET	BET	FCET
12t truck	0.103	0.107	0.056	0.070
40t truck	0.147	0.143	0.098	0.103

Table 2.9 - *Maintenance costs per km* [60]

G. Wang *et al*. [87] developed a study methodology for "advanced technology" powertrains, referring in particular to FCEVs and BEVs for HDVs, based on the literature review of passenger cars M&R costs, and projecting them to HDV applications. Basic idea is that these technologies have still very low diffusion on HDV market, but they are already present in the LDV market, and observations in this sector are possible, even if not abundant.

The approach is based on the breakdown of the overall costs in the major components, estimating the level costs of each one in the different technologies. Starting from long-haul diesel trucks data, for which M&R are quite well known, and assumed here to be 0.20 $/mile, components of the drivetrains are divided in main categories:

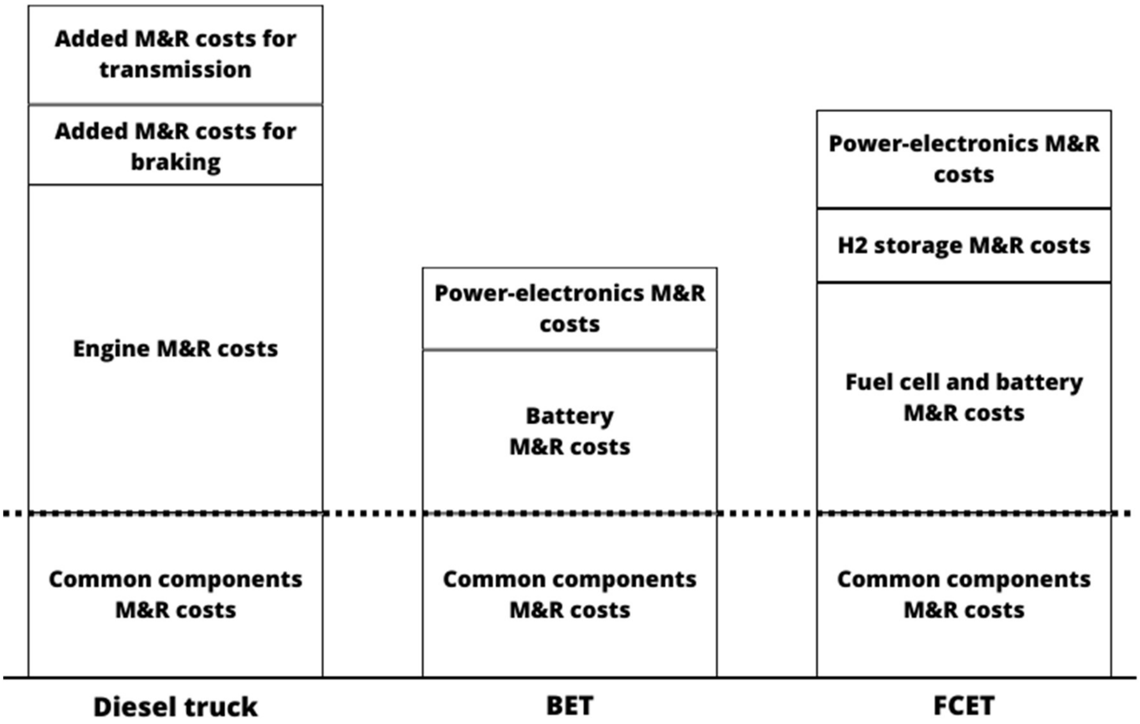

Figure 2.11 - *M&R cost teardown* [87]

Assuming that common components (as brake fluid, brake disk, tires, gear oil…) preserve the same M&R costs, the main focus can move to components specific for BEV and FCEV.

Peculiar components of BEV are assumed to be:

- Battery
- Power electronics

For FCEV, most impacting components are:

- Fuel cell and battery
- Hydrogen storage
- Power electronics

For each of these components, M&R costs for LDV are taken from literature, and a multiplying factor of 1.33 is assumed to project them for HDV applications.
This 1.33 factor is assumed basing on the ratio between long-haul truck diesel and passenger car M&R costs (0.20 $/mile and 0.15 $/mile respectively, as reported by N. Williams and D. Murray [88]).
In G. Wang *et al*. [89], also a learning curve for future costs is assumed, considering that is extremely probable that costs for this kind of "advanced technologies" will drop down in future years, due to technical improvements as well as larger diffusion on vehicles market. This assumption is not considered in this study, as it wants to be referred to current technical background of components and methodologies.

Regarding H2ICEVs, unfortunately it must be said another time that evaluations on costs are extremely scarce.
As in the Retail price evaluation section (2.1.1), similarity with CNG trucks will be exploited, and costs will be assumed equal to this "known" technology: this simplifying approach seems quite justified, considering that a large share of the vehicle components is common to the two technologies.
Among CNG truck studies, that are far from be abundant, it has been considered W. Yaïci and H. Ribberink [77]: it states that maintenance costs for this kind of vehicles are generally slightly higher than diesel ones, due to costs related to gas tank; it also suggests that in future these costs could decrease to a level lower than diesel ones, depending on less aftertreatment devices needed and a cleaner combustion, but at current state this is not reached yet.
Same declaration is also made by F. Kleiner and H. E. Friedrich [60], that indicates a maintenance cost for CNG-fueled HDVs corresponding to +4% compared to diesel case. Observing that maintenance costs connected to the hydrogen tank represent 6% of the total maintenance costs of a diesel truck, according to G. Wang *et al*. [87], these two values have been considered acceptable.
Considering that, maintenance costs for H2ICEVs have been evaluated for this study equal to the costs for diesel vehicles plus a parameter for tank maintenance. This is probably a conservative assumption, considering that in H2ICEVs large part of the aftertreatment components is not present, so some costs could probably be avoided.

To project data from F. Kleiner and H. E. Friedrich [60] to the truck configurations assumed in this study, a linear approximation is chosen: starting from the two values provided for each powertrain technology (12 t and 40 t), linear interpolation is used in order to find costs referred to each weight class. Same approach is followed for simulating diesel trucks maintenance, considering an additional +5% (average between the two values provided by the two documents mentioned above [60], [87]) for H2ICEVs, connected to the tank maintenance.

Considering inspections, most of the tests on the vehicles have to be done each year, if no problems or malfunctions appear during the period between to prescribed controls.
Among the several controls, the main are roadworthiness test, compressed-air brakes check, emissions check, tachographs maintenance...
Prices for these inspections are not fixed but vary from a company to another. As reference, prices declared by a Finnish operator [90] on their website are assumed and reported in Table 2.10 (all prices include VAT)[1]:

Service	**€**
Truck roadworthiness test	80-120
Trailer roadworthiness test	105-145
Compressed-air brakes check	100-160
Emission check	30
Ex-post audit	40
Tachographs check	60
Speed limitation device check	45
VAK/ADR inspection	50

Table 2.10 - *Inspection prices*

In general, costs of the inspections should be almost constant for all the types of powertrains.

As a last consideration, it is useful to remember that these evaluations are based on current (or near future) scenarios: in next years, costs related to BEV maintenance will probably decrease due to improvement of the batteries and the electronic system, FCEV will surely use more reliable fuel cells and auxiliary components will have a higher standardization level. Among the three

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[1] Where a range of prices is provided, it depends on number of axis of the vehicle

technologies, H2ICEV is probably the one where improvements will be more limited, due to the fact that ICE are a relatively known technology, and no important improvements are expected: nevertheless, some components will probably be enhanced, and their maintenance will be less frequent.

2.4.2 Midlife overhaul costs

Midlife overhaul costs include the costs of partial or total substitution of the major propulsion components of the vehicle due to deterioration of many of its parts.

These costs are generally considered separately from the "standard" maintenance and repair costs, as they are normally quite high (and largely impacting on the TCO) and they occur just few times in the lifetime of a vehicle, while the second are lower but almost equally distributed on the entire lifespan.

Being generally high, these costs must be carefully evaluated in the economic analysis on the lifetime of the vehicle: assumptions of different lifetimes of the powertrain technologies can lead one substitution more (or less) on the vehicle lifecycle, giving significantly different results of the TCO.

In case of traditional ICEVs, they could be represented by a replacement of the engine, but in fact it is rare that this is necessary [38], at least for the first owner of the vehicle, so this cost is often ignored in TCO analysis of this kind.

Concerning BEV, midlife costs are represented by the substitution of the battery-pack, due to the decrease of its capacity caused by age and charge-discharge cycles. Usually, a battery is assumed to be suitable for use in vehicles as long as its capacity is above 80% of its initial value: when this limit is reached, battery is generally replaced with a new one, while the used one sees a second-hand use in some stationary applications, where needs of gravimetric or volumetric capacity are less strict than in mobility sectors.

Durability of vehicle batteries is highly increased during the past years, at least for what concerns LDVs. Although deterioration of a battery is mostly related to recharging cycles, many manufacturers offer, for simplicity, a warranty evaluated in years, assuming a (conservative) average annual number of recharges, or in miles.

In fact, in literature there is not a unique opinion on the durability of vehicles batteries, especially concerning HDVs, where electric vehicle market is still very limited.

Typical warranty from manufacturers today is 8-10 years of activity [91] and 300,000 miles [92].

Some studies on electric buses reported that battery life can be even longer, arriving to have warranties up to 12 years and unlimited mileage [93]; unfortunately, it has to be considered that buses operate generally at low loads, with frequents stops and low average speeds: this type of use helps increasing the durability of the battery with respect to a typical truck use, so expected lifespan for vehicles object of this document will probably be lower.

Most of publications agree that durability of batteries is going to increase during next years, reaching up to 500,000 miles warranties for the ones produced in 2030 [92].

In this study, considering that HDV can have different type of use (and, consequently, different daily mileage), a first lifetime of the batteries based on the cumulated mileage is chosen, assuming 500,000 km (about 310,000 miles). Added to this first assumption, it has been assumed that, in case the considered vehicle did not reach 500,000 km on the considered lifetime, a battery substitution is assumed at the 10th year of use, without considering the cumulated mileage: this assumption is justified considering that a small battery could see a very large number of charging cycles also in the case the yearly mileage is maintained relatively low, so an assumption on the battery useful life base only on mileage would be insufficient.

At the replacement of the battery, it must be considered that it is not wasted, but sold as second-hand item, and used for stationary applications; according to H. Basma *et al*. [40], value of a used battery, with a residual capacity of 80% of its nominal one is about 15% of its initial price, while H. Basma *et al*. [39] and SMMT [94] both report 20%.

For a conservative approach, 15% of the initial value has been assumed as resale price in this study.

Concerning FCs, literature is even more inhomogeneous than for batteries, as this technology is still almost unknown also for LDVs, not just for HDVs.

According to Ricardo [95], lifetime of a FC is expected to be 7 years, and the cost of replacing the stack is assumed to be about 33% of the cost of the fuel cell system at the moment of the replacement.

According to H. Basma *et al*. [40], in 2022, useful life of a vehicle fuel cell is 15,000 hours of operation.

Department of Energy (DOE) pointed out that higher durability of fuel cell is required for trucks with respect to cars and set target of 25,000 hours (and 1,000,000 miles) for stacks produced in 2030 for long-haul trucks, with the aim to arrive at 30,000 hours (and 1,200,000 miles) in 2050. In case these targets were reached, fuel cells substitution would probably not be necessary anymore for an average long-haul truck, which has a lifetime mileage of about 1,000,000-1,200,000 miles.

Some demonstrations already showed that is possible to arrive to 30,000 hours, but tests are still limited to transit buses and do not involve trucks yet; same considerations done some lines above for batteries are generally valid also for fuel cells: relatively low-load duty cycle of buses allows to reach better durability of the system than the expected one for trucks.

As for batteries, at the replacement time, the fuel cell stack is not wasted, but it can be resold and utilized in other applications: according to H. Basma *et al*. [40], after a 15,000 h utilization, residual value of the cell is about 25% of its initial value.

For this study, these two values (15,000 h of operation and 25% of residual value) will be assumed.

These assumed values for FCEVs and BEVs are considering the current level of the technologies: it is reasonable to assume that future components will have a longer life, due to the improvement of the technology level.

Considering H2ICEVs, literature reporting data about durability of these engine is extremely limited, as in fact data on this topic are far from being complete.

According to Cummins, H2ICEVs should have the same lifetime of traditional diesel engines in term of years and mileage, if properly maintained [96]. This means that this kind of powertrains could easily travel for 1,300,000-1,600,000 km before a replacement is needed [41], [64], and in fact it is possible to simplify the model stating that no midlife costs are present during the lifetime of the vehicle, as the total expected mileage of a long-haul truck is usually assumed to be that.

Certain researchers have highlighted the potential requirement for a significant engine replacement during midlife, attributed to the degradation of injectors and other integral components. As a result, the Results section will incorporate an extra analysis on scenarios involving high mileage that will include a comprehensive engine rebuild, currently regarded as a worst-case scenario. This approach is adopted in anticipation of more refined analyses that will emerge in the subsequent years.

2.5 Taxes and Fees

Taxes and fees comprehend sales tax, registration, annual fees… and they generally depend on the price and the power of the vehicles, and in some cases also to the powertrain technologies.

It is worth mentioning that many countries have introduced incentives and partial tax exemption for some alternative powertrain vehicles, even if, at the moment, they mostly involve only passenger cars, while heavy duty vehicles and trucks are often not included in the benefit.

2.5.1 Vehicle registration taxes

At the purchase of a vehicle, the owner has to pay some fees before the start of its operation.

Many countries have introduced some incentives on purchase and registration taxes for new alternative powertrain vehicles, to enhance the diffusion of these kind of cars and trucks for environmental targets. Incidentally, it can also be observed how these incentives have impacted on the purchase price of these vehicles: manufacturers have in many cases artificially increased their prices, confident that their surplus will be offset by public subsidies to the costumers. This has created an inflated market that has penalized costumers from those countries where these subsidies are not present.

For example, Finland has a purchase subsidy on BEVs and on FCEVs (but appliable just if their battery can be recharged using grid electricity) up to 2000 €. Unfortunately, this incentive is appliable only to vehicles with a purchase price below 50,000€: this means that mainly passenger cars or small vans are eligible for this kind of support, while large trucks will not benefit of this incentive, as their price is generally above this limit.

At the moment of the writing of this study, no other incentives are present in Finland for alternative powertrain HDVs [97]. This allows to conclude that the three powertrain technologies considered in this analysis will be "equally" considered for their purchase and registration taxes.

The most impacting fee at the time of the purchasing of the vehicle in Finland is the Value-Added Tax (VAT), equal to 24% of the retail price of the vehicle [98].

The other taxes paid at purchase of the vehicle are relatively low, as they include registration tax, tax for the plate and some circulation permits; the overall amount results to be about 30 €.

2.5.2 Annual fees

Beyond purchase taxes, every vehicle's owner must pay each year some annual fees.

Also in this case, many countries have introduced incentives and tax exemptions for alternative powertrain vehicles, basing on their lower polluting impact.

In Finland, annual tax for lorries is just based on their gross mass, axles, and possibility to add a trailer, without any consideration regarding their driving fuel. This is probably due to the low diffusivity that alternative powertrains have today in the HDV fleets, that are mostly based on diesel vehicles: in next future, it is not improbable that the legislation will be updated, in order to define annual taxes basing also on emissions levels.

Today, annual taxes for HDV trucks are defined as a number of cents for each partial or complete 100 kg of gross mass, that must be multiplied for the 365 days over a year; table is here reported (unit is cents/day/100kg):

	No trailer	**Semi-trailer**	**Trailer or center-axle trailer**
2-axle lorry	1.3 cents	2.2 cents	2.1 cents
3-axle lorry	0.8 cents	1.3 cents	1.4 cents
4-axle lorry	0.7 cents	1.2 cents	1.3 cents
5 or more-axle lorry	0.6 cents	1.0 cents	1.2 cents

Table 2.11 - *Annual taxes for lorries* [99]

As a way of example, a 35 t lorry with 4 axles and a semi-trailer will pay 1533 €/year of annual tax.

2.6 Road tolls

Road tolls can represent a non-negligible component on the annual costs of a vehicle, with a high impact on it TCO (see for example Figure 2.1).

Generally, costs connected to road tolls vary depending on the use of the considered vehicle: urban routes have generally low or null costs, while long-haul lorries, that travel mostly on highways, can have high expenses.

Evaluation of this cost element can be relatively easy for countries that use an annual road tax (the so-called vignette) as Switzerland, Hungary or Austria; for countries that use a tax based on travelled kilometers (Italy and France as two examples) the evaluation for the TCO requires to make assumptions on the type of routes that vehicle uses during the year, defining an average price per travelled kilometer.

The case of this analysis considers just lorries driving in Finnish domestic traffic, so just the Finnish legislation is considered.

At the time of writing, zero toll roads or bridges are present in Finland [100], so this component of cost is null in the considered cases.

2.7 Other costs

Considering that this study regards heavy-duty vehicle applications, some additional considerations have to be done in the definition of the TCO.

2.7.1 Payload reduction

Dealing with trucks and freight transport vehicles, the main variable to evaluate their operation is the payload; for this reason, it has been chosen to present results not only reporting TCO [€] but also the LCOT [$cent€/km/t$].

Beside the definition of the average payload (that will be described in Case study section (3.2)), some additional considerations must be reported concerning payload reduction due to alternative powertrains. To quantify this, an evaluation of the energy storage system has been done, and their weight has been subtracted to the assumed payloads.

This estimation is particularly important on BEVs, since batteries are known to have lower energy density compared to fuels, and this can strongly impact on the payload. On the other hand, typical hydrogen storages are not much heavier than standard diesel ones.

For some additional considerations, also the energy density of the storages will be reported.

For the battery weight estimation, Ricardo provides as average specific weight 7 kg/kWh [28], so this datum has been assumed for all the case studies, while energy density is assumed 0.425 kWh/l.

Regarding hydrogen, typical gravimetric density of a 700-bar storage is assumed to be 4.2% [101], while volumetric density is assumed 25 $kg_{H2} \cdot m^{-3}$ [102].

2.7.2 Cost of drivers

Cost of driver, mainly including its wage and benefits, can represent a key element in the evaluation of a TCO, since, on the entire lifetime of the vehicle, it can have an extremely high impact.

According to Finnish statistics, average gross hourly salary for truck drivers is about 22.50 €/h [103].

However, it has been considered that adding the driver cost to the TCO evaluation would have strongly affected the results without adding any important information to the comparison. Indeed, the vehicles are assumed to travel for the same hours in the same conditions with all the possible powertrains, so the drivers' costs would be generally the same.

In conclusion, the cost associated to driver wage and benefits have not been included in the study, with some exceptions connected to the recharging (or refueling) time, that will be discussed in following paragraph.

2.7.3 Additional time spent for recharging and refueling

As discussed in State of the art of technologies paragraph (1.3), one of the main disadvantages connected to BEVs is the time needed for the battery recharging. This time depends on the battery capacity and on the power provided by the recharging spots, but in general a full recharge can last from one to several hours. On the other hand, refueling of hydrogen storages is fast, requiring a time comparable with the refueling of a diesel truck.

In most of the case studies observed in this comparison, as it will be described in following chapters, the vehicle energy storages, both considering batteries or hydrogen tanks, have been designed in order to be able to fulfill the daily activities without any intraday refueling (or recharging), while the recharging is assumed to occur during the night, without impact on the normal activities of the vehicle.

Nevertheless, some differences have to be remarked in the case of extremely long-haul applications: in this situation, to avoid the assumption of a battery size extremely larger than the real ones currently produced, a smaller battery has been assumed, considering the possibility of an intraday recharging.

To give a quantitative evaluation of the time spent during the recharging, it has been considered as an extra-cost in terms of driver costs, multiplying the additional time (removing the 45 min mandatory break) for the driver hourly cost.

It must be added that an intraday stop would also mean a delay in arriving to the final destination and this can have, in some particular cases, larger economic impact than the simple worker wage, meaning a possible interruption of a supply chain. Unfortunately, evaluating these scenarios would have been impossible for this study, as they are connected to specific cases.

No additional time is assumed for the hydrogen refueling, as it has been evaluated that the 45 min mandatory break for the driver is largely sufficient for refilling the tank, if needed.

2.8 Discount rate

TCO methodology is based on a Discounted Cash Flow analysis: this method is used to evaluate the present value of each expense (or revenue), basing on its nominal value in the future.

General idea of this type of analysis is that a nominal cash flow in the future will have a lower value if projected on present day; effect is that two expenses that are nominally equal but occurring in two different years will have different impact on the TCO: at equal nominal values, effect on TCO of cash flows will be gradually less impacting as they are further in the future.

Discounted cash flow in year n is calculated as:

$$DCF_n = \frac{NCF_n}{(1+d)^n} \tag{14}$$

Where:

- NCF_n = nominal cash flow at year n, in €
- d = discount rate

The discount rate is the rate used to discount future cash flows to their present value: it represents the time value of money in a certain time period.

Choice of discount rate is particularly impacting: a high rate would mean that future expenses will have a really low impact on the total discounted cash flow (and, consequently, on the TCO), even if their nominal value is relatively high.

This parameter is influenced by many factors, including:

- Risk-free discount rate: systemic risk connected to an investment that is considered "guaranteed" (e.g., short term government bonds)
- Required rate of return: minimum return that an investor is expecting to receive for their investment [104]
- Annual inflation rate
- Real escalation rate

Unfortunately, even if the discount rate may seem precisely defined through equation, many of the assumptions connected to its calculation are only a "best guess" regarding future trends and economic movements.

Furthermore, a unique discount rate is assumed for a cash flow analysis, when, in fact, interest rates and risk profiles are constantly changing in dramatic ways [105].

In literature, discount rates for evaluations referred to HDV are relatively high, generally above 5%.

A. Burnham *et al.* [41] assumes 5%, justifying this value with the consideration that it should be kept at least above the interest rate on treasury notes, which have historically averaged about 3.2% [106], to push investors into transport business instead of bonds. This value is generic for HDVs, without considering the specific case of alternative powertrain technologies; regarding new technologies, interest rate is generally maintained slightly higher than for traditional devices, to take into account possible technical and economic developments.

B. Noll *et al*. [44] assumes 7% for its low-carbon HDV, while H. Basma *et al*. [39] uses 9.5%.

This disagreement between different studies, as well as the obvious struggles in defining parameters referred to future economic trends, takes the need for a sensitivity analysis, that will be discussed in Variable discount rate section (4.3.6).

3. Case study

3.1 Heavy-duty traffic in Finland

In Finland, the largest share of freight transport, considering both a weight basis ($tons$) and a weight-mileage basis ($t \cdot km$), occurs on roads. In 2020, freight transport by roads has represented 89.6% (259 million t) and 74.6% (27,861 million $t \cdot km$) of domestic transport, with a trend that has been almost constant in the past years [107].

Major traffic nodes are represented by the biggest cities of the country and their outskirts: Helsinki, Turku, Tampere, Vaasa, and Oulu [108].

Transportation can develop on different routes, according to the needs: final distribution, transport between production sites, long transport across the country… These different needs are represented by lengths of the journeys that can vary from few kilometers to several hundred.

A first glance to this division is offered by Figure 3.1:

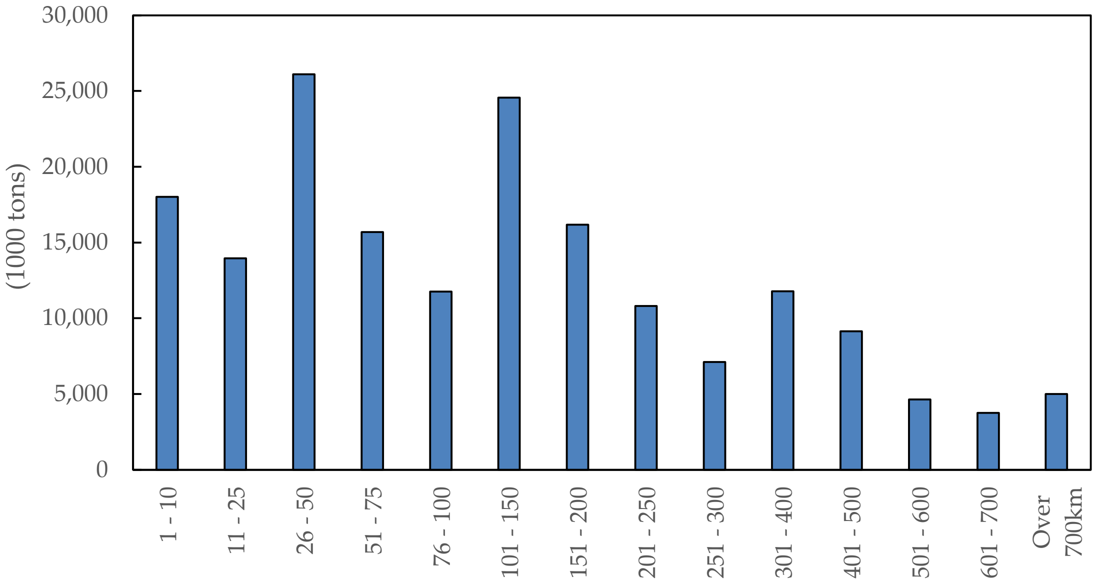


Figure 3.1 - *Transported freight by mileage in 2022* [109]

This division also interests the use of different truck types for various needs: short routes are mainly travelled on urban routes, so the use of low-weight trucks is usually preferred (medium-duty vehicles, range 3.5-12 t), while for long journeys HDV are more suitable.

This division of truck segments is represented by Figure 3.2:

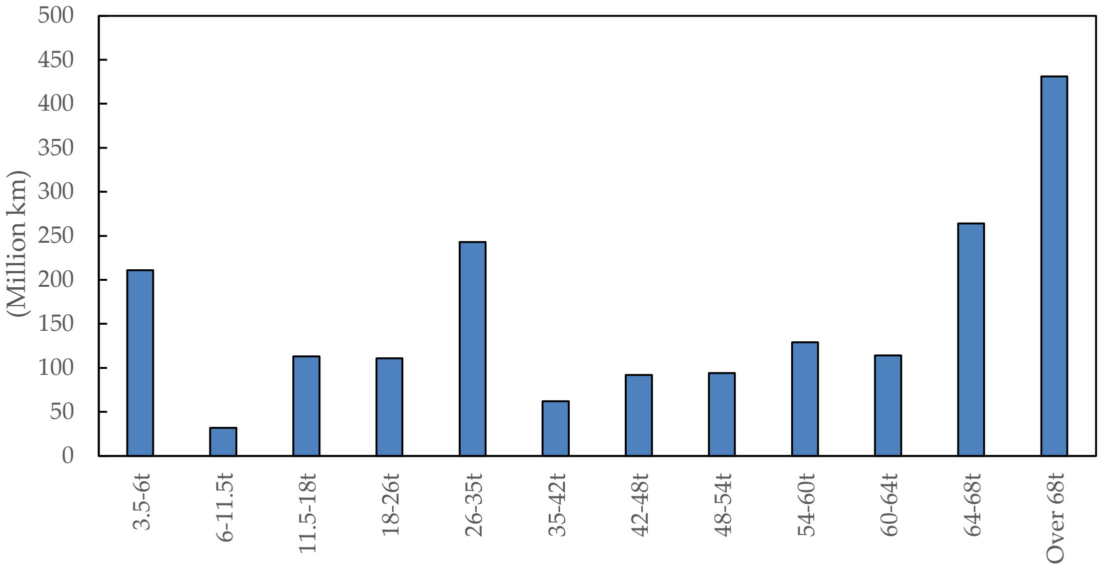


Figure 3.2 - *Vehicle mileage by truck gross weight* [110]

This trend represents the fact that most of the goods (in tons) are transported for short journeys, as visible in Figure 3.1, so, presumably, with low-weight trucks. At the same time, HDV are mainly used on longer routes, and this gives the peak that is present in the last two columns of Figure 3.2.

Regarding weight segments, and in particular the ones referred to HDVs, it must be considered that in October 2013, Finland changed its size limits on the different classes of HDVs, allowing full trailer combinations with a length of 25.25 m and maximum weight 76 t [78], commonly referred to as Long and Heavy Vehicles (LHV), while most of other European and North American countries typically use 18.75 m and 44 t vehicles, commonly called Heavy Goods Vehicles (HGV) [111]. Then, starting from January 2019, Finland introduced the category of High-Capacity Transport (HCT), with limit sizes of 34.50 m and maximum weight maintained at 76 t [112], to avoid the necessity of strengthening of the road infrastructure that a weight increase would have required, but with some piloting activities with maximum weight up to 104 t [111]. According to Finnish Ministry of Transport and Communication, this increase of maximum size had great environmental benefits, reducing fuel use in heavy road transport up to 15%, with the consequent emissions cutting.

Table 3.1 summarizes the new weight limits for trucks in Finland according to 2013 law:

Truck type	**Max gross vehicle weight**		**Max payload weight**	
	Old	**New**	**Old**	**New**
4-axle truck without trailer	32 t	35 t	18 t	21 t
5-axle truck without trailer	38 t	44 t	21 t	25 t
8-axle articulated truck	60 t	68 t	37 t	45 t
9-axle articulated truck	60 t	76 t	35 t	51 t

Table 3.1 - *Weight limits for trucks* [111], [113]

At present day, almost the entire market of heavy-duty vehicles is still based on traditional internal combustion engines: according to Stat.fi, in 2022, on a total of 92,633 vehicles above 3.5 t in use in Finland, only 694 uses as fuel neither petrol or diesel, and just 25 are reported to have electric powertrains [114].

Due to climate impact and new directives from European Union, this scenario has to be changed as soon as possible, and in next paragraphs possible case studies will be described.

3.2 Assumed cases definition

Road freight transport is a complex system, with an enormous number of variables, working together in order to find best solution to fulfill the needs connected to the transport of goods.

These variables are strictly connected to the geographical and economic context where the transport is operated: choice of some large trucks instead of a larger fleet of smaller ones can be influenced by many factors, as fuel price, roads, type of goods…

As seen in the model definition section, many parameters defining the TCO depend on the type of truck that is considered, its weight and its typical route.

A comprehensive review of all the possible combinations of vehicles and mileages would be impossible, considering the limited length of this report.

For this reason, this document has not the aim of describing every possibility of HDV application in road transport, but the author wants to provide a methodology for the calculation of the TCO in this particular context, with the hope that data and methods here provided can be easily adapted for a large number of cases and needs. According to this purpose, some fundamental cases have been assumed, in order to represent a good comparation between the three considered technologies and a starting point for the same evaluation on the particular cases.

Two main characteristics of the vehicle have been evaluated for the definition of these representative cases:

- Weight: the gross weight of the vehicle is fundamental in the definition of many parameters, as powertrain rated power, fuel economy, insurance costs… Beyond that, it is important to remember that LCOT is evaluated per unit of travelled km and tons of payload: for this reason, it is essential to know in advance which is the amount of freight that can be transported (or, in this case, assume one as representative case). In European Union, vehicles are considered part of the heavy-duty category if their gross weight is above 12 t [78].
- Mileage and route: many parameters of the TCO are evaluated basing on a mileage assumption, as maintenance or fuel costs. In this parameter also type of routes is included: as representative cases, long routes are assumed to be travelled mainly on highways, while short ones are considered to have a more urban context

To develop a model able to schematize a large number of possible cases, three types of trucks are considered, assuming their weight classes basing on the new limits of the Finnish legislation, and possible uses are displayed:

- 18 t: typically rigid 4x2 truck, used for freight distribution, engine power about 200-220 kW, maximum payload of 12 t
- 42 t: 5-axles truck, rigid or tractor, 340 kW engine, payload up to 25 t, used for transport between industries or production sites
- 76 t: limit for 9-axles articulated truck, tractor, 560 kW engine, payload up to 51 t, used for long-haul freight transport

Regarding representative mileage, three types of routes of the trucks were chosen:

- Short route: mainly on urban routes, typical of retail distribution activities, with frequent stops due to traffic and discharge of goods
- Medium route: mainly travelled on regional roads, connected to freight transport between two production facilities
- Long-haul route: mainly on highways, related to long travel freight transport

Combination of these considerations takes to the assumption of some representative cases for this report. For each discussed truck, two average daily mileage are assumed, in order to give a range of results for each evaluation, a single route-type and a payload profile.
Cases results to be:

- 18 t, rigid 4x2 truck, day cab, with 200 kW powertrain, used in urban routes for freight distribution; as an example, typical use can be imagined considering the distribution of goods to the supermarkets of a large city. Starts and stops are frequent due to the type of route and the needs of loading-unloading and average speed is relatively low.
  Maximum payload is 12 t, but the average payload is considered 6 t, to simulate a gradual discharge of the load during the daily activity.
  Two daily mileages are assumed in the calculation: 80 and 120 km, travelled in Helsinki; these numbers are chosen considering that they could represent two "limits" for a typical activity of this kind of trucks: lower mileages would be probably covered by smaller size delivery vans, while higher ones would probably involve regional transport routes, typically solved by larger trucks

- 42 t, 5-axles tractor with semitrailer, day cab, 340 kW powertrain, used on regional roads; typical use can be the exchange of components between industries in different cities. Travel is generally at medium speeds, with some starts and stops due to traffic. Average payload is assumed to be near the limit of 25 t: typical activity of this kind of trucks is done exchanging the trailers at the two ends of the journey, so it is quite rare the vehicle travels unloaded.
  Daily mileage is assumed considering distances between some of the main cities in Finland, which also represent the crucial nodes of road traffic [115]: Helsinki and Turku are about 160 km far from each other, and distance between Helsinki and Tampere is similar; the two assumed mileages represent a direct travel between these cities (first case), or a two-direction travel (e.g. Helsinki-Tampere-Helsinki), resulting in 160 km and 320 km on the Helsinki-Tampere route
- 76 t, 9-axles articulated truck with trailer, sleeper cab, 560 kW, used for long-routes on highways. Typical travel is maintained at high average speeds, generally near to the 80 km/h limit [116]. Average payload is about 50 t, for the same reason reported above: trailer exchange prevents the vehicle to travel unloaded.
  Daily mileages are assumed equal to 500 km and 720 km, travelled on Helsinki-Oulu route; the upper limit (720 km) is assumed considering a maximum travel for a single-driver truck: driving time for a truck operator in EU can reach maximum 9 h/day [117], so, assuming an average speed of 80 km/h, 720 is considered the maximum the truck can travel in a single day.

For all the cases, the trucks are assumed to start operating for 330 days per year. According to common use, managers of large fleets operating on long distances use to employ new vehicles for longer yearly mileages, while they usually try to decrease the mileage on older trucks, either by decreasing the average daily mileage, or by using them for fewer days. This is done because the overall efficiency of a vehicle tends to decrease with age, due to higher fuel economy, maintenance costs and rate of broken components.

Considering this, it has been assumed a decrease of the yearly mileage of 5% each year for 42 t truck, and equal to 10% per year in case of the long-haul trucks; for the urban trucks, having short mileage, no decrease has been assumed.

Useful life of the vehicles is assumed 15 years for case studies with lower mileages, while for long-haul cases it is reduced, in order not to overcome

1,400,000 km of cumulated mileage (assumed as maximum useful life for an ICEV).

These six cases will have, as it will be described in following sections, parameters of the TCO that are deeply different: retail cost, insurance, fuel economy and others are mainly connected to gross weight of the vehicle (and its engine power), while maintenance, fuel cost and depreciation strongly depend on mileage.

For all the cases, the three considered powertrain technologies (H2ICE, FCEV, BEV) are considered and compared, with the aim to provide some suggestions for the choice of the correct powertrain depending on the different duty-cycle needed.

Parameters of each case[1] are here reported in table:

	U1	**U2**	**EU1**	**EU2**	**LH1**	**LH2**
Type	Rigid 4x2	Rigid 4x2	5-axle with semitr.	5-axle with semitr.	9-axle with trailer	9-axle with trailer
GVW	18 t	18 t	42 t	42 t	76 t	76 t
Average payload	6 t	6 t	22 t	22 t	45 t	45 t
Powertrain	200 kW	200 kW	340 kW	340 kW	560 kW	560 kW
Daily mileage	80 km	120 km	160 km	320 km	500 km	720 km
Operating hours per day	5 h	6 h	5 h	6 h	8 h	9 h
Rate of decrease of yearly mileage	0%	0%	5%	5%	10%	10%
Useful period	15 years	15 years	15 years	15 years	12 years	8 years

Table 3.2 - *Design parameters*

3.3 TCO parameters

The many components of the TCO evaluations are here summarized with their effective values depending on the case study.

---

[1] U: Urban
EU: Extra-Urban
LH: Long-Haul

3.3.1 Vehicle purchase cost

As described in Model section (2.1), purchase cost of the vehicles has been evaluated on a component-based approach.
Final retail prices (excluding VAT) are here reported for the different case studies (in €):

Case	BET	FCET	H2ICET
U1	158,754	237,607	129,220
U2	173,705	246,635	140,318
EU1	240,213	363,142	143,890
EU2	314,963	381,797	179,222
LH1	416,740	543,036	206,842
LH2	461,590	571,018	234,785

Table 3.3 - *Final retail prices (in €)*

As observable, the cheapest solution concerning vehicles retail price is H2ICETs, for all the considered cases. This is due to the relatively simple technology, that allows to keep prices quite low at least for the engine itself.
Final prices, besides some constant components as the chassis and the cab, are mainly dependent on the energy storage and the rated power of the powertrain (detailed description on dimensioning of the energy storage is provided in Fuel cost (3.3.2)).
Decomposition of purchase cost is observable in Figure 3.3 and Figure 3.4 for case studies U2 and LH1 (excluding the Retail Price Equivalent Factor, assumed equal to 1.3, and the VAT):

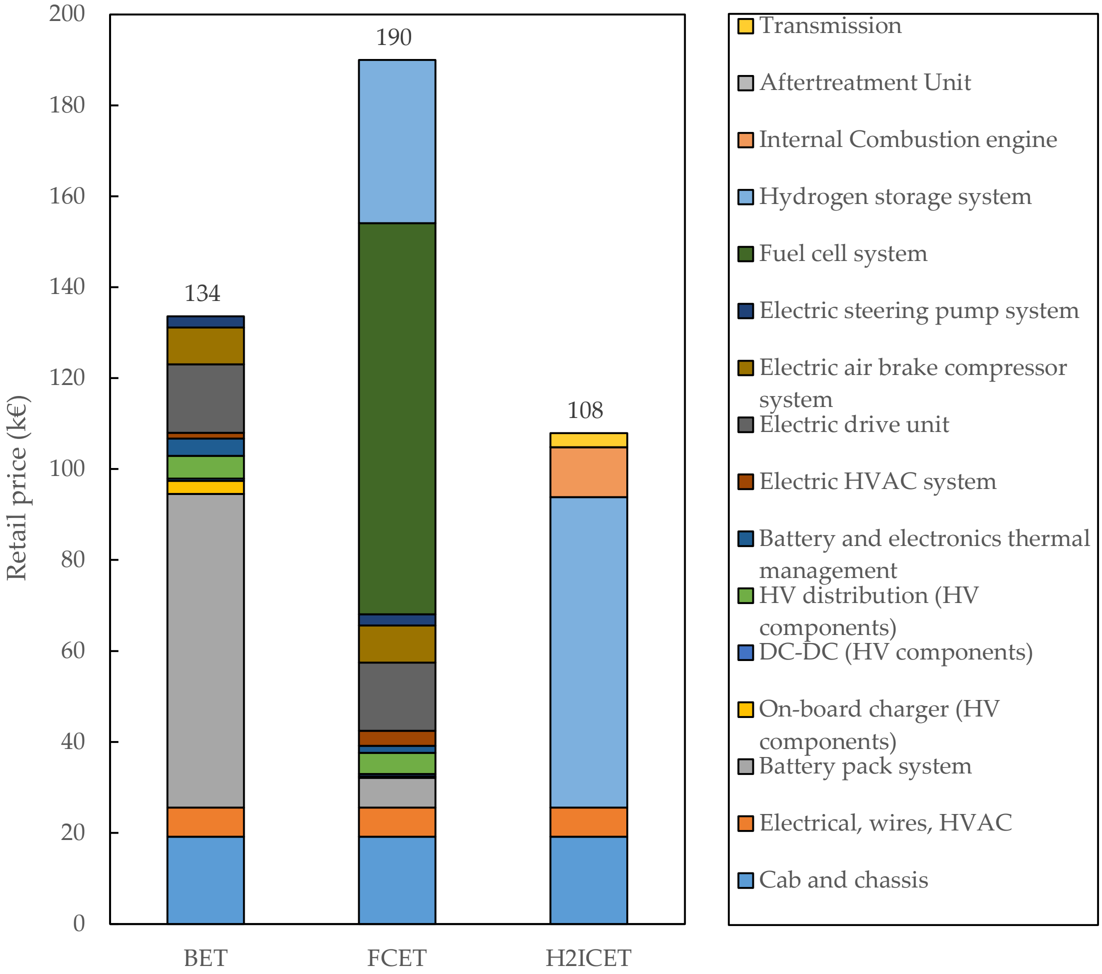


Figure 3.3 - *Retail price, case study U2*

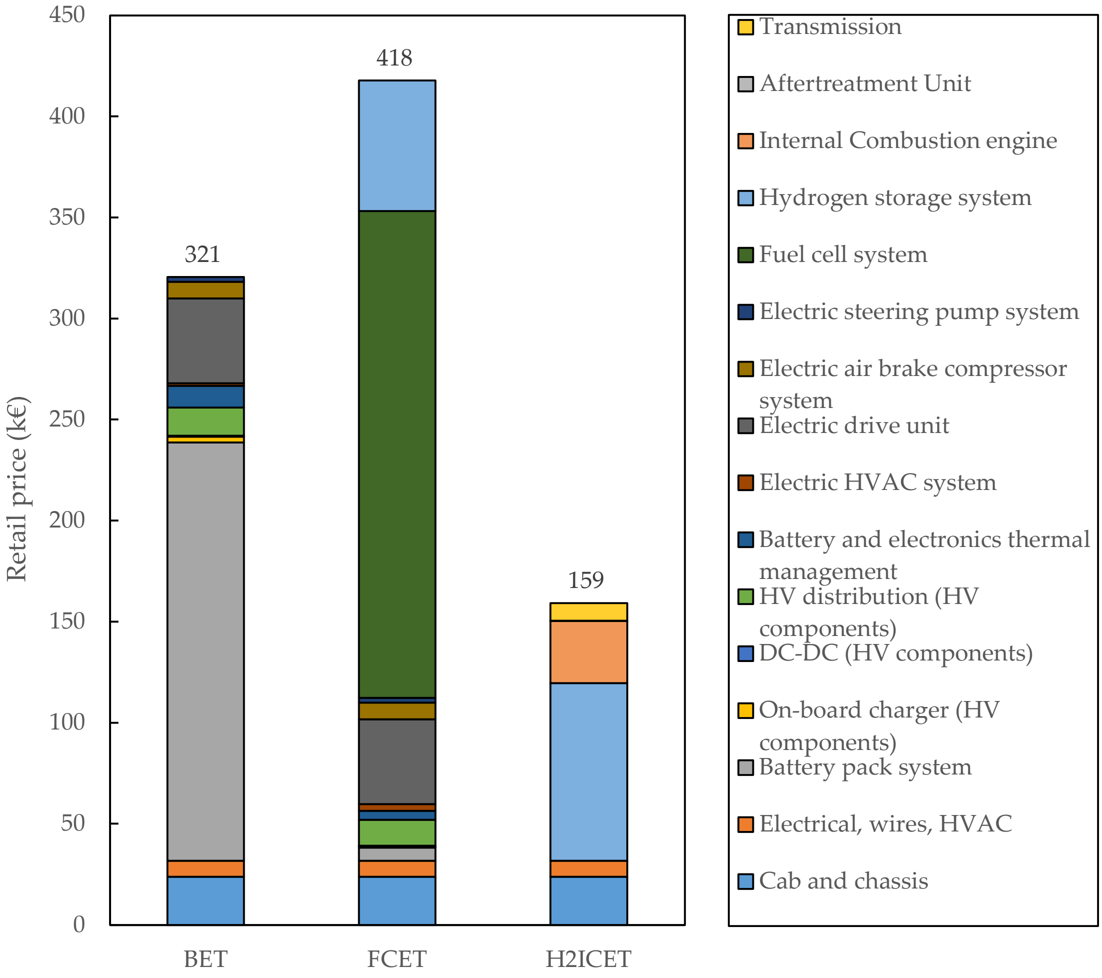


Figure 3.4 - *Retail price, case study LH1*

Concerning BET case, the most impacting component is clearly the battery system: this means that the final price of the vehicle will be strongly dependent on the required driving range; the other components of the powertrain, whose price is connected to the power, are drastically less impacting.

In the FCET, the fuel cell system is by far the most expensive component, and its price is determined on the basis of the power required to the powertrain, which varies according to the weight class; hydrogen storage system represents a non-negligible share of the total cost as well. In conclusion, the final cost of the FCET is mainly dependent on the rated power of the vehicle, with a lower dependency also on driving range.

H2ICET has his major cost component in the hydrogen storage system, since the engine, whose cost depends on the power, is relatively cheap; so, final cost is strongly connected to the driving range.

The vehicles are all assumed to be bought with a 5-year financing.
According to data provided by Suomen Pankki [118], loan interest rates have been assumed:

- 5% for loans below 250,000 €
- 4.5% for loans between 250,000 € and 1,000,000 €

These two percentages are slightly decreased compared to the data provided by the Pankki report, in order to consider a possible partial rebound of the rates toward values more similar to the previous years' ones.
These values are considered as APR, so no other taxes or costs are assumed for the financing of the vehicles.
Yearly payments of the loans in the different cases are here reported (evaluated on the purchase cost including VAT) (in €):

Case	BET	FCET	H2ICET
U1	44,590	66,732	36,297
U2	48,788	69,352	39,413
EU1	67,464	101,983	40,416
EU2	88,454	107,221	50,337
LH1	117,033	152,497	58,093
LH2	129,627	160,355	65,940

Table 3.4 - *Loan yearly payments (in €)*

Resale value of the vehicles is evaluated according to the provided equation (see Vehicle depreciation (2.1.3)), basing on the cumulated milage and the age of the vehicle in each case study.
Results are reported in table (in €):

Case	BET	FCET	H2ICET
U1	31,540	47,206	25,673
U2	30,872	43,886	24,938
EU1	43,351	65,536	25,968
EU2	41,318	50,086	23,511
LH1	61,687	80,381	30,617
LH2	90,783	112,305	46,176

Table 3.5 - *Resale values (in €)*

However, it is important to mention that the real impact of these incomes on the TCO is lower that it could appear, as it is affected by the discounted cash flow:

occurring in a "far" future, the discounted entering cash flow from the resale of the vehicle is drastically lower than its nominal value.

3.3.2 Fuel cost

In Model section (2.2.1) equations for evaluation of fuel economy of the vehicles depending on their weight class and use have been provided. Results are here reported (in kWh/km):

Case	BET	FCET	H2ICET
U	1.064	2.331	4.506
EU	1.387	2.888	3.587
LH	1.613	3.278	4.126

Table 3.6 - *Fuel economies, base case (in kWh/km)*

BETs have drastically lower fuel economy compared to the other two: the high efficiency of the battery allows to reach efficiency of the powertrain up to 90% for every load, giving really low consumptions.

FCETs have fuel consumptions that are about doubled compared to the BETs: this is because, even if the electric powertrain can reach extremely good efficiencies, the fuel cell is not as efficient as a battery, having average efficiencies in the order of 50-60%.

H2ICE technology is the worst one considering fuel efficiency, as it is based on combustion engine. Compared to the other two, the main difference is that, while fuel economies of FCET and BET depend only on the weight class of the vehicle, in the H2ICET case it has been assumed a variation depending on the type of route: this means that in case studies U1 and U2, even if they have the smallest vehicle, the fuel economy is higher than in the extra-urban and long-haul cases.

While in the case of H2ICETs the reported fuel economies have not been modified, in the case of electric powertrains the contribution of added energy need for cabin heating has been considered.

To do that, the monthly average temperatures in representative cities have been observed (reported in °C):

	Helsinki	Tampere	Oulu	Rovaniemi
Jan	-3.8	-5.7	-8.4	-12.2
Feb	-4.3	-6	-8.7	-12.1
Mar	-1	-2.3	-4.4	-7
Apr	4.5	3.8	1.7	-0.4
May	10.4	9.6	8	6.4
Jun	14.9	14.1	13.4	12.1
Jul	18	17.2	16.7	15.4
Aug	16.7	15.6	14.6	12.8
Sep	12	10.5	9.5	7.7
Oct	6.2	4.6	3.1	0.7
Nov	1.8	0.1	-1.9	-4.9
Dec	-1.3	-3.4	-5.7	-9.2

Table 3.7 – *Temperatures (in °C)*

Evaluating an annual average on the considered routes of the case studies, the average contribution of cabin heating to the fuel consumption is in the range of 0.03-0.04 kWh/km, depending on the cabin and the average speed. In fact, this effect impact for few percent on the final fuel economies, with effects much less dramatic than in the case of passenger cars described in Model section (2.2.1); in any case, evaluation of this effect can help making the model more precise and adapt it to Finnish context.
Final energy consumptions result in (reported in kWh/km):

Case	BET	FCET	H2ICET
U	1.103	2.370	4.506
EU	1.426	2.928	3.587
LH	1.652	3.317	4.126

Table 3.8 - *Fuel economy, final evaluation (in kWh/km)*

Once evaluated the fuel economies, it is possible to define the sizes of the energy storages, both batteries and hydrogen tanks.
First, a "worst case scenario" has been defined:

- For electric vehicles (FCET and BET) it corresponds to a travel with constant outside temperature of -30°C
- For H2ICET, it is defined as a route where a +10% increase on the average fuel economy is registered

Then, a "safety mileage" is assumed, in order to arrive to the destination (or to the refueling station) with the possibility of travelling some km more in case it was necessary. Safety mileages are assumed:

- 100 km for BET
- 200 km for hydrogen-fueled trucks

The needed driving range is assumed equal to the daily mileage in the cases U and EU, while for LH cases an intraday recharging is assumed, as summarized in following table (for BET the recharging time is indicated, while for FCET and H2ICET it has been provided the number of intraday refueling):

Case	BET	FCET	H2ICET
U1	No	No	No
U2	No	No	No
EU1	No	No	No
EU2	No	No	No
LH1	45 min	1	1
LH2	1.5 h	1	1

Table 3.9 - *Rechargings and refuelings*

The intraday recharges are assumed in order to limit the size of the battery: without recharges, the LH2 case would need a battery of about 1600 kWh, but this, beside causing really high purchase costs of the vehicle, is far from the current availability on the market (vehicle with bigger battery is today the Tesla Semi, 900 kWh).

In the LH1 case, 45 min recharging is sufficient to limit the battery to 900 kWh, and this does not represent an additional time for the travel, as drivers in Europe are obliged to take a 45 min break every 4.5 h of driving.

In the LH2 case, a 1.5 h break is assumed: with this recharge time, battery can be assumed 1050 kWh, that is not far from the current availability on the market. It must be pointed out that this break represents a “loss of time” in the daily activity, meaning that the BET would arrive at its destination with delay compared to the FCET and H2ICET. To economically quantify this delay, it has been considered the additional expense for the driver wage, and it has to be remembered that the price of electricity at fast charging spots is higher than the cost during overnight recharges.

In both cases, the intraday recharges of the batteries are assumed at 350 kW.

Resulting energy storages are:

Case	BET	FCET	H2ICET
U1	250 kWh	20 kg	40 kg
U2	300 kWh	25 kg	50 kg
EU1	450 kWh	35 kg	45 kg
EU2	700 kWh	45 kg	60 kg
LH1	900 kWh	45 kg	60 kg
LH2	1050 kWh	60 kg	75 kg

Table 3.10 - *Energy storages*

Assumed electricity and hydrogen costs are respectively 0.10 €/kWh and 5 €/kg for overnight recharges, while fast intraday recharge is assumed to cost 0.35 €/kWh (no difference is assumed for hydrogen cost). In any case, considering the high margin of error on forecasts in this field, a sensitivity analysis will be provided.

Levelized fuel costs of U2 and LH1 (chosen as representative cases) are:

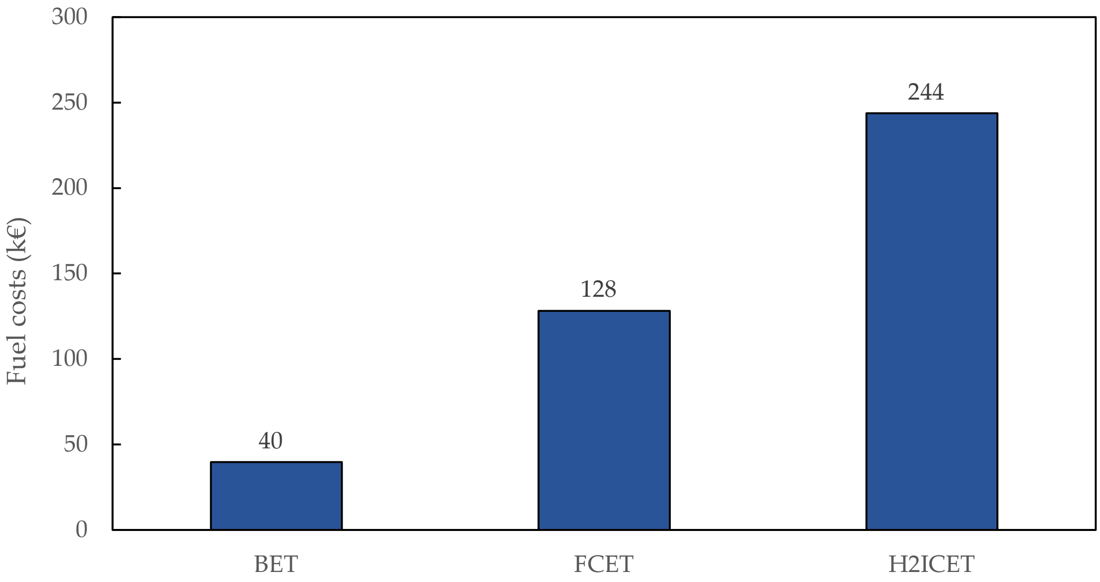


Figure 3.5 - *Fuel costs, case study U2*

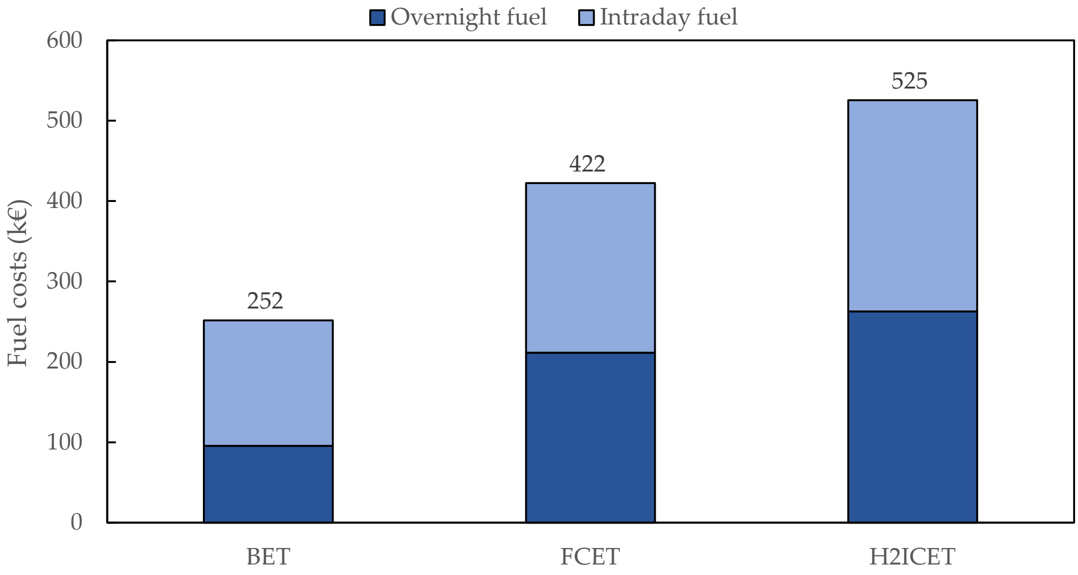


Figure 3.6 - *Fuel costs, case study LH1*

In both cases, BET has drastically lower costs for fuel, due to the higher efficiency and to the lower cost of electricity compared to hydrogen (on a $€/kWh$ basis). It is remarkable that, in LH1 case, even if the intraday recharges provide about 30% of the yearly energy need, they represent more than 60% in terms of cost, due to the higher price of electricity in fast charging spots.

In the urban case, FCET and H2ICET cases observe big difference between their costs, while in long-haul application this difference become less marked: this is due to the different efficiency of H2ICET, that has high fuel economy in urban conditions, while it decreases on extra-urban routes. In LH1 case, the division between intraday and overnight H2 refueling is reported for completeness, but price of hydrogen is assumed the same in both cases.

3.3.3 Insurance costs

Insurance annual premium is assumed to be equal to 5% of the residual value of each truck in the considered year, evaluating both the age and the cumulated mileage, as defined in Equation 7. This percentage is assumed not influenced by the powertrain technologies, since all the three can be described as “innovative” in the same way.

Being based on the purchase cost, insurance costs affect more strongly the BETs and FCETs, while they are lower in H2ICETs, having lower retail prices.

3.3.4 Maintenance and Repair costs

Cost per km of maintenance and repair is assumed linearly varying with the weight class of the vehicles.
Resulting costs are (reported in €/km):

Case	**BET**	**FCET**	**H2ICET**
U	0.065	0.077	0.118
EU	0.101	0.105	0.158
LH	0.152	0.145	0.214

Table 3.11 - *Maintenance costs (in €/km)*

Advantage of electric powertrains compared to combustion engines is clear: while FCEVs and BEVs have similar costs, H2ICETs is between +30% and +100%, arriving to costs similar to traditional diesel ones.

On the opposite, electric powertrains have not negligible midlife costs, which consist in battery or fuel cell replacements.
Battery lifetime is assumed to be 500,000 km or 10 years (in case 500,000 km are not reached before). Substitution of the battery represents a very impacting cost, as the cost of the battery itself represent a large share of the purchase price of the entire vehicle, and the resale of the used battery (15% of initial value) represents just a low income; moreover, in the case of longer routes applications (EU2, LH1 and LH2), two substitutions are needed due to the high yearly mileage. An additional reason for the reduced lifetime of batteries in LH1 and LH2 scenario is the presence of the intraday fast charging, unfortunately responsible for a faster degradation.
Concerning fuel cells, their lifetime is evaluated 15,000 h of activity, which means that in most of the case studies just one substitution is necessary (only LH1 needs two substitutions); compared to BEVs, impact of midlife costs is reduced, as the cell substitution only represent about 33% of the cost of the FC system, and residual value is evaluated 25% of its initial cost.
In case of H2ICETs, no midlife costs are assumed in major scenarios, but some additional considerations will be reported in Results section.

Midlife and maintenance costs are here represented for two cases:

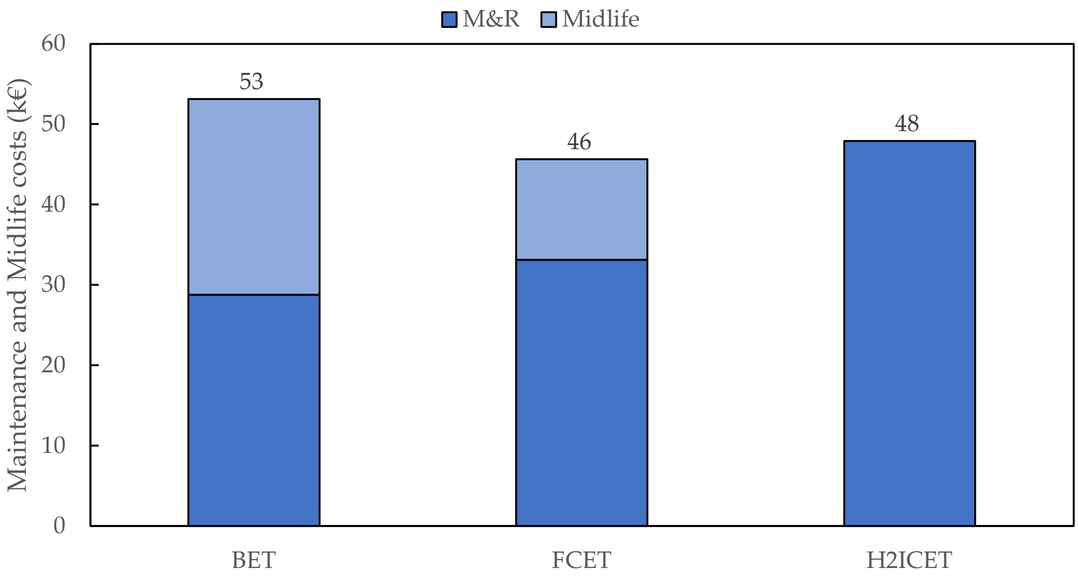


Figure 3.7 - *M&R and Midlife costs, case study U2*

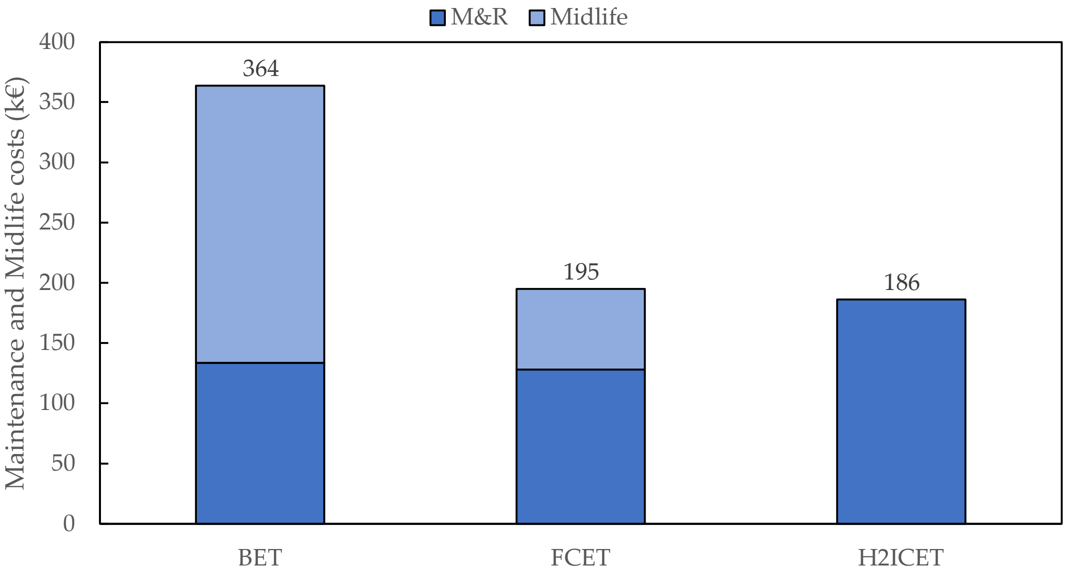


Figure 3.8 - *M&R and Midlife costs, case study LH1*

From these plots it is clear that, on short mileages, the three solutions are roughly equivalent, as the lower maintenance costs of BEVs are compensated by higher midlife costs.

On long mileages, the battery replacements become extremely impacting, making BEV solution the most expensive one for which concerns maintenance and replacements.

According to Table 2.10, costs for yearly inspection are assumed between 550 and 625 €/year, depending on the case study.

3.3.5 Taxes and Fees

Beside 24% of VAT, taxes paid at the purchase of the vehicle are limited in Finland, and they have been evaluated in 30 €.

Annual taxes for the considered vehicles, according to Traficom.fi [99], results to be:

	cent/day/100kg	€/year
U	1.3	547.50
EU	1.0	1533.00
LH	1.2	3328.80

Table 3.12 - *Annual fees*

3.3.6 Road tolls

As reported in Model section (2.6), toll roads or bridges are not present in Finland, so this cost component null for all the considered vehicles.

3.3.7 Other costs

Assumed weight of energy storages, and consequent reductions of payloads, are (in kg):

Case	BET	FCET	H2ICET
U1	1750	476	952
U2	2100	595	1190
EU1	3150	833	1071
EU2	4900	1071	1428
LH1	6300	1071	1428
LH2	7350	1429	1786

Table 3.13 - *Weight of energy storages (in kg)*

It is observable that, while hydrogen storages are relatively light (or at least their weight is comparable to diesel tanks), weight of the batteries can have a non-

negligible impact on the payload, reducing the amount of freight that can be transported.
Corresponding volumes are reported in table (in m^3):

Case	**BET**	**FCET**	**H2ICET**
U1	0.588	0.800	1.600
U2	0.706	1.000	2.000
EU1	1.059	1.400	1.800
EU2	1.647	1.800	2.400
LH1	2.118	1.800	2.399
LH2	2.471	2.400	3.000

Table 3.14 - *Volumes of energy storages (in m^3)*

In the case of the BET, the battery is relatively easy to "shape", giving the possibility of place it in the lower part of the tractor, between the two axles, with minimum impact on the payload (in terms of volume).
On the other hand, hydrogen tanks are generally placed behind the cabin: H. Basma and F. Rodriguez [119] describes that, in this position, for a 2.01 m^3 storage, a length of 0.9 m would be needed. Considering that the length limit for a trailer truck and a road train in Finland are respectively 18 and 34.50 m, the impact of this loss is extremely low (in the worst cases, about 5% of the total load capacity); in addition to that, due to the limitations on weight, it is rare that a truck reaches the limit on volume basis. For these reasons, it has been chosen not to report a volume analysis in the assumed scenarios, since the results would be roughly equal to the ones obtained on the TCO analysis.

Drivers' cost has been evaluated only considering the additional time spent for the intraday recharge of the truck in LH cases; in all the other cases, no differences in time are assumed between the different trucks of each case study, so the drivers' cost has been ignored, since it does not represent a discriminant in the comparison.
In LH1 case, just additional 15 min are assumed each day, resulting in 82.5 h per year (15 min is the time assumed for the operations at the beginning and end of the recharge): assuming a cost of 22.50 €/h, the discounted cash flow due to the drivers' wage on the entire lifetime (12 years) is 14,744 €.
In LH2 case, the additional time spent for recharging has been evaluated in 330 h per year, costing 44,337 € on the entire lifetime (8 years).
Once again, it is worth remembering that the BET of LH2 case reaches the destination with 45 min delay on the other trucks: this time, evaluated only considering the driver's pay, could also cause economic losses due to

interruption of a supply chain for example, but this effect could not be evaluated in this study, as it can change depending on the case.

3.3.8 Discount rate

Basing on reviewed literature, the discount rate for this analysis in the major scenario is assumed to be 7%.
This choice has been taken considering A. Burnham *et al.* [41] explanation about the need of a premium above the bond interest rate (as described in the Discount rate section (2.8)). Furthermore, the 5% value proposed by that report has been increased in this study due to the fact that this analysis is dealing with alternative powertrain technologies, which gives a higher degree of uncertainty on future cash flows.
In any case, a sensitivity analysis will be described in the Results section (4.3.6), to observe which impact the discount rate has on the final results.

4. Results

In this section, the results (TCO, in €, and LCOT, in $cent€/km/t$) obtained from case studies will be presented.
Moreover, to provide a more extensive analysis, some additional studies will be provided, both considering additional scenarios or sensitivity analysis on the base case studies.

4.1 Major scenario

Resulting TCOs and LCOTs, calculated according to the parameters described above, are here reported.

Urban cases:

Results of U1 are reported in Figure 4.1 and Figure 4.2:

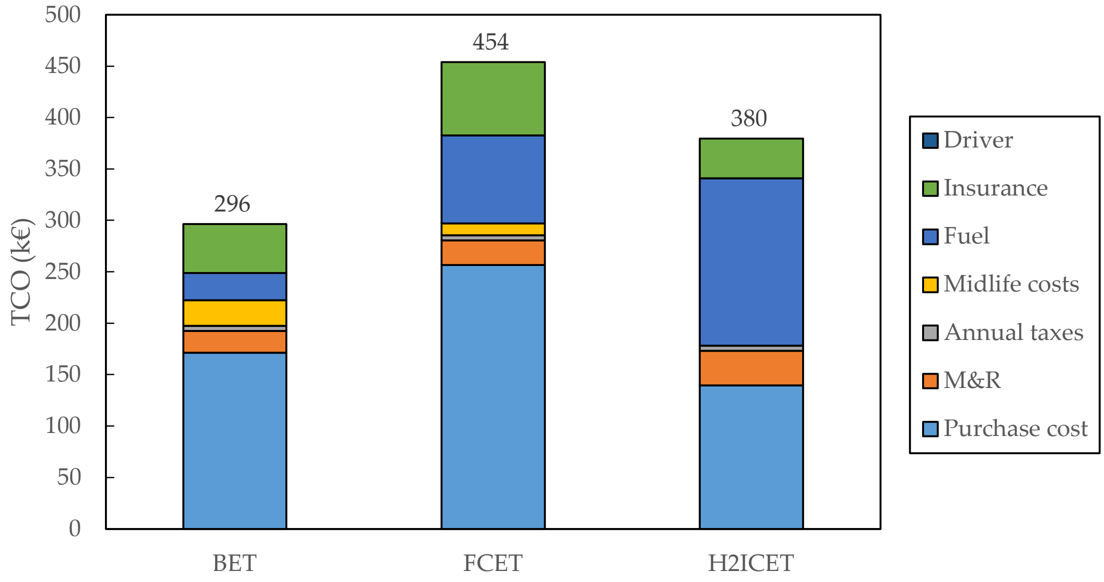


Figure 4.1 - *TCO, case study U1*

In the TCO evaluation, BET is the most convenient solution: compared to FCET, it has lower costs in all the categories excluding the midlife substitutions, that in any case are relatively low also in the case of the BET, due to the small size of the battery. Compared to H2ICET, it has slightly higher purchase costs, but the major discriminant is the cost for the fuel, that is drastically lower in the case of the electric vehicle, due to the higher efficiency (it is useful to remember that the H2ICET in urban mode has particularly bad fuel economy).

Due to the low mileage and high efficiency, purchase costs represent the higher cost component for the electric vehicles, while the engine solution has high fuel costs.

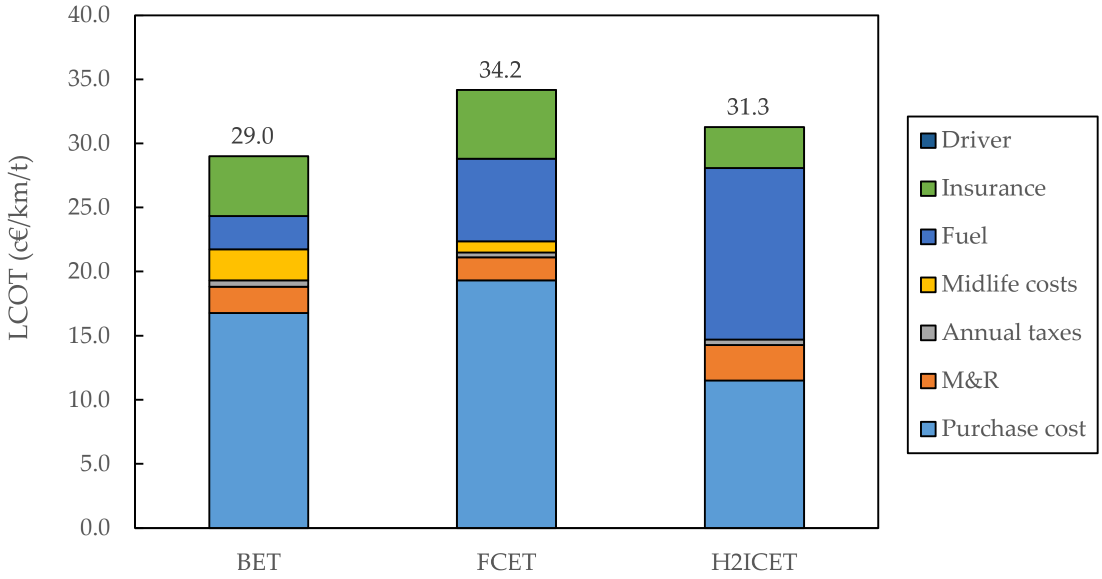


Figure 4.2 - *LCOT, case study U1*

Looking at the LCOT, results are still favorable to BET, but the differences are reduced, due to the loss of payload caused by the weight of the battery pack, that reduces the denominator.

In general, it can be stated that in situations where the payload cannot reach the 100% for causes connected to the freight itself, BET represents by far the best solution; on the other hand, if the maximum payload can be reached (for example the transported freight is composed by many small items), the three alternatives are quite comparable.

U2 case takes to similar conclusions, as observable in Figure 4.3 and Figure 4.4:

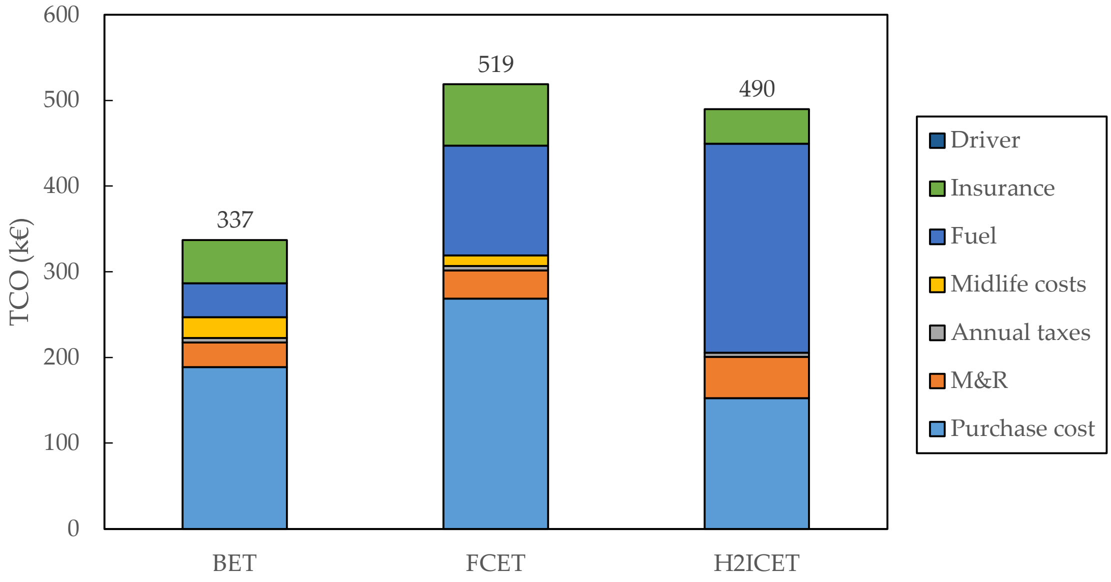


Figure 4.3 - *TCO, case study U2*

The result is similar to U1 case study, with BET resulting best solution. In this case, the higher daily mileage causes increased costs for fuel but also to the purchase costs, since the energy storages have larger sizes.

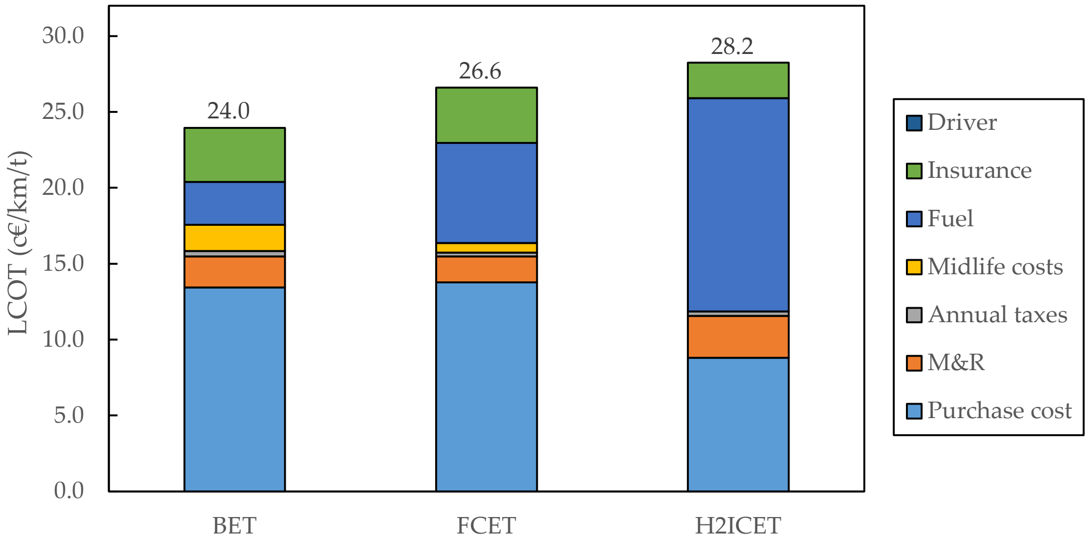


Figure 4.4 - *LCOT, case study U2*

Differently from case U1, FCET becomes more convenient than H2ICET, due to the smallest size of the hydrogen tank, that allows to carry a higher payload.

In any case, best solution remains BET thanks to the low fuel economy and maintenance costs.

Extra-urban cases:

Figure 4.5 and Figure 4.6 summarize the results on EU1 case (160 km):

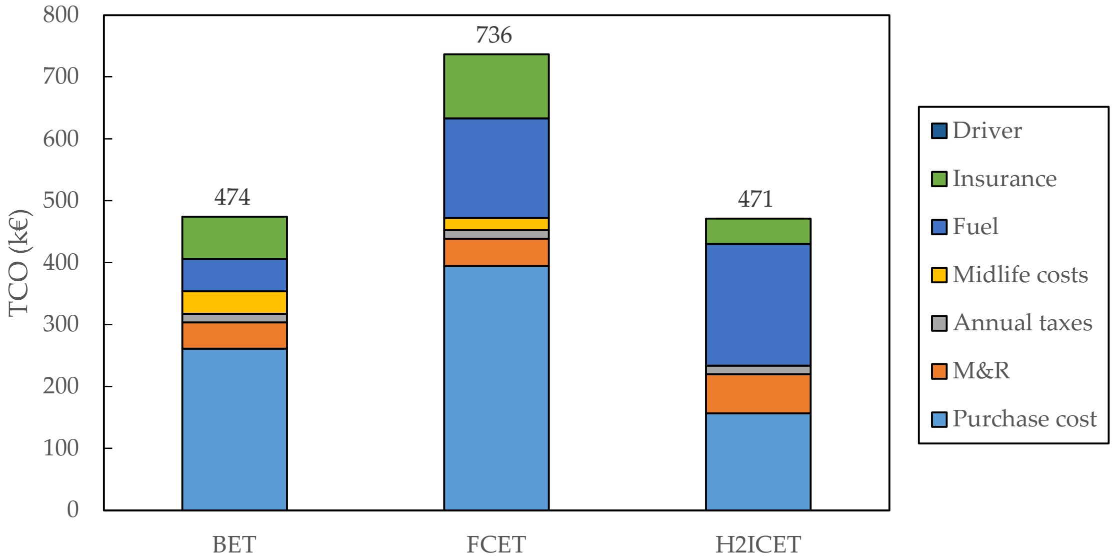


Figure 4.5 - *TCO, case study EU1*

In this case, H2ICET becomes comparable to BET, since the higher fuel costs are compensated by the lower purchase price and the null midlife maintenance.
The FCET has TCO significantly higher, due to both high purchase costs (that are projected also on insurance costs) and fuel required (compared to the BET). This is due to the increased power of the vehicle (340 kW), that causes high costs for the fuel cell, and a relatively low travelled mileage, which does not valorize the better fuel efficiency of FC compared to the combustion engine and the lower costs of hydrogen tank compared to a large battery.

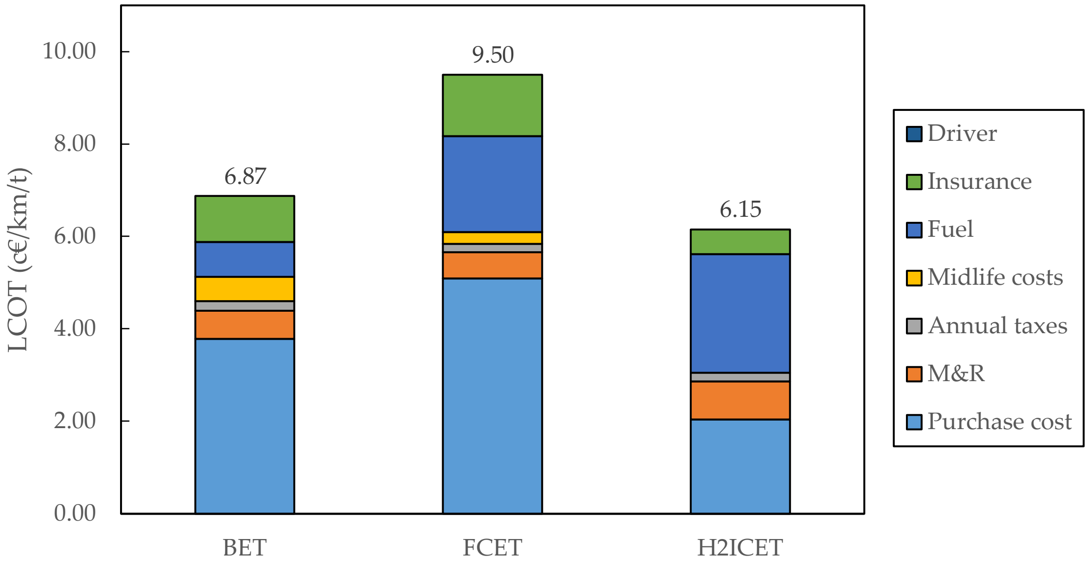


Figure 4.6 - *LCOT, case study EU1*

Considering the LCOT, the H2ICET becomes more convenient than the BET, since the large battery required for a 160-km daily mileage has a double disadvantage for the BET:

- It increases the purchase costs, since battery pack represents the largest share of the total price of the vehicle
- It causes loss of payload, due to the high weight (about 3 t, versus 1 t of the hydrogen tank in the H2ICET)

EU2 case is reported in Figure 4.7 and Figure 4.8:

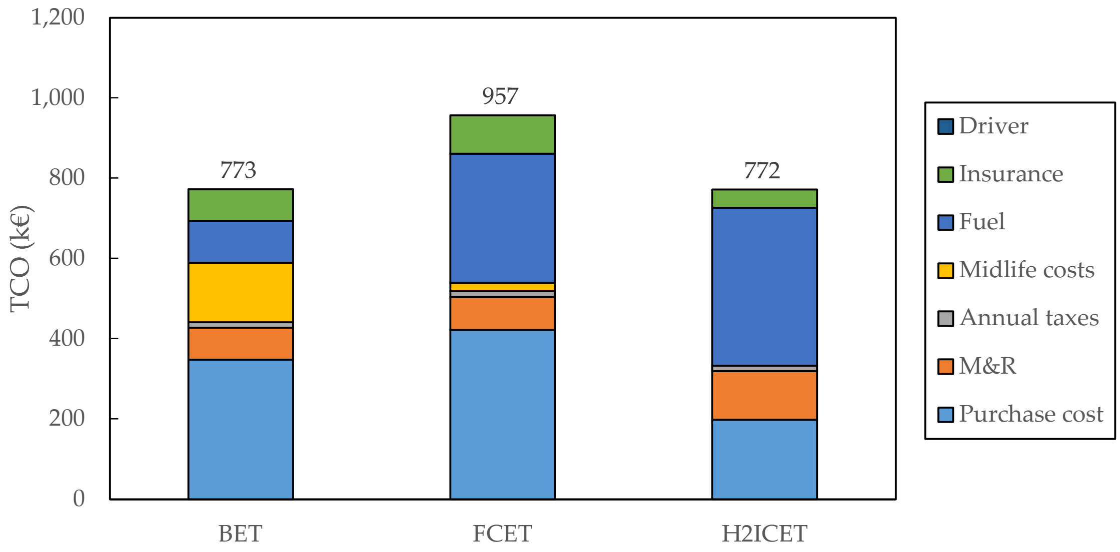


Figure 4.7 - *TCO, case study EU2*

Increasing the daily mileage, the FCEV becomes more competitive with the other two:

- The larger energy storage is not so impacting as it is for the BEV, for which the battery becomes notably more expensive
- The higher efficiency of the electric powertrain compared to the ICE is not negligible on these high mileages

Nevertheless, the FCET still remains the most expensive solution, while the other two have similar TCOs.

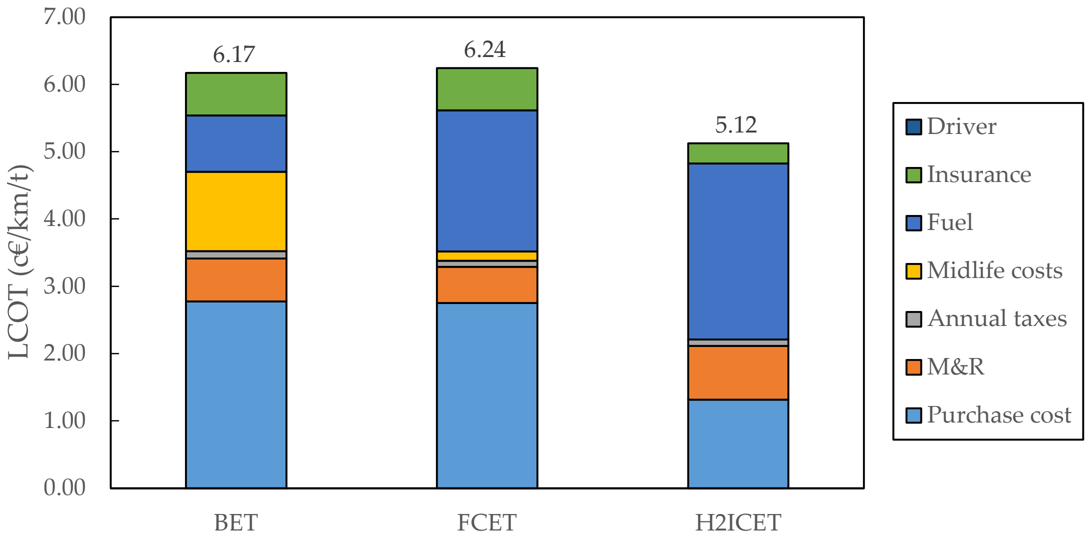


Figure 4.8 - *LCOT, case study EU2*

In the LCOT, the advantage of low purchase costs of H2ICET become evident, and it results to be the most convenient solution.
The other two vehicles are roughly comparable: the difference in the TCOs is canceled by the loss of payload due to the large battery, giving costs per $km \cdot t$ almost equal.

Long-haul cases:

Figure 4.9 and Figure 4.10 report the results for LH1 case:

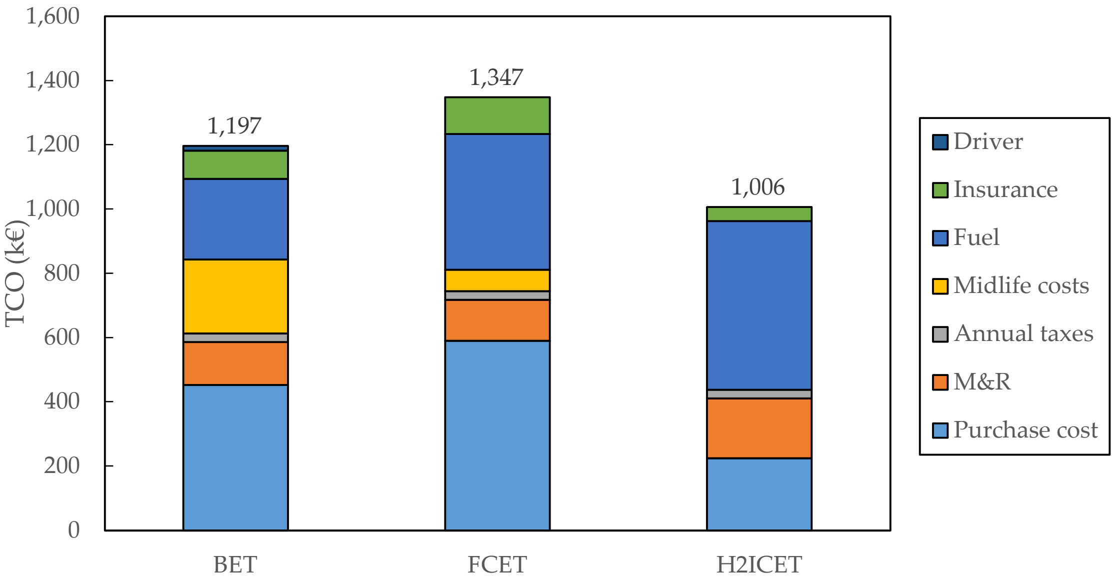


Figure 4.9 - *TCO, case study LH1*

As in previous case, the low purchase cost is the major cause for the convenience of the H2ICET, overcoming the disadvantage given by the high fuel costs.
The midlife costs become heavily impacting for the BET, since the battery has large size due to the needed driving range (250 km plus the “safety range”). The FCET remains the most expensive solutions, due to the high power required by the fuel cells (560 kW), that make purchase costs levitate.

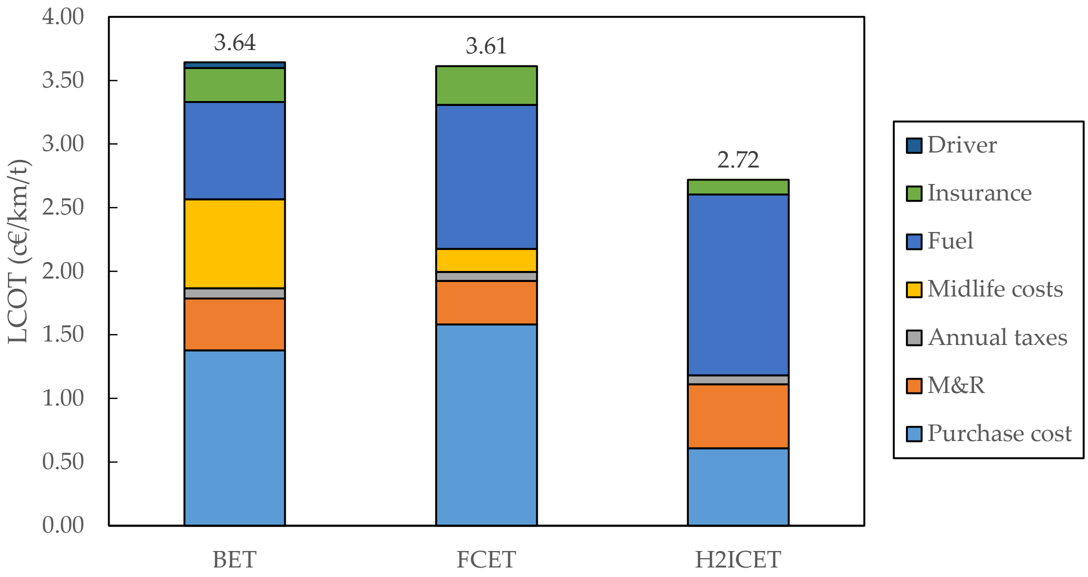


Figure 4.10 - *LCOT, case study LH1*

As in EU cases, the H2ICET is the most convenient option.
As for EU2 case, BET and FCET are substantially equal basing on the LCOT: midlife costs of the BET are compensated by the higher fuel costs of FCET.
Regarding energy costs, it is interesting to notice the division of costs between intraday and overnight recharging (0.10 and 0.35 €/kWh respectively):

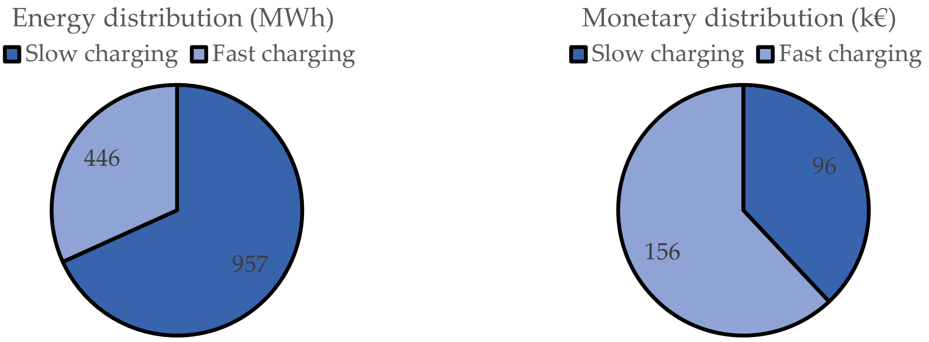


Figure 4.11 - *Slow and fast charging distribution (LH1)*

Even if in energy terms the intraday recharges represent about 30% of the yearly energy needs, due to the higher cost of electricity at fast chargers they correspond to more than 60% of the annual energy costs for the BET.

As observable in Figure 4.12 and Figure 4.13, LH2 case is similar:

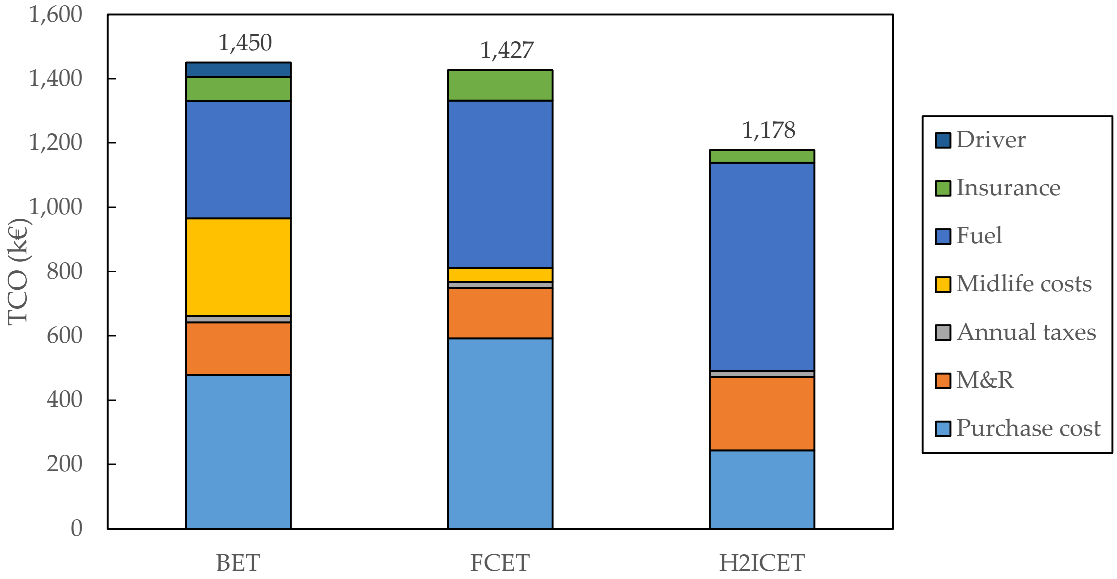


Figure 4.12 - *TCO, case study LH2*

With large weight class and high mileages, the midlife costs of the BET become very important, corresponding to more than 60% of the purchase costs of the vehicle (two substitution in 8 years of lifetime are assumed).
For the FCET, midlife costs are quite low, but the lower fuel economy compared to the BET and the high purchase costs make it almost equal to BET.
H2ICET is the cheapest one, and its TCO is largely due to fuel costs, but also maintenance component is not negligible, because of the high mileage.

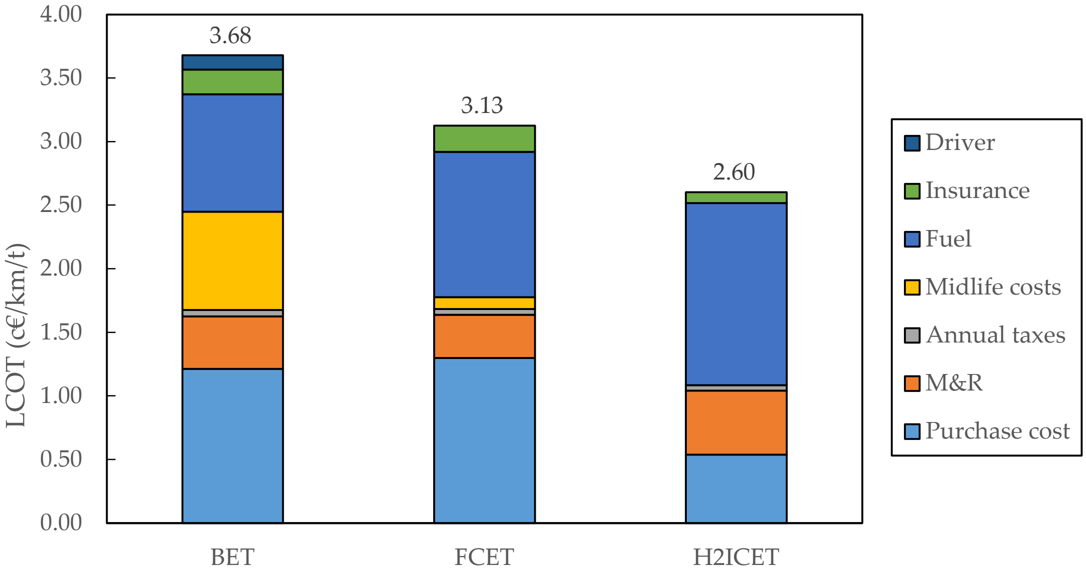


Figure 4.13 - *LCOT, case study LH2*

It is worth mentioning that, while for urban cases the LCOT was in the order of 25-30 $cent€/km/t$, in the long-haul options results are about one tenth, because of the high mileage travelled and the payload carried during the lifetime, that make the cost per unit of travel relatively low.
H2ICET results to be the cheapest solution for very long-haul applications, while BET is the most expensive. In this case, energy costs of the BET are still the lowest among the three solutions, but they are not so far from the FCET ones: this is because an important share of the electricity is provided by the fast chargers during intraday breaks, that are more expensive than hydrogen in terms of $€/kWh$.
Considering the distribution of energy price for the BET:

Figure 4.14 - *Slow and fast charging distribution (LH2)*

In LH2 case, the intraday recharges become more important even in energy terms, as the charging time is assumed to be 1.5 h to reach the needed daily mileage with a feasible battery. In monetary terms, the fast charging ends up representing almost the 75% of the total annual energy cost.

Looking at the plots in this section, a possible conclusion could be that, in the considered scenario of components cost, M&R, fuel prices etc… in general, BEVs are the most suitable solution for short routes and low weight classes, while H2ICEVs are more suggested for long-haul applications; FCETs appear to be a viable option, but they are not the best option for either long-haul applications or urban routes.
Unfortunately, this conclusion is far from being exhaustive, since many other factors could intervene: for example, if the payload reduction due to the battery is not considered a problem (in a case where the truck would not travel in any case in full-load conditions), BETs are the best solution in most of the cases, also considering medium mileages applications, since the TCO is lower. On the other

hand, if the additional time needed for the intraday recharge represents an issue for logistic reasons, a BET is not a viable option for long distances.

4.2 Additional cases

Some additional cases, with different assumptions than the ones used in the previous case studies, will be presented in this section, in order to give the possibility of appreciating the difference in results with just one parameter change.

Case LH2 without intraday recharging/refueling:

In this case, energy storage must be increased, to be able to last for the entire day; this means the battery must be at least 1600 kWh, while the FCET and H2ICET hydrogen tank must be filled with 95 and 125 kg respectively (it must be remembered that at present day, 900 kWh is the largest size for a vehicle battery on the market). It is necessary to mention that this is mostly a theoretical case, because on a real truck a battery of this size would probably be impossible to place, due to the weight distribution on the tractor and not only to the reduction of the payload. Anyway, results are reported in Figure 4.15 and Figure 4.16:

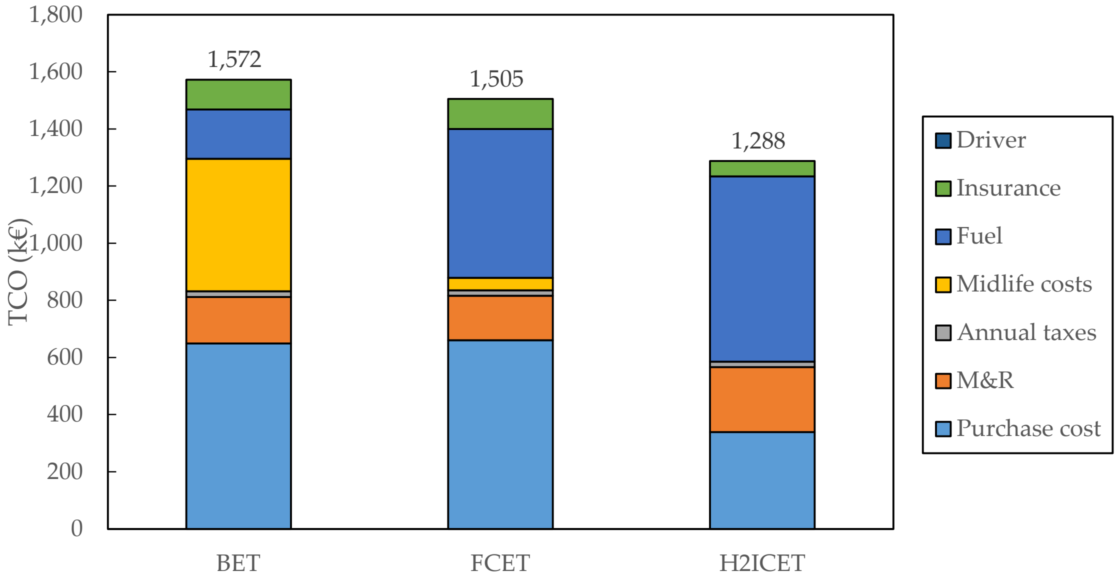


Figure 4.15 - *TCO, case study LH2 without recharging*

The large size of the battery does not only impact on the purchase costs, but it means very high midlife costs, due to the two replacements needed during the lifetime and the high price of the battery (about 370,000 €). On the other hand, the larger hydrogen storages have a cost (136,000 and 180,000 €), but it is not so impacting on the final price and, even more important, does not reflect on midlife costs.

The result is that TCO of the BET is the highest of the three.

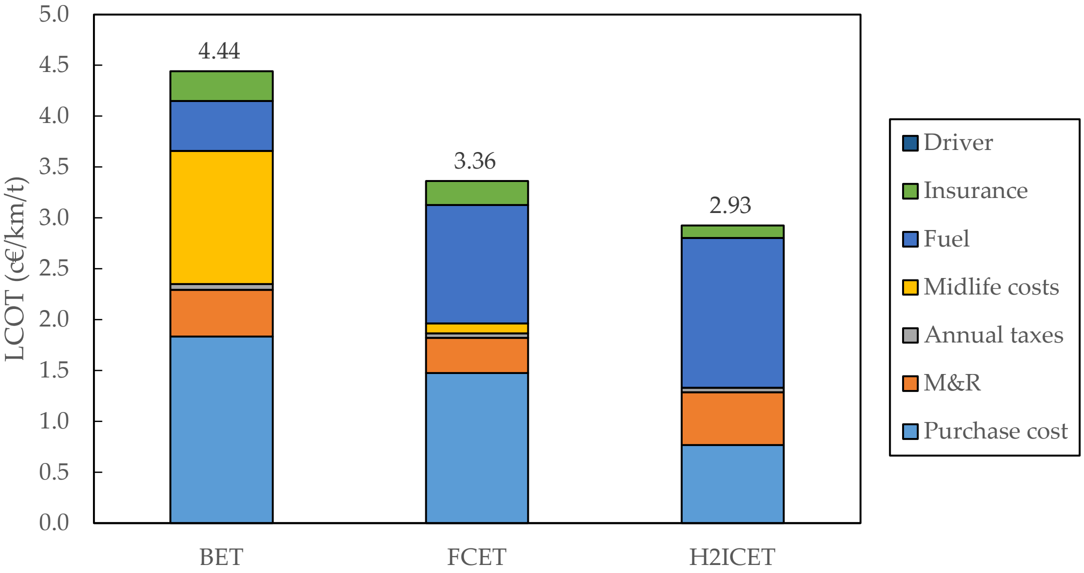


Figure 4.16 - *LCOT, case study LH2 without recharging*

The large size of the battery also means the loss of payload (more than 11 t), resulting in higher LCOT.

Case LH1 with a small truck:

In this case, the route conditions are the same as in LH1 (500 km/day, 10% yearly decrease, 12 years of operation), but the considered truck is the 18-t rigid (average payload is assumed 11 t).

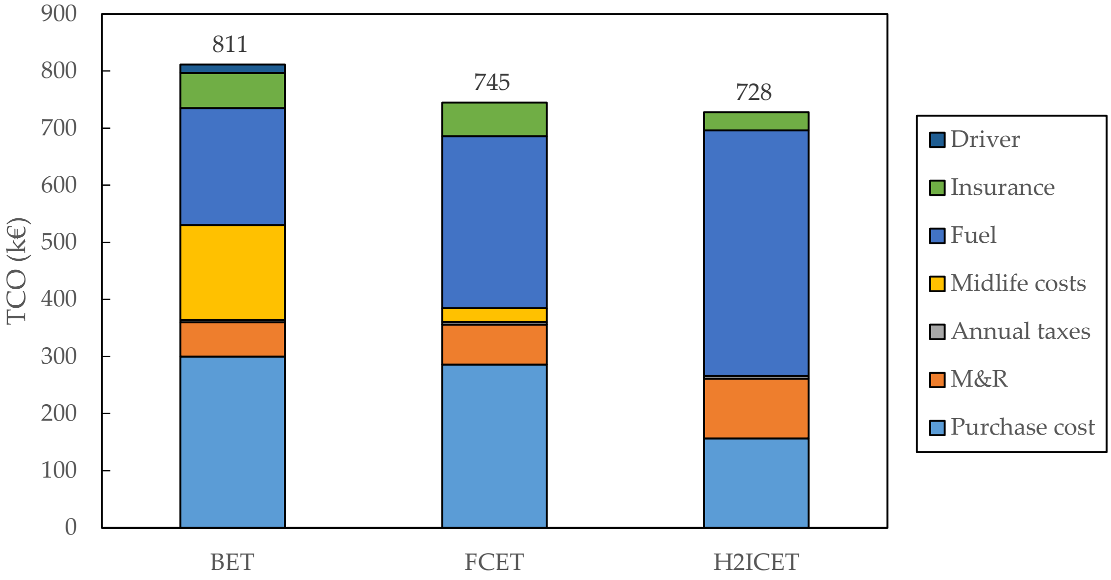


Figure 4.17 - *TCO, case study LH1 with 18t truck*

In this case, the TCOs are similar for the three technologies: the purchase and midlife costs of the BEV are high, due to the large battery needed for the high mileage, but at the same time the high efficiency allows to have low fuel costs; FCET has relatively low purchase costs, since the fuel cell stack is small due to the small powertrain needed by the vehicle, but the difference between BET and

FCET fuel efficiency is evident with this high mileage; ICET has very low purchase costs, but its fuel costs are quite high.

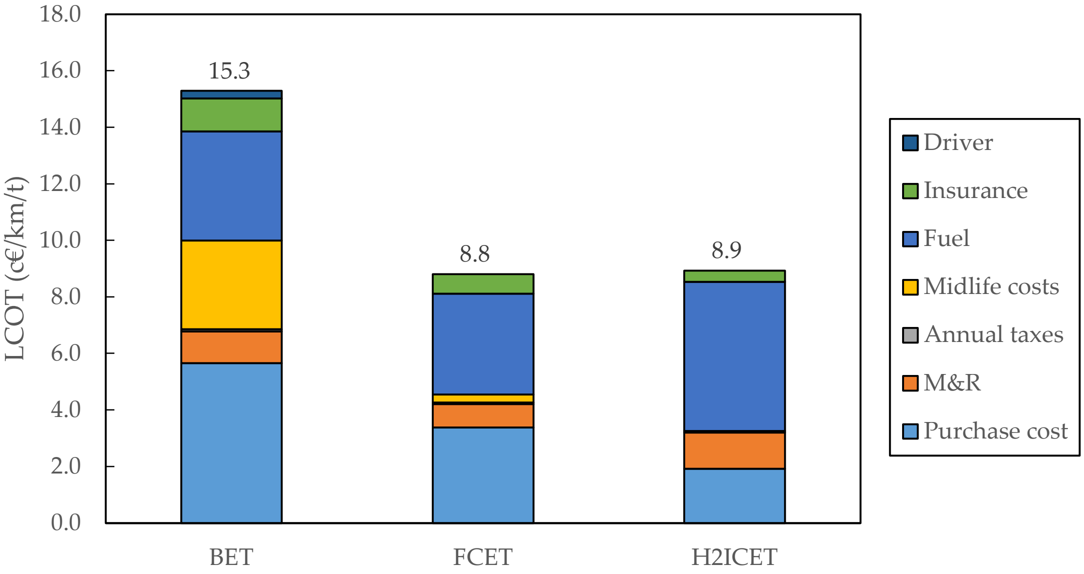


Figure 4.18 - *LCOT, case study LH1 with 18t truck*

The low weight of hydrogen storages compared to batteries makes the hydrogen trucks the best solutions for this combination of truck and duty-cycle. Indeed, the weight of the battery pack reaches 4.5 t, that is dramatic for a vehicle with a maximum payload of 12 t, and best solution for low-weight and high-mileage combinations is achieved by the FCET.

Case EU2 with reduced fuel cell cost:

In Model section (2.1.1) it was stated that the estimation of the FC price is particularly difficult, since market is still at early stages and there is not a well-defined unit cost.

Moreover, it's important to bear in mind that prices will likely go down in the coming years, thanks to standardization of production processes and proliferation of manufacturers.

In this case study, EU2 case is analyzed, maintaining the same parameters as in the original case study, except for fuel cell price: in this model, unit cost of 150 €/kW is assumed (notice that, besides being a possible price in the future, it is not even the lowest provided by current literature referring to today prices (see Table 2.3)). TCO and LCOT are represented in Figure 4.19 and Figure 4.20:

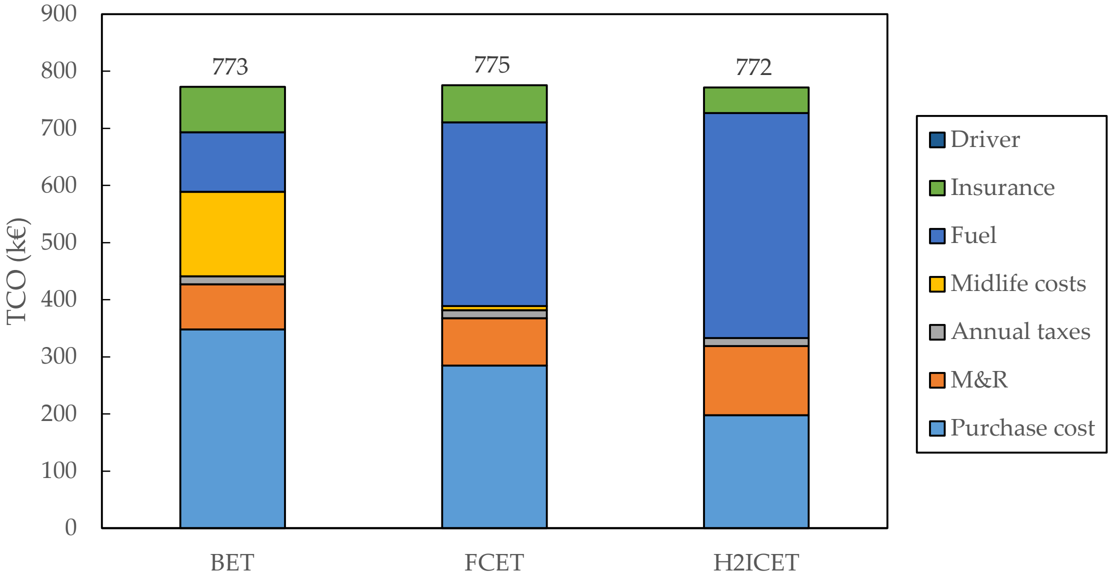


Figure 4.19 - *TCO, case study EU2 reducing FC cost*

With this FC cost, the purchase cost of FCET is lower than the BEV, arriving to parity of TCOs between the three.

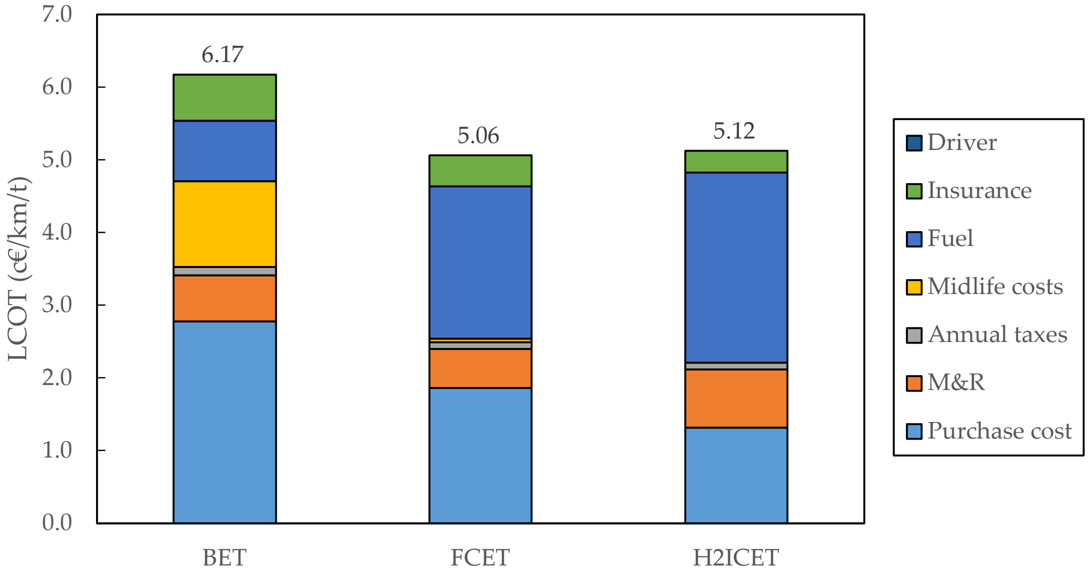


Figure 4.20 - *LCOT, case study EU2 reducing FC cost*

Starting from a substantial parity of TCOs, the best solution from LCOT point of view is achieved through FCET, due to the reduced weight of its storage compared to the other two.

Case LH1 with reduced lifetime of the H2ICE:

As declared in previous sections, data about the maintenance and durability of H2ICEs are still extremely limited. In general, the lifetime of the engine has been assumed equal to a standard diesel or CH4 engine, but in this additional scenario the possibility of a reduced useful life of the engine is evaluated.
In the plot, the LH1 case is reported, assuming the possibility of a complete substitution of the engine after 6 years of use (corresponding to about 15,000 h and 750,000 km), while FCET and BET are maintained the same as in the base case:

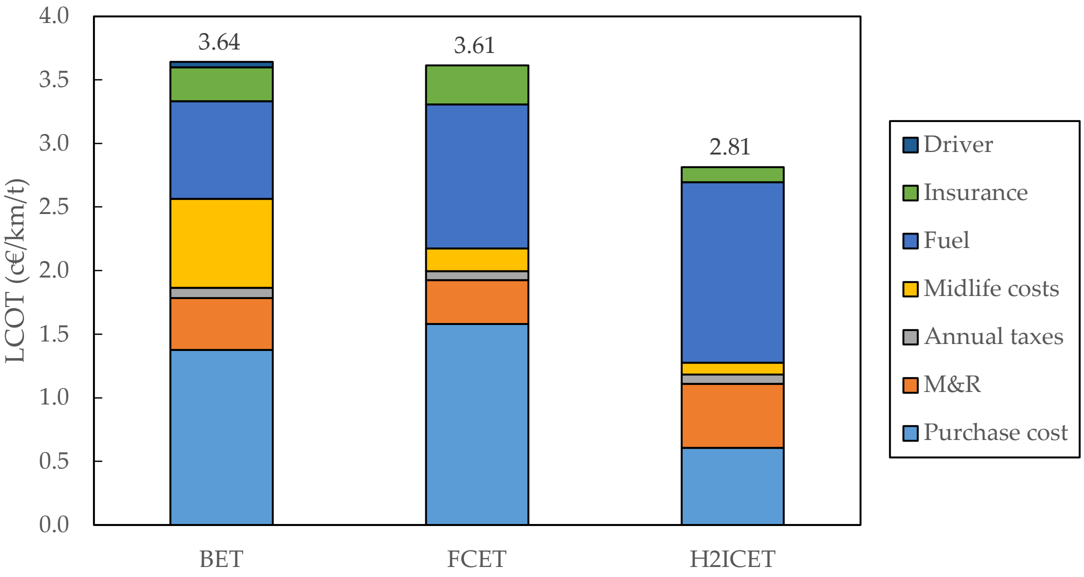


Figure 4.21 - *LCOT, case study LH1 assuming engine rebuild*

The engine substitution is reported as "midlife cost" of the H2ICET: even assuming a complete engine replacement, it is clear that the TCO is not strongly impacted, and this assumption does not change the results of the comparison. This is because the engine is relatively cheap (about 51,000 €) so its weight on the TCO is not so remarked.

4.3 Sensitivity analysis

Considering that price of electricity and hydrogen cannot be precisely defined for future scenarios, a sensitivity analysis on "energy" prices has been judged necessary for the representation of the TCO results.
Other variables are analyzed, as useful life, in order to find best combination for minimizing TCOs and LCOTs and define which are the most impacting ones.

4.3.1 Variable price of electricity

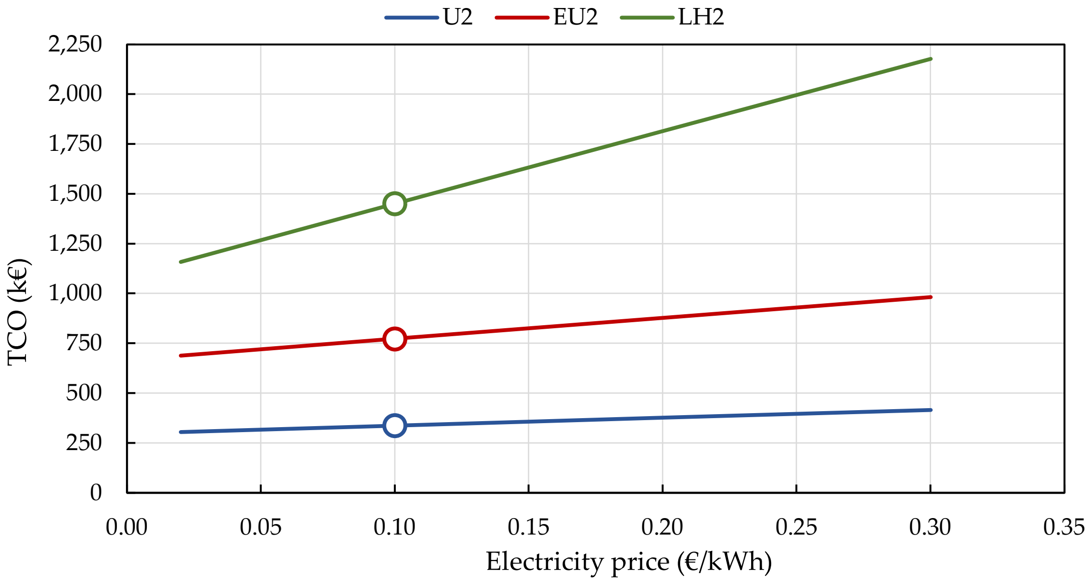


Figure 4.22 - *BET TCOs and electricity prices.*

In Figure 4.22 TCOs for BETs in three cases (U2, EU2 and LH2) are represented, with electricity prices varying between 0.02 and 0.30 €/kWh (fast chargers' electricity price is varied proportionally).
This simplified approach assumes that electricity prices solely impact fuel costs, resulting in a purely linear dependency of TCO; however, in reality, an increase in electricity prices would likely affect other components too, as the purchase cost.
As expected, electricity prices have the most significant impact on cases where the share of fuel costs is higher, typically associated with higher daily mileages.

4.3.2 Variable price of hydrogen

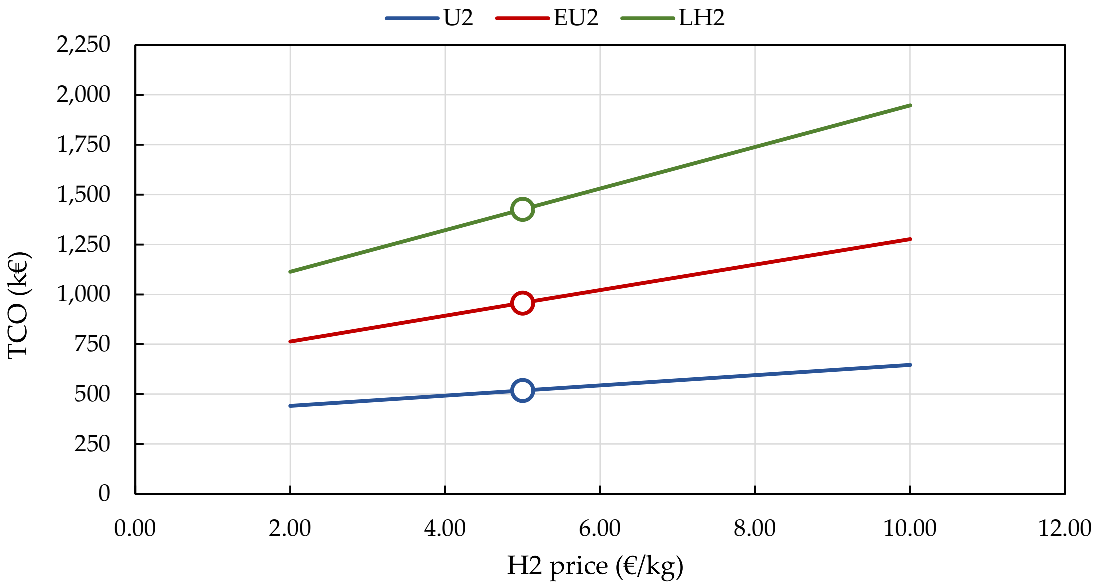


Figure 4.23 - *FCET TCOs and hydrogen prices*

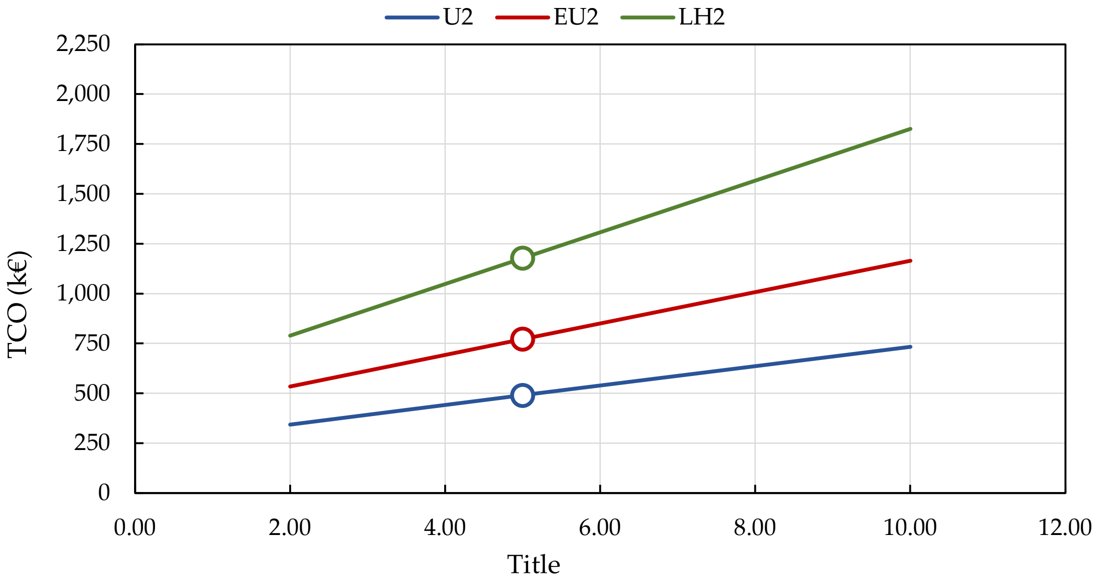


Figure 4.24 - *H2ICET TCOs and hydrogen prices*

In Figure 4.23 FCETs' TCOs are represented, while in Figure 4.24 H2ICETs cases are reported. As in the sensitivity analysis regarding electricity prices, the relationship between TCOs and fuel price is purely linear, as it only affects the fuel costs: in this case, the model is probably more similar to reality than in the electricity case, since the other cost components are not directly connected to the hydrogen price; in any case, hydrogen sold at 10 €/kg would probably be caused by a high electricity price, that would impact on purchase costs and other components of the TCO.

As before, hydrogen price has higher impact on the cases with higher daily mileage, since their share of fuel cost is larger. In particular, H2ICETs' TCOs are strongly affected by H2 cost, due to the lower efficiency and the consequent high consumptions.

4.3.3 Sensitivity of TCOs to energy price

To summarize the dependency of TCOs on energy price, an additional analysis is proposed:

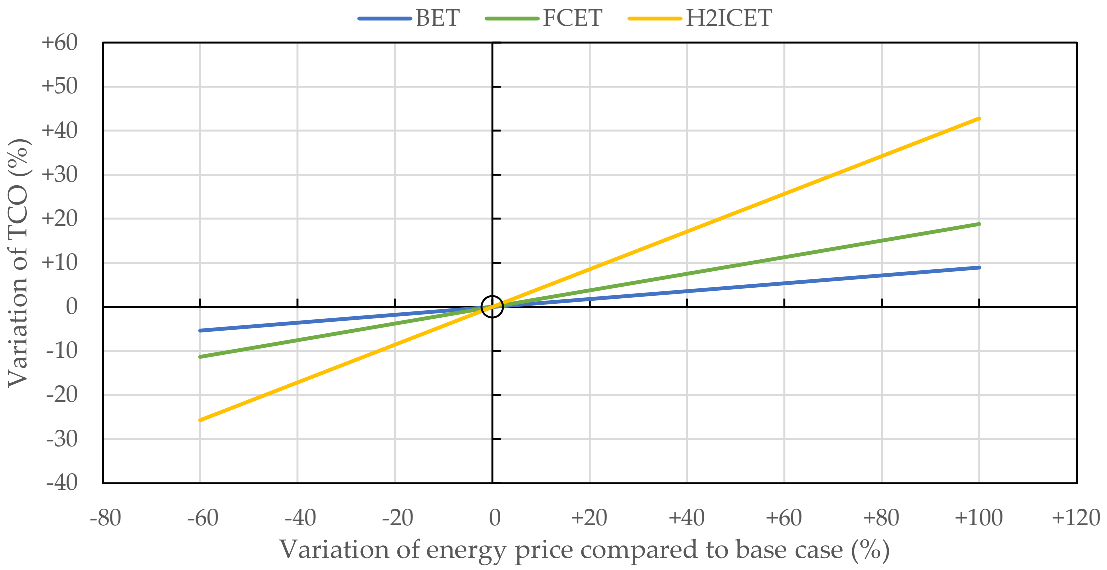


Figure 4.25 - *TCOs and energy price (U1)*

In the plot, the variation of TCOs with the change of energy (electricity and hydrogen) price: 0.10 €/kWh and 5 €/kg are assumed as 0%, as well as the TCOs resulting from the base case studies.

The vehicle that presents the strongest dependency on energy price is the H2ICET, as it has the highest share of fuel costs on the TCO: doubling the hydrogen price, the TCO of the truck increases of more than +40%; for BEV the dependency is weaker, as its fuel costs represent a smaller share of the total.

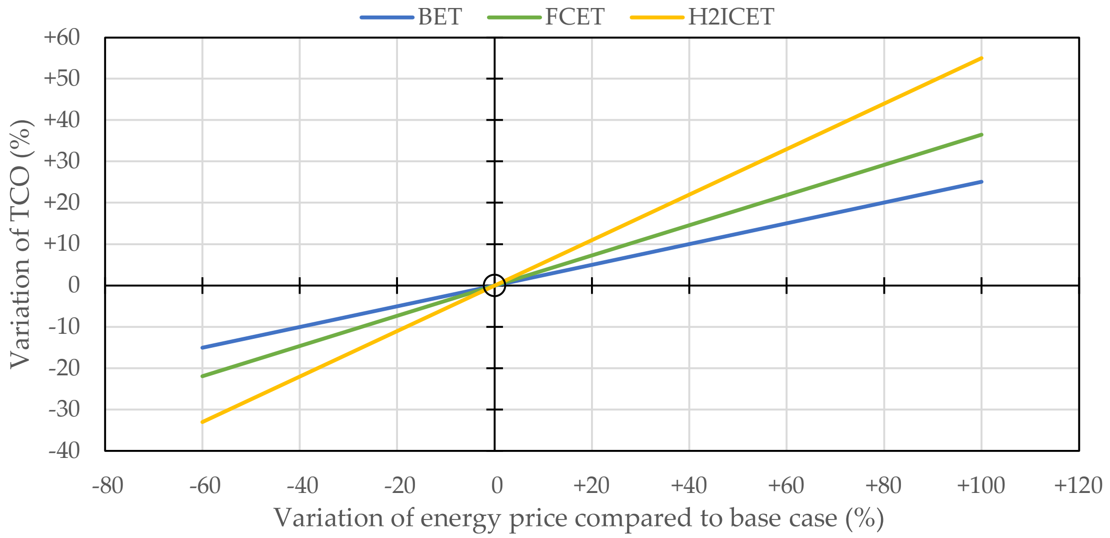
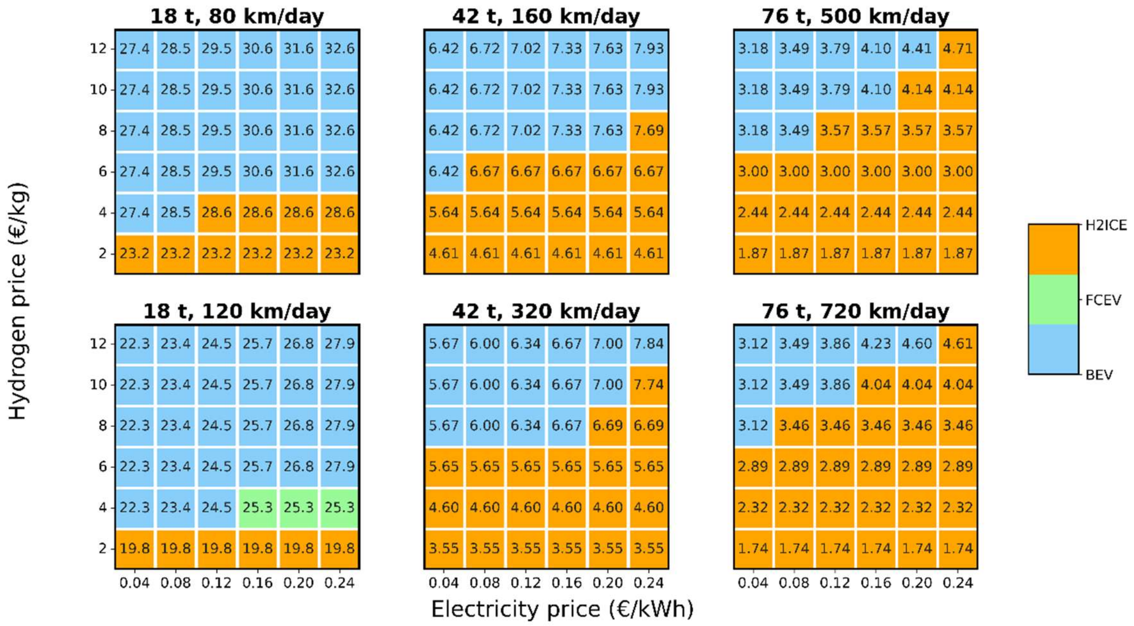


Figure 4.26 - *TCO and energy price (LH2)*

With high mileages, as LH2 case, the dependency TCO-(energy price) is deeper, since the fuel costs represent a high share of the total. Also in this case, the H2ICET is strongly affected by hydrogen price, due to the high consumptions, arriving to +55% of the TCO with a doubling of the hydrogen price.

For a summarized view of this analysis, in Table 4.1 all the case studies are reported, indicating the best powertrain possibility and its corresponding LCOT with a particular couple of hydrogen and electricity prices.



Hydrogen price (€/kg)

Electricity price (€/kWh)

18 t, 80 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	27.4	28.5	29.5	30.6	31.6	32.6
10	27.4	28.5	29.5	30.6	31.6	32.6
8	27.4	28.5	29.5	30.6	31.6	32.6
6	27.4	28.5	29.5	30.6	31.6	32.6
4	27.4	28.5	28.6	28.6	28.6	28.6
2	23.2	23.2	23.2	23.2	23.2	23.2

42 t, 160 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	6.42	6.72	7.02	7.33	7.63	7.93
10	6.42	6.72	7.02	7.33	7.63	7.93
8	6.42	6.72	7.02	7.33	7.63	7.69
6	6.42	6.67	6.67	6.67	6.67	6.67
4	5.64	5.64	5.64	5.64	5.64	5.64
2	4.61	4.61	4.61	4.61	4.61	4.61

76 t, 500 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	3.18	3.49	3.79	4.10	4.41	4.71
10	3.18	3.49	3.79	4.10	4.14	4.14
8	3.18	3.49	3.57	3.57	3.57	3.57
6	3.00	3.00	3.00	3.00	3.00	3.00
4	2.44	2.44	2.44	2.44	2.44	2.44
2	1.87	1.87	1.87	1.87	1.87	1.87

18 t, 120 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	22.3	23.4	24.5	25.7	26.8	27.9
10	22.3	23.4	24.5	25.7	26.8	27.9
8	22.3	23.4	24.5	25.7	26.8	27.9
6	22.3	23.4	24.5	25.7	26.8	27.9
4	22.3	23.4	24.5	25.3	25.3	25.3
2	19.8	19.8	19.8	19.8	19.8	19.8

42 t, 320 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	5.67	6.00	6.34	6.67	7.00	7.84
10	5.67	6.00	6.34	6.67	7.00	7.74
8	5.67	6.00	6.34	6.67	6.69	6.69
6	5.65	5.65	5.65	5.65	5.65	5.65
4	4.60	4.60	4.60	4.60	4.60	4.60
2	3.55	3.55	3.55	3.55	3.55	3.55

76 t, 720 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	3.12	3.49	3.86	4.23	4.60	4.61
10	3.12	3.49	3.86	4.04	4.04	4.04
8	3.12	3.46	3.46	3.46	3.46	3.46
6	2.89	2.89	2.89	2.89	2.89	2.89
4	2.32	2.32	2.32	2.32	2.32	2.32
2	1.74	1.74	1.74	1.74	1.74	1.74

Table 4.1 - *Optimal LCOT (c€/km/t) in the six case studies*

In case of small trucks (18 t), the BET is the most convenient solution almost all the cases, excluding the ones with very low hydrogen cost.
In the LH cases, the H2ICET is generally the best solution, due to its low purchase costs, and BET is limited to those scenarios with really high hydrogen costs, due to the low efficiency of the ICE.
In current scenario, the FCET represents the best solution for a very limited number of cases, since the purchase costs is not competitive with the H2ICET, and the fuel efficiency is not as high as the BET.

4.3.4 Reaching parity between solutions

Two main case studies are selected: U2 and LH2.
To reach parity, two variables are identified: fuel costs and purchase costs.

Variable energy prices

In this paragraph, it has been analyzed the effect of varying energy price in case study U2, calculating where the parity between the solutions is reached.
Energy prices are changed maintaining the same ratio between the two vectors (starting from base assumption 0.10 €/kWh and 5 €/kg, assumed as 0%).

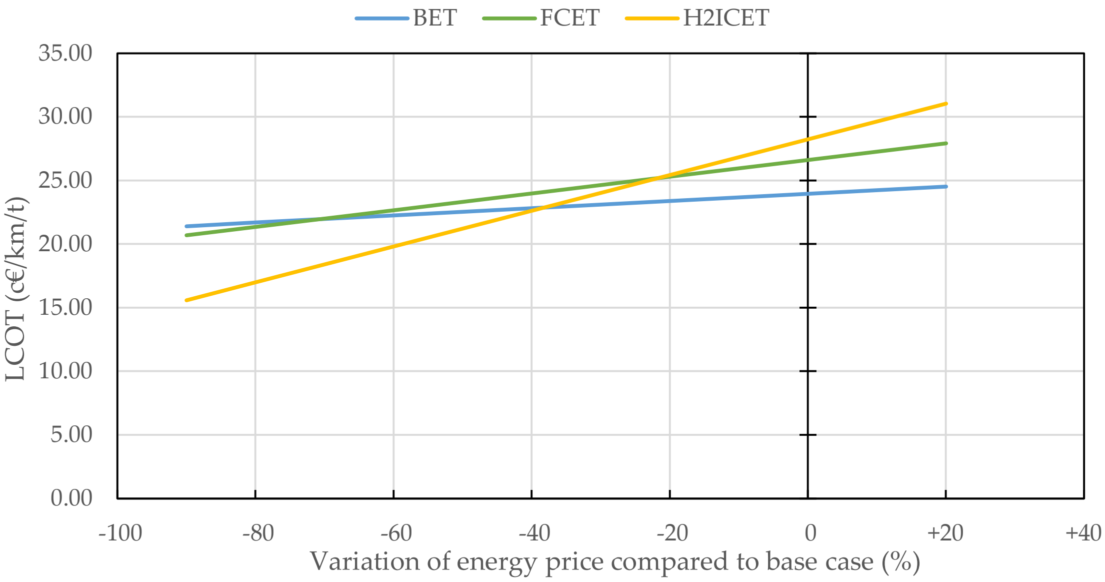


Figure 4.27 – *Parity between solutions (U2)*

LCOTs at 0% represent the base case (as reported in Figure 4.4): H2ICET is the worst solution, due to its high fuel economy on urban routes; however, for the same reason, it is the first to benefit from a decrease of energy prices: with electricity slightly above 0.06 €/kWh and hydrogen at about 3 €/kg, it becomes the best solution, since the difference in fuel costs does not counterbalance the higher purchase price of the BET.
Regarding the FCET, its fuel economy is better than that of the H2ICET, preventing it from benefiting from the decrease of energy prices, so, even if it has a better LCOT than H2ICET with base case prices, its parity with BET is reached only around 0.03 €/kWh and 1.5 €/kg (which is definitely too optimistic, at least in the near future).

Variable fuel cells prices

Among the three technologies, FCEV is the one with the highest potential changes in purchase price: batteries are a relatively diffused, even if not in HDV applications yet, so it is not likely that their prices will decrease a lot in future years; concerning H2ICEVs, their technology is largely derived from standard ICEs, so prices will probably remain constant during the years.
Fuel cells prices are still largely variable, not only in future scenarios, but also concerning current market; a sensitivity analysis on this topic has been evaluated necessary, both considering future development of prices, but also the possibility of a wrong evaluation in current scenario.
LH2 case is reported:

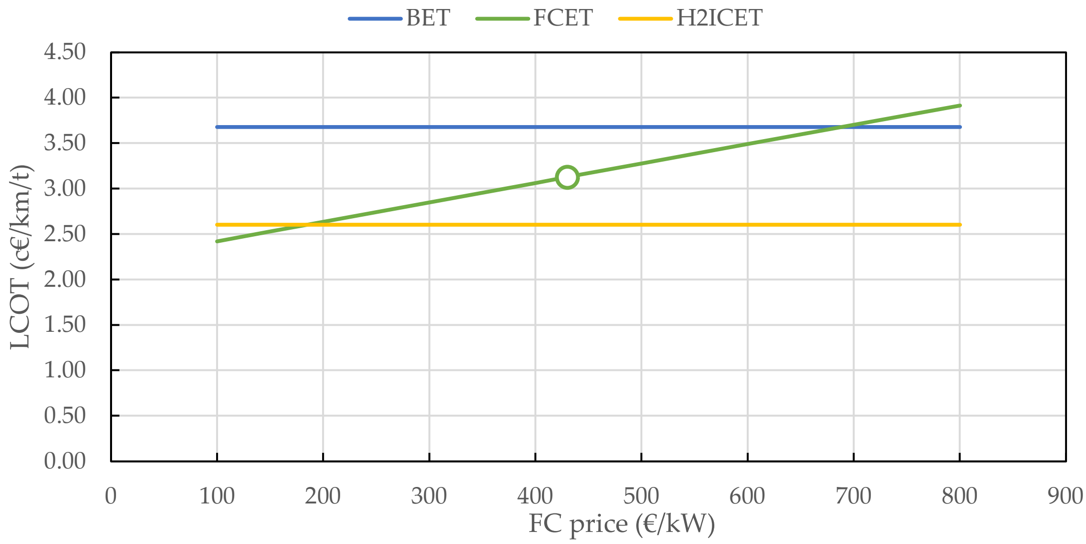


Figure 4.28 - *Parity between solutions (LH2)*

In LH2 case, at current scenario (430 €/kW), FCEV represents an intermediate solution between the two other vehicles. Requiring high mileage and large truck, the parity of FCET with BET is reached at about 700 €/kW.
To reach the LCOT of H2ICET, it is needed to decrease to about 180 €/kW: this is because the fuel economies of the two vehicles are not so different on these distances, so to obtain parity the purchase costs have to be almost the same.
This scenario is not completely unlikely, since development of this technology has been investigated a lot during recent years, and some studies already report that these prices could be reached in the next future.

4.3.5 Variable useful lives

The assumed useful life has a significant impact on the definition of the results, especially in the cases with short mileages.
In the plots, it has been reported the change in the LCOT assuming different useful lives:

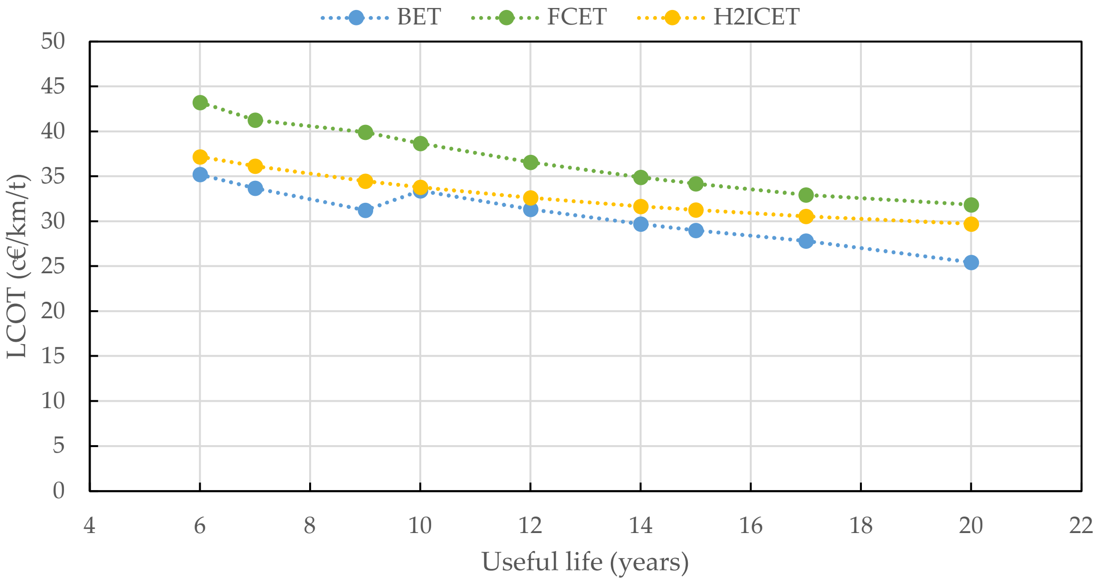


Figure 4.29 - *Variable useful life (U1)*

LCOT generally decreases increasing the useful life: this is understandable, considering that the fixed purchase costs are distributed on a longer mileage and a larger transported mass. In the case of H2ICET, the trend is purely monotone, as there is no variation of costs between the years; for FCET and BET, midlife costs impact on one particular year, so the trend is not purely decreasing, but there is a relative maximum in the year of the FC or battery substitution (for FCET, midlife costs are low, so this peak is not so visible).

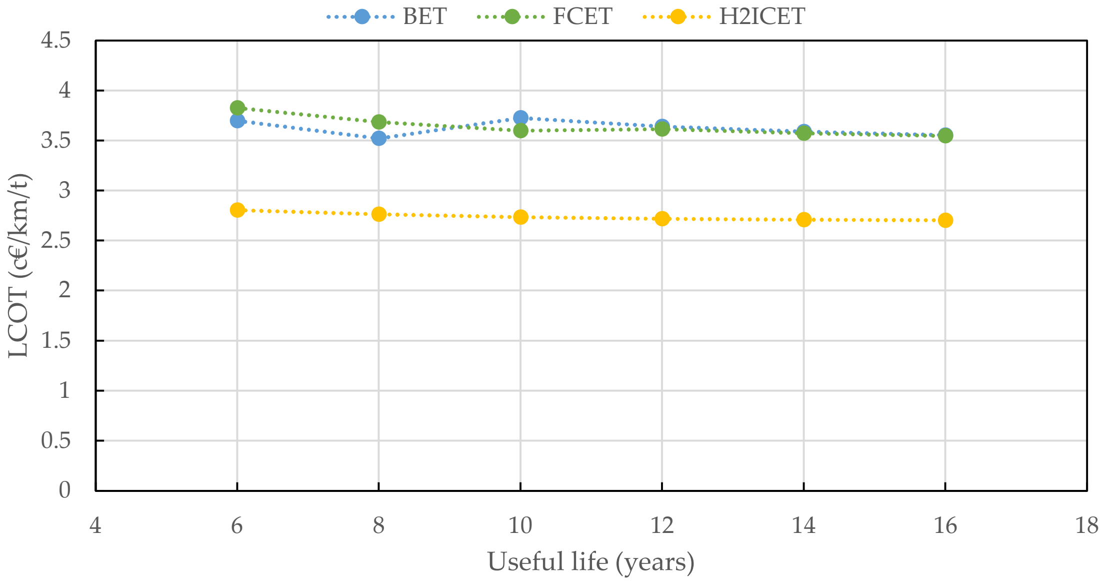


Figure 4.30 - *Variable useful life (LH1)*

With longer cumulated mileages, the steepness of the curve is lower: the purchase costs have lower impact on the LCOTs, which are basically influenced by operational costs, so assuming different useful lives is not so significant.

As before, the only peaks in the curves are due to the midlife costs, which are not constant every year: in the case of battery replacement, its cost, due to the large size of the cells, is strongly impacting, and a maximum in the curve is visible at the tenth year: it is interesting to notice that for periods shorter than 10 year, the BET is cheaper than the FCET, while increasing the period of analysis, FCET becomes convenient.

4.3.6 Variable discount rate

Considering that the TCO is based on Discounted Cash Flow Analysis, the results are strongly affected by the assumed discount rate, since it gives more or less weight to future costs (OPEX) compared to capital costs.

On the contrary, the dependency of LCOTs on discount rate is less remarked, because in the LCOT equation both numerator (annual cash flow) and denominator (annually transported freight) are discounted: the discount rate factor is not elided, but its importance is reduced.

Considering the LH2 case, results are reported in tables:

	Discount rate	TCO [k€]	TCO variation
BET	7%	1,450	0%
	2%	1,707	+17.7%
	15%	1,148	-20.8%
FCET	7%	1,426	0%
	2%	1,659	+16.3%
	15%	1,149	-19.4%
H2ICET	7%	1,178	0%
	2%	1,389	+17.9%
	15%	935	-20.6%

Table 4.2 - *TCOs and discount rate (LH2)*

	Discount rate	LCOT [c€/km/t]	LCOT variation
BET	7%	3.67	0%
	2%	3.62	-1.5%
	15%	3.74	+1.6%
FCET	7%	3.12	0%
	2%	3.04	-2.8%
	15%	3.23	+3.3%
H2ICET	7%	2.60	0%
	2%	2.57	-1.4%
	15%	2.65	+1.8%

Table 4.3 - *LCOTs and discount rate (LH2)*

In both cases (TCOs and LCOTs) the variations are quite proportional, so the results of the comparison are not modified by the different discount rates.
Concerning LCOTs, the variations are drastically less significant, and reversed, since higher discount rates gives higher LCOTs: this is because the effect of the discount is more impacting on the transport factor than the cash flow.

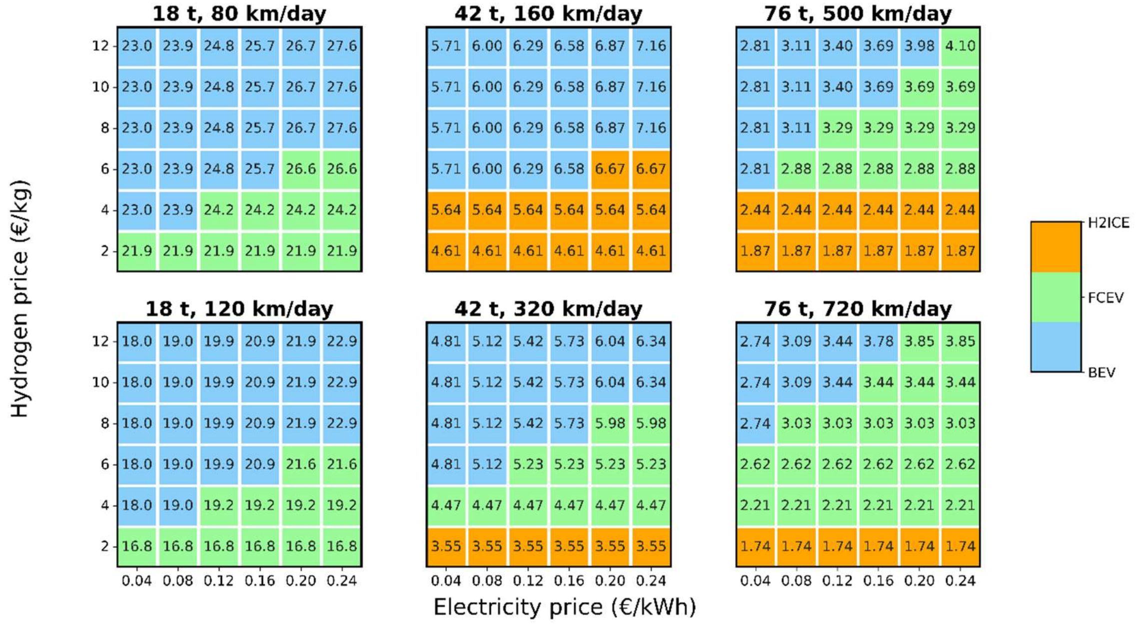
4.3.7 Future scenario for fuel cells and batteries

Regarding the potential improvement of FC and battery technology, both considering their efficiency and their production costs, it seems useful to include an additional analysis concerning the best solutions depending on electricity and hydrogen costs in the six considered case studies (see Table 4.1).
Regarding the battery, the foreseen improvements are:

- Reduction of purchase cost to 200 €/kWh
- +30% increase of the specific energy of the battery pack

Concerning the fuel cell, future parameters are assumed:

- Purchase cost of the FC stack reduced to 150 €/kW
- Increase of the powertrain efficiency equal to +10%



18 t, 80 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	23.0	23.9	24.8	25.7	26.7	27.6
10	23.0	23.9	24.8	25.7	26.7	27.6
8	23.0	23.9	24.8	25.7	26.7	27.6
6	23.0	23.9	24.8	25.7	26.6	26.6
4	23.0	23.9	24.2	24.2	24.2	24.2
2	21.9	21.9	21.9	21.9	21.9	21.9

42 t, 160 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	5.71	6.00	6.29	6.58	6.87	7.16
10	5.71	6.00	6.29	6.58	6.87	7.16
8	5.71	6.00	6.29	6.58	6.87	7.16
6	5.71	6.00	6.29	6.58	6.67	6.67
4	5.64	5.64	5.64	5.64	5.64	5.64
2	4.61	4.61	4.61	4.61	4.61	4.61

76 t, 500 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	2.81	3.11	3.40	3.69	3.98	4.10
10	2.81	3.11	3.40	3.69	3.69	3.69
8	2.81	3.11	3.29	3.29	3.29	3.29
6	2.81	2.88	2.88	2.88	2.88	2.88
4	2.44	2.44	2.44	2.44	2.44	2.44
2	1.87	1.87	1.87	1.87	1.87	1.87

18 t, 120 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	18.0	19.0	19.9	20.9	21.9	22.9
10	18.0	19.0	19.9	20.9	21.9	22.9
8	18.0	19.0	19.9	20.9	21.9	22.9
6	18.0	19.0	19.9	20.9	21.6	21.6
4	18.0	19.0	19.2	19.2	19.2	19.2
2	16.8	16.8	16.8	16.8	16.8	16.8

42 t, 320 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	4.81	5.12	5.42	5.73	6.04	6.34
10	4.81	5.12	5.42	5.73	6.04	6.34
8	4.81	5.12	5.42	5.73	5.98	5.98
6	4.81	5.12	5.23	5.23	5.23	5.23
4	4.47	4.47	4.47	4.47	4.47	4.47
2	3.55	3.55	3.55	3.55	3.55	3.55

76 t, 720 km/day

	0.04	0.08	0.12	0.16	0.20	0.24
12	2.74	3.09	3.44	3.78	3.85	3.85
10	2.74	3.09	3.44	3.44	3.44	3.44
8	2.74	3.03	3.03	3.03	3.03	3.03
6	2.62	2.62	2.62	2.62	2.62	2.62
4	2.21	2.21	2.21	2.21	2.21	2.21
2	1.74	1.74	1.74	1.74	1.74	1.74

Table 4.4 - *Optimal LCOT (cent€/km/t) in the six case studies, future scenario for FC and battery*

In this scenario, FCET represents the best choice in many case studies, since the purchase costs become almost competitive with the H2ICET, so that the lower efficiency compared to BET is overcome in most of the cases, except for the ones with very high hydrogen price.

The only exception is represented by the EU1 case study: in this case, the combination of a short daily mileage (160 km/day) and a large truck (42 t) makes the FCET less convenient that the other two solutions, since the purchase cost is higher than the H2ICET, but the higher efficiency cannot be appreciated on such a short duty cycle.

On the other hand, in the urban case studies FCET and BET "compete" in the most probable zones of future energy prices and the difference of LCOTs is subtle: the payload reduction due to the battery is reduced, but still higher than the one due to the hydrogen storage, and the higher efficiency of the BET makes it convenient when the energy cost is high.

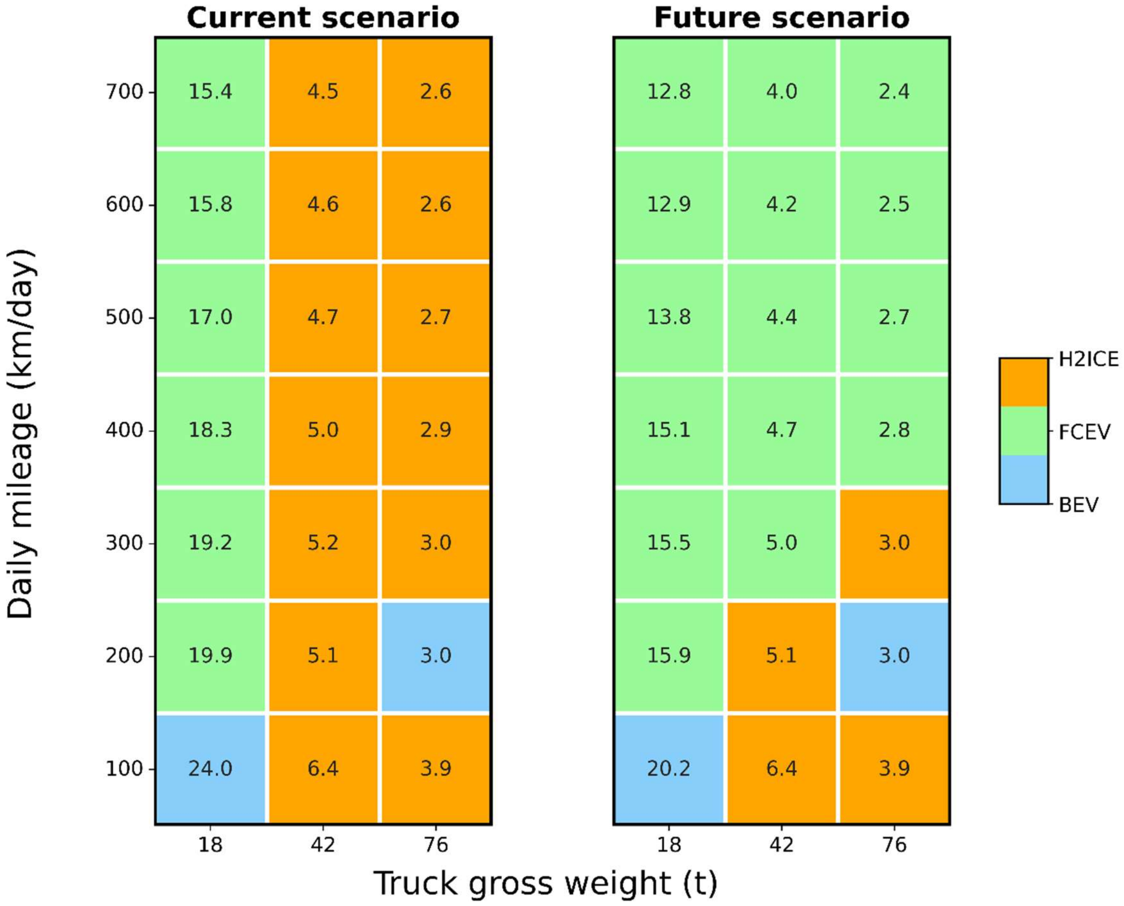
It must be added that some reports are even more optimistic on future developments of the technologies and their costs, in particular regarding FC [39], [40], that would obviously make the corresponding vehicles more competitive in the different scenarios. Nevertheless, in this study it has been decided to follow a more conservative approach for assumptions about future perspective.

5. Discussion

In the previous section, different case studies were presented, in order to comprehend the vastest number of cases in the current scenario.
The results can be summarized in some considerations:

- Operating with "small" (as 18 t) trucks on short (urban) routes, the best choice is generally a BEV: the possibility of using a small battery pack contributes to keep purchase price and midlife costs of the vehicle relatively low, while the high efficiency of the electric powertrain results in limited operational costs; moreover, the small battery does not impact on the payload capacity, being in the order of 1.5-2 t maximum
- For big vehicles operating on long mileage activities, H2ICET is the most suitable solution: due to the "simple" technology of the engine, the purchase cost of the vehicle is significantly lower than the other two, and this difference is so remarked that it is not compensated by the higher fuel and maintenance costs
- In most of the case studies, FCETs can be seen as a middle solution: in short-mileage urban cases, the lower efficiency and the higher cost of hydrogen compared to electricity contribute to make them more expensive than the BETs; for heavy trucks, their higher efficiency is not sufficient to overcome the difference in the purchase costs with the H2ICETs. In current scenario, the best work condition for FCETs is a duty-cycle composed of a "small" truck operating on long-routes: in this case, the FC power is low, limiting the purchase cost, and the long driving range required allows to exploit the potential of hydrogen storage compared to a battery

Table 5.1 enlarges the scenario presented in Results section, in order to consider, in a summarized representation, a global view of the possible case studies (some of them are in fact quite unusual, as the 76-t truck on 100 km/day duty cycle, but are reported for completeness). Each cell represents a case study, identified by the type of truck and its daily kilometers. In the cells, the lowest LCOT is reported among the three technologies, and the colors indicate which powertrain is associated to the LCOT (reported in $cent€/km/t$).



Daily mileage (km/day)	Current scenario			Future scenario		
	18	42	76	18	42	76
700	🟩 15.4	🟧 4.5	🟧 2.6	🟩 12.8	🟩 4.0	🟩 2.4
600	🟩 15.8	🟧 4.6	🟧 2.6	🟩 12.9	🟩 4.2	🟩 2.5
500	🟩 17.0	🟧 4.7	🟧 2.7	🟩 13.8	🟩 4.4	🟩 2.7
400	🟩 18.3	🟧 5.0	🟧 2.9	🟩 15.1	🟩 4.7	🟩 2.8
300	🟩 19.2	🟧 5.2	🟧 3.0	🟩 15.5	🟩 5.0	🟧 3.0
200	🟩 19.9	🟧 5.1	🟦 3.0	🟩 15.9	🟧 5.1	🟦 3.0
100	🟦 24.0	🟧 6.4	🟧 3.9	🟦 20.2	🟧 6.4	🟧 3.9

🟧 H2ICE
🟩 FCEV
🟦 BEV

Table 5.1 - *Global LCOT overview*

For the smallest truck, the BET is the most suitable solution only if the daily mileage is low, so that a small size battery is sufficient. Increasing the mileage, the FCET becomes the best solution, even if its fuel efficiency is lower than the BET, due to the fact that the FC size is relatively low, because of the "low" power required by an 18-t truck.

For larger trucks, the FC becomes too expensive compared to H2ICET, and the efficiency of the FCET is not sufficient to overcome this difference; similar situation occurs for the BET, where the battery represents a too high cost, impacting on both purchase and midlife costs. The only exception is represented by the 76-t truck on 200 km/day duty cycle: in this case, the BET results to have the best trade-off between purchase costs and fuel economy, becoming the most convenient solution. For lower mileage, the fuel efficiency is not so impacting since the fuel costs are already low due to the few kilometers, while for longer routes the battery becomes too expensive.

An additional analysis is included, considering the possible improvements of FC and battery technology: in this case, the FC cost is assumed 150 €/kW, and their efficiency is increased of 10%, while battery price is assumed 200 €/kWh and the specific energy is increased of +30%. In this context, the FCET becomes the most convenient solution for most of the duty cycles, and the few situations where it is not are the 18-t truck operating on 100 km/day and the ones seeing a relatively large truck operating on short routes, due to the high purchase costs (compared to H2ICET) that are not optimized on those short mileages (in any case, it must be added that these uses are quite unusual, because large trucks generally operate on long distances).

5.1 Comparison of results

As mentioned in previous chapters, ICCT presented in 2020 a TCO comparison of diesel trucks with BETs [39] and in 2022 a similar study regarding FCETs [39], [40], analyzing different contexts in Europe considering both present conditions and future projections.

Assuming a 42-t truck traveling 500 km per day, final results obtained for BETs by ICCT are coherent with the ones reported in this study, but a couple of considerations are needed:

- ICCT assumes a 5-year useful life of the vehicle: the TCO for 2020 analysis are mostly between 750,000 and 850,000 € (depending on the considered country), while with the parameters assumed in this study the TCO is about 840,000 €, so they can be considered quite coherent. On opposite, ICCT projections for 2023 are drastically more optimistic, giving results in the order of 550,000-600,000 €: this is due to the lower price of the battery, because ICCT evaluated it would have significantly decreased during the following 3 years, but in fact it has not, due to the increase of lithium price [120]

- Price of electricity in all the countries considered by ICCT is assumed considerably higher than in Finland (about 0.40 vs 0.10 €/kWh), giving higher "fuel" costs
- In the assumed period of 5 years, no battery substitution is assumed in the ICCT report, while in this study, due to the high mileage, one substitution is considered necessary

In the case of the FCET, ICCT reports a TCO in 2022 between 950,000 and 1,100,000 €, while result of this study is about 900,000 € for the same driving activity. The difference is mainly due to the higher hydrogen costs, assumed to be between 8 and 11 €/kg, while in Finland it has been assumed 5 €/kg.

So, basing only on the TCO, with this duty transport needs (42-t truck and 500 km/day), BET appears more convenient than FCET both in ICCT analysis and in this thesis.

Unfortunately, ICCT does not provide an evaluation based on the LCOT to compare, and this would be interesting since in this case results are reversed: due to the high weight of the battery and the consequent loss of transportable payload, the cost per transported freight becomes lower in the FCET (but H2ICET solution is the cheapest one).

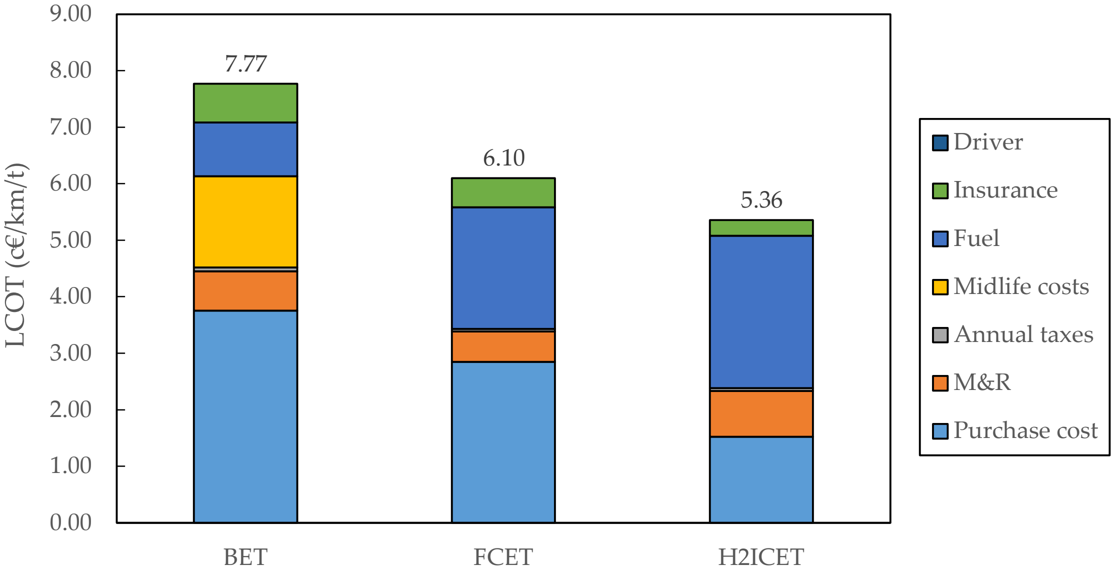


Figure 5.1 - *LCOT of ICCT case study (42t, 500 km/day)*

B. Noll *et al.* [44] provides a similar analysis, comparing different powertrains assuming many European countries as background. Its results are more pessimistic on the potentialities of FCEVs compared to BETs and diesel

trucks, since even on long-haul applications they appear more expensive than the other two solutions.
This difference between results presented in this thesis, more favorable to FCEVs at least on long mileages, and the ones provided by B. Noll *et al.* [44] are justified by some considerations on the mentioned study:

- During the 8-year lifetime of the vehicle, it does not assume a battery replacement, while this study includes two substitutions, taking into account the high mileage of the vehicle (more than 1,200,000 km on the entire lifetime)
- Cost of the battery pack is assumed significantly lower compared to this report (140 vs 230 €/kWh)
- Hydrogen price is assumed 8 €/kg in the entire Europe, while in this document a lower price is forecasted, looking at the low price of electricity that Finland expects in near future
- Results are provided on a €/km basis: this unit of measurement is indicated for passenger cars, but it is considered quite limiting for trucks evaluation, since the major goal of a HDV is to transport freight, and the possibility of a reduced payload due to the weight of the battery pack must be analyzed

Assuming B. Noll *et al.* [44] operating parameters and combining them with the cost assumptions made in this thesis, final results would be:

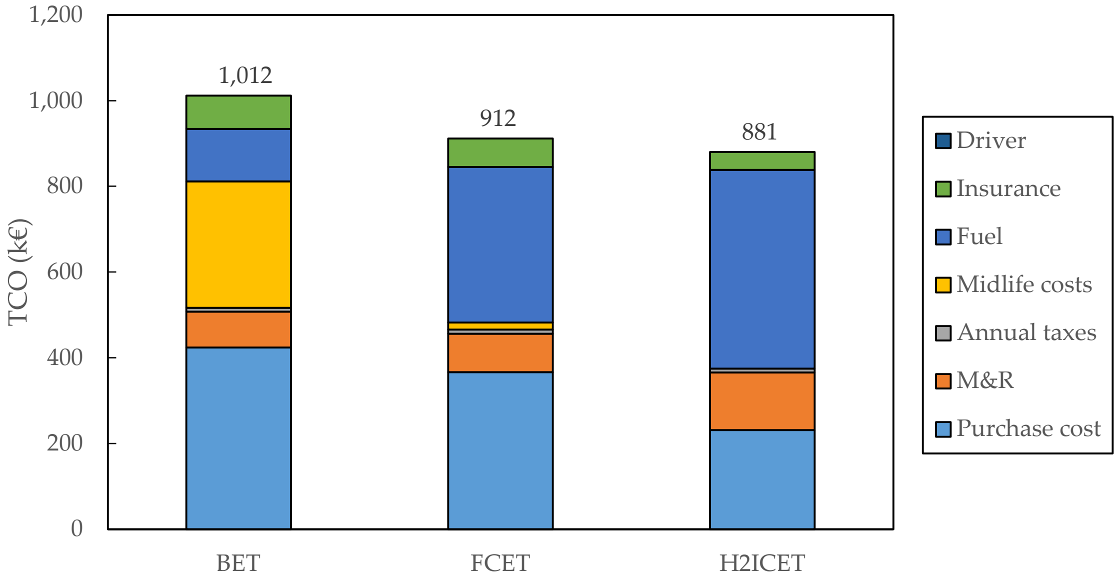


Figure 5.2 - *TCO of B. Noll et al.* [44] *case study (32t, 600 km/day)*

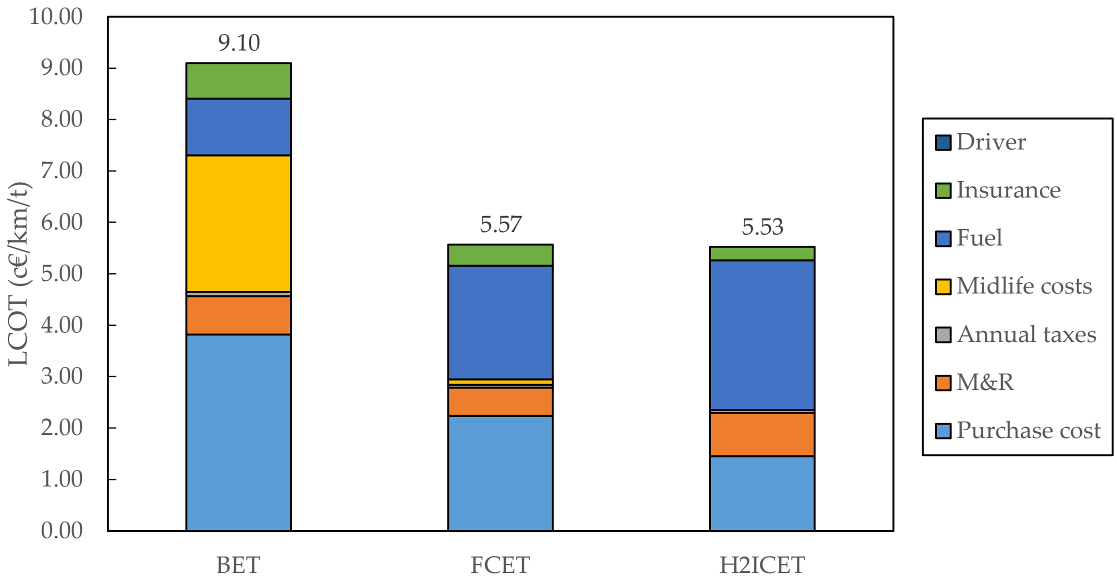


Figure 5.3 - *LCOT of B. Noll et al.* [44] *case study (32t, 600 km/day)*

As it is immediate to observe, the TCOs of FCET and BET are similar, but the LCOT case is completely different: the high weight of the battery (needed to provide 600 km driving range) does not only impact on the purchase costs, but it reduces payload of about 7 t, resulting in a very high cost per transported freight. The best solution for this case is the H2ICET, but the higher efficiency of FCET makes the two LCOTs quite similar.

Y. Ruf *et al.* [42] published a study in 2020 with Roland-Berger, providing many case studies designed for specific routes in Europe, varying both the weight class of the vehicles and the daily mileage. Designing similar cases on the model assumed in this study, the obtained TCOs and LCOTs are similar to the one from Roland-Berger: the biggest difference is due to the assumption of no midlife costs in the 10-years period.

Differently from the other studies mentioned above, Roland-Berger is more optimistic about the potential of FCEVs: in most of the cases, the calculated purchase costs are lower than BEVs, especially on long-haul routes, and, even with a lower efficiency of the powertrain, the final TCO of the FCEV is convenient. It must be mentioned that of the three reported studies, this is the only one calculating the LCOT[1] on a $cent€/km/t$ basis, taking into account the loss of payload due to the weight of the battery. At the same time, it must be

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[1] In Roland-Berger report, both TCO [€] and LCOT [c€/km/t] are called generically TCO, but the two results are easily comparable to the ones obtained in this thesis

considered that the good results obtained by FCETs compared to BETs are partially due to a combination of “fuel” cost relatively favorable to hydrogen, since in current scenario electricity is assumed 0.30 €/kWh, while 700 bar hydrogen 7.30 €/kg. This assumption is quite optimistic, at least in a green hydrogen scenario, since hydrogen price would correspond to 0.22 €/kWh, including not only production costs but also transport and compression, but it can be justified if it was assumed that the recharges of the BETs were mainly operated in high power charging points (where electricity price is higher than the national average).

6. Conclusions

In this thesis, an economical comparison between alternative powertrain solutions has been provided, analyzing them through the Total Cost of Ownership methodology.

As it could be expected, the best choice is not unique for all the case studies, but "it is more complicated than that": different operation conditions and background parameters impact on the results, orienting the decision on certain vehicle instead of another. Several case studies have been analyzed in this document, also providing sensitivity analysis, with the aim of offering an overview as accurate as possible on the main parameters affecting the results and giving a general idea of the strengths of every technology.

The general outcome of this work is that, in current scenario, BETs are the most convenient ones while operating with smaller trucks on short mileages, while increasing their trips, FCETs become competitive. For bigger trucks, the H2 engine will probably be the best powertrain, due to its lower purchase costs.

Variations of energy prices in next future could take to different results, according to the sensitivity analysis presented in previous sections: generally, BET has better response to high energy prices, due to its high efficiency, while for low energy prices, the two H2-based powertrains can become convenient.

Nevertheless, this thesis has not the ambition of being exhaustive on the topic, since the choice of the input data of the analysis cannot be completely suitable for every specific need. Moreover, even with the optimistic assumption that the parameters chosen in this document are precise and complete, they are referred to a current scenario: in few years, possible improvements of the technologies or different economic conditions could lead to completely different results. The hope of the author is that the data provided in this document will be soon overcome by better results in term of purchase cost of the vehicles, efficiency of

the powertrains, cost of fuel… thanks to a continuous progress of the technologies.
For this reason, the final goal of this work is to provide a model that could be easily modified to make it suitable for different needs and situations.

As a final consideration, it must be remembered that one of the major assumptions of this study is a properly developed infrastructure, in order to make the diffusion of alternative powertrain possible in the entire road transport sector. Unfortunately, this condition appears quite optimistic at the moment, even in a virtuous environment as Finland. For a complete exploitation of the results presented in this thesis, further studies are necessary in particular on the recharging and refueling network, with the purpose of make its diffusion as fast as possible not only in Finland but in entire Europe.

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