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Technical assessment and economic analysis of zero-carbon freight road transportation vehicles☆

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ABSTRACT

The transition to hydrogen fuel as an alternative energy source for heavy-duty vehicles (HDVs) can reduce greenhouse gas emissions and dependency on fossil fuels. This study quantifies and compares the total costs of ownership and transportation of light-duty and heavy-duty commercial trucks, across five drivetrain technologies: conventional diesel internal combustion engine (ICE), hydrogen internal combustion engine (H_2-ICE), battery electric vehicle (BEV), constant power fuel cell electric vehicle (C-FCEV), and variable power fuel cell electric vehicle (V-FCEV). To the best of our knowledge, the present study provides the first comparison of TCO and LCOT across all these drivetrain technologies, filling a gap in the literature and offering quantitative evidence to guide future zero-emission vehicle strategies. The findings indicate that conventional diesel remains the cost-optimal option across most driving ranges and vehicle weight classes. However, FCEVs are a competitive solution at middle to high mileages (i.e $\geq$ 300 km) and for low to middle class weight (i.e 3.5 t, 5.2 t, and 18 t). Depending on the vehicle category, the levelized cost of transportation of FCEVs is 45%–55% lower than that of BEVs.

1. Introduction

The European Commission aims to reduce greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels, as a step towards climate neutrality by 2050 [1]. The European Union's strategy for low-emission mobility includes increasing transportation efficiency, accelerating the use of low-emission energy, and transitioning to Zero-Emission Vehicles (ZEVs). Road transportation is a significant source of local pollutants and CO_2 emissions, with medium and heavy-duty vehicles contributing substantially [2]. In the U.S., these vehicles were responsible for nearly 26% of CO_2 emissions and significant portions of NO_x and particulate matter in 2016 [3]. In Europe, buses and trucks produced about 27% of road transport CO_2 emissions in 2015 [4]. Regulations have progressively tightened emission limits, leading to advanced exhaust after-treatment systems in diesel engines, increasing vehicle complexity and costs. Despite the importance of ZEVs, over 80% of cars sold still use traditional internal combustion engines [5,6], while the share of diesel trucks sold in the EU as of 2022 was 96.6% [7]. Battery electric vehicles dominate the ZEV market [8], but fuel cell electric vehicles offer advantages such as higher energy density, longer range, and shorter refueling times [9–11]. Fuel cell electric vehicles also support renewable energy integration due to their flexible fuel production, storage, and delivery. They combine fuel cells and batteries, optimize design and performance [12–14]. However, challenges such as higher costs, weight, and reliability concerns hinder their widespread adoption [15].

To improve energy efficiency and reduce emissions, electricity and hydrogen are considered promising alternatives to traditional fuels. Most studies focus on passenger cars, but recent interest has grown in medium- and heavy-duty vehicles such as buses and trucks, which are major contributors to urban pollution. Studies show that battery electric trucks have limited potential to reduce CO_2 emissions with current technology, while hydrogen fuel cell trucks offer a promising alternative [16–19]. The 2024 IEA hydrogen review [20] reveals that trucks are the fastest-growing sector for fuel cell vehicles, showing a stock increase of over 50% in 2023, three times faster than cars. The use of hydrogen in transport sector had increased by 40% in 2022, entailing a growing positive trend. This is especially driven by heavy-duty vehicles being deployed in China. However, recent withdrawal of companies from the market [21] also suggests that further detailed economic analysis should be undergone with a scientific approach.

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Nomenclature

Symbols

C	Specific consumption
C_x	Aerodynamic coefficient
D	Yearly distance traveled
DR	Driving Range
E	Specific emissions
F_{res}	Resistance force
G	Cost
I	Current
J	Lifetime of the analysis (years)
LHV	Lower Heating Value
M	Vehicle's mass
P	Power
Q	Electrochemical capacity
S	Vehicle's front area
TW	Transported Weight
V	Voltage
$\Gamma_{mission}$	Total driving cycle's energy
η	Efficiency
ρ	Air density
σ	Payload
a	Vehicle's acceleration
g	Gravitational acceleration
i	Discount rate
k	Roll friction coefficient
m	mass
n	Number of cells
v	Vehicle's speed

Abbreviations

BEV	Battery Electric Vehicle
C-FCEV	Constant-Power Fuel Cell Electric Vehicle
EC	Energy Consumption
EM	Electric Motor
H2-ICE	Hydrogen Internal Combustion Engine
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LCOT	Levelized Cost of Transportation
RPE	Retail Price Equivalent factor
RV	Selling Revenue of the vehicle
TCO	Total Cost of Ownership
TPC	Total Purchase Cost
V-FCEV	Variable-Power Fuel Cell Electric Vehicle
VAT	Value Added Tax
ZEV	Zero-Emissions Vehicle
FC	Fuel Cell

Greek Letters

α	tank weight
β	power specific weight

Subscripts

aux	auxiliary
b	battery
drt	drivetrain
eff	effective
G	Generator
SoC	State of Charge
p	parallel
pm	prime mover
s	series
w	mechanical

Also, re-powering conventional vehicles to become Hybrid Electric Vehicles (HEVs) is of great interest. HEVs can have series, parallel, or combined architectures, each suited to different driving conditions.

Danielis et al. [22] reviewed the total cost of ownership of hydrogen-powered trucks compared to diesel trucks, concluding that H_2 trucks might become competitive by 2030, although the price of hydrogen adds uncertainty to such findings. Maintenance costs are found to be lower for H_2 trucks than for diesel trucks. Di Ilio et al. [23] focused on designing a new propulsion system for a heavy-duty yard truck used in port logistics. An on-field measurement campaign was conducted to analyze the duty cycle of a diesel-engine yard truck currently used in ports. Results show that the hybrid vehicle can achieve excellent energy performance, with an estimated 12 kg of hydrogen required for the most demanding port operations, ensuring 6 h of continuous operation. The hydrogen-fueled yard truck offers benefits such as zero local emissions, reduced noise, lower maintenance costs, improved energy management, and increased operational efficiency. Danielis et al. [24] conducted a review study on the competitiveness of battery electric trucks and diesel trucks in terms of total cost of ownership. They find that light-duty and medium-duty trucks started becoming cost competitive with diesel trucks around 2021, whereas heavy-duty trucks are not expected to be competitive in the near future, primarily due to high battery costs. In addition, they analyze different geographic scenarios, concluding that battery electric vehicles are even less competitive in North America than in Europe, Asia, and Oceania, due to different fuel prices and taxation policies. The authors conclude that significant challenges remain for heavy-duty battery electric trucks, but government interventions, subsidies and investments can be crucial in accelerating their utilization. Lombardi et al. [25] compared the energy performance and environmental impact of four types of commercial vehicles: conventional diesel internal combustion engine, Plug-In Hybrid Electric Vehicle (PHEV), battery electric vehicle, and Plug-In Fuel Cell Vehicle (PFCV). Results show that the highest greenhouse gas emissions are from diesel thermal vehicles, while battery vehicles and PFCVs have significantly lower emissions, especially when using renewable energy sources. The study highlights the potential of PFCVs and battery vehicles to reduce emissions in the freight transportation sector. Ferrara et al. [26] present a comprehensive study on the cost-optimal design and energy management of fuel cell electric trucks for road freight transport, particularly on hilly and mountainous routes. The authors propose a predictive energy management system (EMS) based on dynamic programming, aiming to minimize the total cost of ownership by optimizing fuel consumption, battery state-of-charge control, and component degradation. Simulation results demonstrate that predictive EMS significantly reduces the Total Cost of Ownership (TCO) and component size requirements compared to non-predictive strategies, especially under demanding topographies. The study also highlights the dominant influence of hydrogen price on TCO and the necessity of balancing fuel cell and battery degradation for long-term efficiency. Magnino et al. [27] evaluated and compared three potential solutions for decarbonizing heavy-duty freight transport: Battery Electric Trucks (BETs), Fuel Cell Electric Trucks (FCETs), and Hydrogen-fueled Internal Combustion Engine Trucks (H2ICETs). The analysis uses the TCO and Levelized Cost of Transportation (LCOT) methods to assess all cost components throughout the vehicle's life cycle. The study finds that BETs are best for small trucks with short driving distances, H2ICETs are more cost-effective for larger trucks on longer hauls, and FCETs are competitive for small trucks traveling long distances.

Despite the positive outlook of zero-carbon freight road transportation vehicles presented in technical literature, the real impact in terms of companies committing to the business seems to be limited. Therefore, further technical assessment and detailed economic analysis with a scientific approach is needed. Also, to the best of our knowledge, the research literature lacks a comprehensive investigation on the energy consumption and total costs of ownership and transportation of commercial trucks powered by many different drivetrain technologies. Especially, a direct comparison of TCO and LCOT for fuel cell electric trucks and conventional diesel trucks is hereby presented and discussed.

This paper compares the energy performance, environmental impact, and total costs of ownership and transportation of five types of commercial vehicles with different powertrain solutions, both traditional and Zero-Emissions. The analysis includes driving cycle simulations and a Well-To-Wheel (WTW) analysis to evaluate overall energy consumption and greenhouse gas emissions for four different driving ranges (100 km, 300 km, 500 km, and 700 km). We comment that, according to [28], less than 1% of the European truck fleet have a daily mileage higher than 700 km. Therefore, such value is hereby taken as maximum driving range. We generalize the previously reported studies on a European level and four weight classes, i.e., 3.5 ton, 5.2 ton, 18 ton, and 44 ton. While 3.5 ton and 5.2 fall within the light/medium-duty category (ranging from 3.5 up to 12 ton), 18 ton and 44 ton are generally labeled as heavy-duty vehicles [24]. We note that the generalization to a global level would require the analysis of additional weight classes and energy costs. Also, the analyzed range would be higher because in continents with population density lower than Europe, refueling stations can be even 2000 km far from each other.

We provide a cost analysis in order to compare the LCOT of the four configurations and define the most promising one for long-haul missions. TCO and LCOT are critical financial metrics in the trucking industry, since they aid commercial truck owners in making informed decisions on investments, operational strategies, and cost-efficiency. TCO includes the full life cycle costs associated with owning and operating a commercial truck. It is essential for assessing the true financial impact of purchasing a vehicle, including both direct and indirect costs [29]. LCOT is a metric used to assess the cost efficiency of transporting goods over time, accounting for all the costs related to running the vehicle and considering total mileage and amount of goods transported. Therefore, different drivetrain configurations and driving ranges will be compared in terms of TCO and LCOT.

2. Methodology

First, we model the power required by the different configurations following standard certified driving cycles. Leveraging from these results, we size the components of the vehicle for the analyzed weight classes (3.5 t, 5.2 t, 18 t, and 44 t). Once the sizing is complete, we calculate payload and costs (both capital and operational). In detail, the five drivetrain structures analyzed in this work are (see Fig. 1 and Table 1): conventional diesel Internal Combustion Engines (ICEs), Battery Electric Vehicles (BEVs), Constant Power Fuel Cell Electric Vehicles (C-FCEVs), Variable Power Fuel Cell Electric Vehicles (V-FCEVs), and Hydrogen Internal Combustion Engine (H2-ICE).

2.1. Driving cycles

The FIGE cycle [30] and the CARB-HHDDT [31] cycle are two certified driving cycles defined especially for trucks that are utilized in this study to size the vehicles and assess their performance. The speed profiles are reported in Fig. 2. Both cycles are representative of long-haul missions, since power and capacity of BEVs and FCEVs are mutually linked. In turn, the power of the powertrain is primarily a function of the acceleration peaks, rather than depending on relatively long periods of fairly constant energy delivery. In particular, we use the CARB-HHDDT cycle, with a total driving length of 41.3 km, for light-duty vehicles (3.5 t and 5.2 t), while we use the FIGE cycle, with a total driving length of 29.5 km, for the heavy-duty trucks (18 t and 44 t). Both cycles consist of a first part in urban mode (low speed), followed by extra-urban mode (high speed with frequent variations), and highway mode (constant high speed).

Table 1
Summary of the analyzed cases. Drivetrain type refers to Fig. 1 nomenclature. Drivetrain strategy can be Load-Following (LF) or Constant-Power (CP).

Case	Drivetrain	Energy source	Drivetrain strategy
ICE	ICE	diesel	LF
H2-ICE	ICE	hydrogen	LF
C-FCEV	FCEV	hydrogen	CP
V-FCEV	FCEV	hydrogen	LF
BEV	BEV	electricity	LF

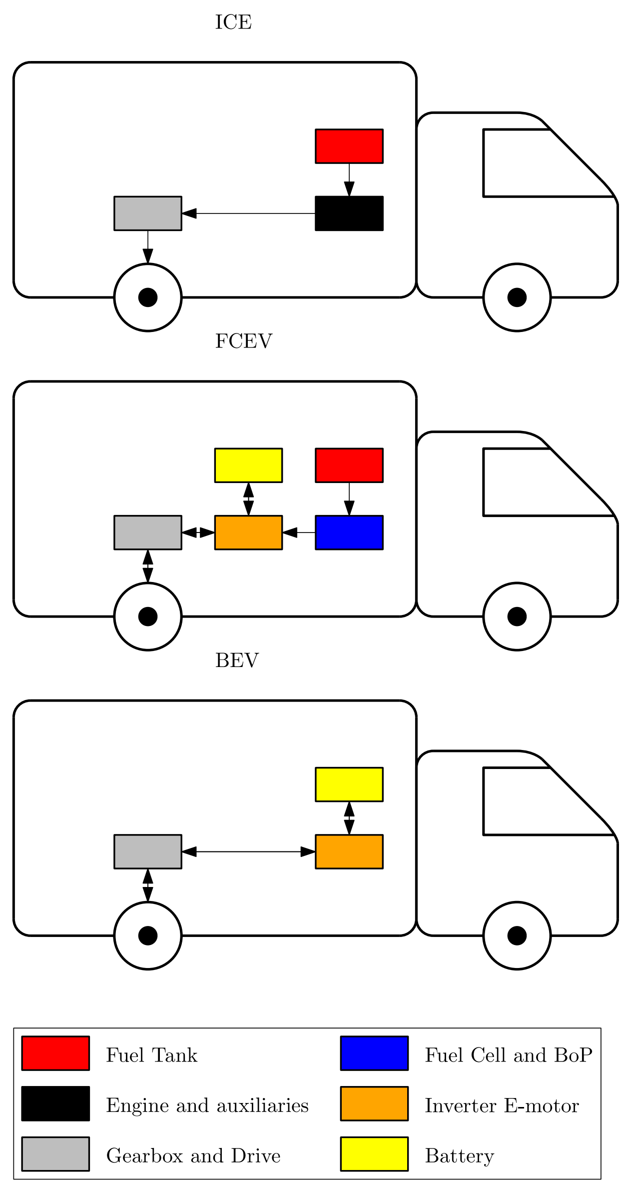

Fig. 1. Analyzed drivetrain configurations.

Table 2
Trucks characteristics and assumptions for each weight class, retrieved from [25,33].

Vehicle weight class [t]	Unladen weight [kg]	Fuel and tank mass [kg]	Engine and gearbox mass [kg]	P_{aux} [W]	Front area [m^2]	C_x	k_1 [10^{-3}]
3.5	2122	82	262	1680	4.56	0.46	2.15
5.2	114	346	1680	4.86	0.53	2.50	
18	3812	254	440	1960	7.17	0.69	3.25
44	8438	688	1128	2520	9.34	0.79	3.75

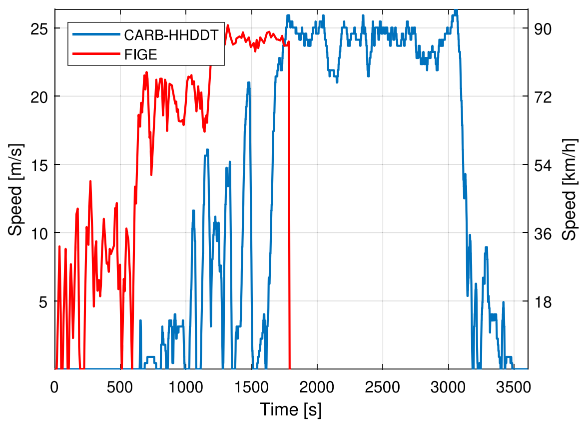

Fig. 2. Velocity profiles for CARB-HHDDT and FIGE driving cycles.

The vehicle's instantaneous acceleration is derived from the driving cycles speed v.

The number of cycles needed to cover the total distance of the selected driving range (100, 300, 500, or 700 km), is:

$$n_{\text{cycles}} = \frac{DR}{\int_0^T v\,dt}, \tag{1}$$

where T is the total time needed to cover one cycle (3,600 s and 1,800 s for the CARB-HHDDT and the FIGE cycles, respectively) and DR is the driving range [m].

2.2. Powertrains

The two main constraints considered to calculate the optimal size of the components of the vehicles are: **(a)** the powertrain is designed on the maximum power requested by the driving cycle, and **(b)** the energy stored on-board has to be sufficient for the desired driving range. The instantaneous power requirement of the vehicle is calculated according to the longitudinal balance of forces applied to the vehicle. The resistance force is given by Eq. (2):

$$F_{\text{res}} = \frac{1}{2}\rho v^2 S C_x + M\,g\,(k_1 + k_2 v^2) + M\,a, \tag{2}$$

where $\rho = 1.22\,\text{kg/m}^3$ is the air density, S the front area [m^2], C_x the aerodynamic coefficient [-], M the vehicle total mass [kg], k_1 and k_2 the coefficients for roll friction resistance, g and a the gravity and the instantaneous acceleration respectively [m/s^2]. Values of S, C_x and k_1 for the different vehicle weight classes are reported in Table 2, while k_2 is a constant value of 1.8×10^{-6} s^2/m^2 [25,32]. The rolling resistance is modeled with a constant term and a term proportional to the squared speed. Such an approach has been specifically developed and extensively validated to model trucks rolling resistance [25,32]. We note that the first and second term in Eq. (2) are always positive representing the resistive part of the vehicle dynamics. Whereas, the third term is positive when acceleration is positive (speed increases), and is negative when acceleration is negative (speed decreases).

We then evaluate the mechanical power that has to be provided to the wheels as:

$$P_{\text{w}} = F_{\text{res}} v. \tag{3}$$

Table 3
Parameters of the vehicles' powertrain [25,34].

Parameter		Value
Drivetrain efficiency	η_{drt}	0.892
3.5t ICE efficiency	$\eta_{\text{ICE}_{3.5}}$	0.236
5.2t ICE efficiency	$\eta_{\text{ICE}_{5.2}}$	0.288
18t ICE efficiency	$\eta_{\text{ICE}_{18}}$	0.268
44t ICE efficiency	$\eta_{\text{ICE}_{44}}$	0.351
3.5t H2-ICE efficiency	η_{H_2}	0.212
5.2t H2-ICE efficiency	η_{H_2}	0.259
18t H2-ICE efficiency	η_{H_2}	0.241
44t H2-ICE efficiency	η_{H_2}	0.316
EM efficiency	η_{EM}	0.97
Generator efficiency	η_{G}	0.96
Charge efficiency	$\eta_{\text{b,charge}}$	0.96
Discharge efficiency	$\eta_{\text{b,discharge}}$	0.96
Diesel tank weight	α_{diesel}	0.2 kg/kg$_{\text{fuel}}$
Hydrogen tank weight	α_{H_2}	12 kg/kg$_{\text{fuel}}$
EM specific weight	β_{EM}	0.95 kg/kW
ICE specific weight	β_{ICE}	3.0 kg/kW
FC specific weight	β_{FC}	2.5 kg/kW
Battery specific weight	β_{b}	2 kg/kW
Battery energy density		140 Wh/kg

The payload σ [kg] is the difference between the vehicle weight and the unladen weight, also considering fuel and tank mass. Each powertrain has a different payload, since the weight of the storage tank and of the drivetrain is a function of the used technology. Table 3 reports the parameters used to evaluate the mass and volume of each powertrain.

For the WTW analysis, we calculate the following consumption C and specific emissions E [25,35,36]:

$$C = \frac{\Gamma_{\text{mission}}\,c}{\sigma\,DR}, \tag{4a}$$

$$E = \frac{\Gamma_{\text{mission}}\,e}{\sigma\,DR}, \tag{4b}$$

where c and e are the consumption and emissions factors of the selected fuel, respectively. Their values are reported in Table 4, and are retrieved from a detailed study of JRC [35]. The consumption factor is the inverse value of the efficiency. Γ_{mission} is the energy consumed by the vehicle to transport the required payload over the specified driving range, considering all auxiliaries. For ICEs, H2-ICEs, C-FCEVs, and V-FCEVs, $\Gamma_{\text{mission}} = m_{\text{fuel}} \cdot LHV_{\text{fuel}}$. For BEVs, Γ_{mission} is the electric energy needed to recharge the battery stack. c and e take into consideration all the conversion steps prior to the final use. Specifically, we assume conventional diesel production for ICEs, renewable grid energy for BEVs, and green hydrogen for H2-ICEs, C-FCEVs, and V-FCEVs. The green hydrogen factors account for the losses during the H_2 production, storage, and usage. In particular, we assume local green H_2 generation from renewables at the refueling site, i.e., no transportation losses. A PEM electrolyzer generates H_2 (average efficiency 75%) from PV or wind power plants and a reciprocating compressor (average efficiency 90%) delivers it to station refueling tanks. Then, the hydrogen is converted to electric energy by the onboard fuel cell assuming the efficiency reported in Fig. 3.

Table 4
Consumption and Emissions factors per powertrain.

	Consumption factor c [kWhp/kWhf]	Emissions factor e [gCO_{2eq}/kWhf]
Diesel	1.21	319
RES grid	1.19	0.0
Green H_2	2.55	0.0

Table 5
Assumptions for the battery stack.

Parameter		Value
Capacity of the cell	Q_{cell}	19.6 Ah
Nominal current	I_{cell}	15 A
Nominal voltage	V_{cell}	3.24 V
Minimum State of Charge	SoC_{min}	0.25
Maximum State of Charge	SoC_{max}	0.8

2.2.1. ICE and H2-ICE

The thermal engine directly converts the fuel energy from the tank into mechanical energy to the gearbox, the mechanical drive, and the wheels (see Fig. 1). The following sizing procedure is valid for both conventional (diesel) and non-conventional (hydrogen) fuels.

The engine power is calculated in Eq. (5):

$$P_{eff}^{ICE} = \frac{max[0; P_w]}{\eta_{drt}} + P_{aux}, \tag{5}$$

where P_{eff} is the effective powertrain power, η_{drt} is the drivetrain efficiency, while the auxiliary power P_{aux} includes water pump, cooling fan, air compressor, and oil pump (see Table 3). We note that only positive values of P_{eff} must be considered, because negative values are handled by the braking system.

The mass of fuel needed for an ICE vehicle to cover the desired range is expressed as follows:

$$m_{fuel}^{ICE} = \frac{\int_0^T P_{eff}^{ICE}\, dt}{\eta_{ICE}}\, n_{cycles}\, \frac{1}{LHV_{fuel}}, \tag{6}$$

where LHV_{fuel} is the Lower Heating Value of the fuel (diesel or hydrogen) and η_{ICE} must be selected among the four weight classes.

The mass of the tank and the prime mover mass are evaluated as follows:

$$m_{tank}^{ICE} = m_{fuel}^{ICE}\, \alpha_{fuel}, \tag{7}$$

and:

$$m_{pm}^{ICE} = P_{eff}^{ICE}\, \beta_{ICE}, \tag{8}$$

where α and β are the tank weight and specific weight, respectively (see Table 3).

2.2.2. BEV

As zero-emissions vehicles, BEVs convert the electrochemical energy of the on-board batteries into mechanical energy of the wheels. No fuel is stored on board the vehicle, while the battery pack is recharged externally from the grid.

The effective power of the electric vehicles P_{eff}^{EV} (i.e., BEVs, C-FCEVs, and V-FCEVs), is:

$$P_{eff}^{EV} = P_w \frac{1}{\eta_{drt}} \qquad \text{if } P_w > 0, \tag{9a}$$

$$P_{eff}^{EV} = P_w\, \eta_{drt} \qquad \text{if } P_w \le 0. \tag{9b}$$

This equation differs from Eq. (5) because it can also reach negative values that can be partly recovered by regenerative braking. We assume that regenerative braking power cannot exceed the maximum power that the battery can supply to the electric motor. Any excess value is managed through the conventional braking system.

Consequently, the electric motor power P_{EM} is evaluated as follows:

$$P_{EM} = P_{eff}^{EV} \frac{1}{\eta_{EM}} \qquad \text{if } P_{eff}^{EV} > 0, \tag{10a}$$

$$P_{EM} = P_{eff}^{EV}\, \eta_G \qquad \text{if } P_{eff}^{EV} \le 0. \tag{10b}$$

where $\eta_{EM} = 0.97$ and $\eta_G = 0.96$ are the efficiency of the electric motor and the generator, respectively [25]. In these cases, the auxiliary power P_{aux} is directly electrical power that has to be supplied by the fuel cell and the buffer battery.

The batteries are assumed to be of the Li-ion type and the data reported in Table 5 are used, while we select a voltage of 400 V for the EM, since it is the conventional architecture for electric vehicles, in spite of the emerging 800 V models [37]. An inverter is placed between the battery stack and the electric motor.

For each cell, we assume the nominal voltage and current, as well as the weight and energy capacity. Since the nominal voltage of the single cell, V_{cell}, is known, the number of cells in series, n_s, is:

$$n_s = \frac{400\,V}{V_{cell}}. \tag{11}$$

Similarly, the number of strings in parallel, n_p, is evaluated as the greatest value between $n_{p,1}$ and $n_{p,2}$, where $n_{p,1}$ is the lowest number of parallels which guarantees that the minimum battery power, $P_{b,min}$, is equal to the rated EM power, $P_{EM,max}$:

$$n_{p,1} = \frac{P_{EM,max}}{n_s\, V_{cell}\, I_{cell}\, \overline{\eta}_b}, \tag{12}$$

where $\overline{\eta}_b$ is the average value for the battery efficiency, V_{cell} is the nominal cell voltage and I_{cell} is the nominal continuous current, and P_{EM} is the power of the electric motor; $n_{p,2}$ is the number of stacks in parallel, which allows the battery to satisfy the driving range:

$$n_{p,2} = \frac{Q_{b,d}}{Q_{cell}}, \tag{13}$$

where Q_{cell} is the nominal capacity of the individual cell, and $Q_{b,d}$ is the desired battery capacity, given by the following equation:

$$Q_{b,d} = \frac{\Gamma_{mission}}{V_b\, \overline{\eta}_b\, |\Delta SoC_{max}|}. \tag{14}$$

In case the battery's power is greater than the rated power of the electric motor, $P_{EM,max}$, multiplied by a specific tolerance factor that takes losses and inefficiencies into account:

$$n\, P_{cell} \ge 1.1\, P_{EM,max} \text{ AND } n_s\, V_{cell} > 350\,V, \tag{15}$$

then the number of cells in series is decreased by one unit $n_s' = n_s - 1$ and the total number of cells becomes:

$$n = n_s'\, n_p \qquad , \tag{16}$$

where $350\,V = 0.875 * 400\,V$, considered as safety factor [38]; n is the total number of cells in the battery. Such procedure is repeated iteratively until the condition is verified. We assume that we do not oversize the battery and the power.

2.2.3. C-FCEV

The fuel cell provides a steady, fixed power output, and it is designed to supply a consistent amount of power regardless of changes in driving conditions or demand. Since the power output of the fuel cell is constant, the energy management system of the vehicle must balance the energy demands between the fuel cell and other power sources (e.g., battery). When extra power is necessary, the vehicle will draw from the battery. In contrast, during periods of reduced power demand, surplus energy can be utilized to replenish the battery (see Eq. (9)). The buffer battery is smaller than that of a battery electric vehicle but is sized following the same procedure described for BEVs.

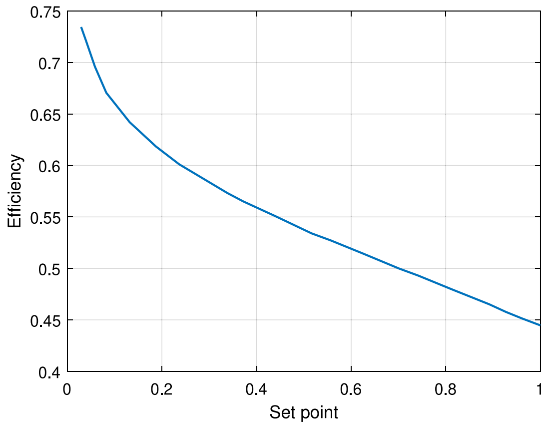

Fig. 3. Fuel Cell efficiency curve, adapted from [43]. Horizontal axis represents the ratio between actual power and nominal power. The vertical axis represents the efficiency calculated as the ratio between output electric power and input chemical power (fuel).

Efficiency is potentially higher than in a V-FCEV, provided that the Fuel Cell operates in its optimal range for a given driving condition.

The nominal power rate for the FC, P_{FC}, is selected as such to cover the power demand at constant maximum highway speed. To cover all European countries, we assume 100 km/h for light-duty vehicles (i.e., 3.5 t and 5.2 t) and 90 km/h for heavy-duty vehicles (i.e., 18 t and 44 t). The mass of hydrogen needed for the desired driving range is calculated as follows:

$$m_{\text{fuel}}^{\text{C-FCEV}} = \frac{\int_0^T P_{FC}\, dt}{\eta_{FC}\, LHV_{H_2}}\, n_{\text{cycles}}. \tag{17}$$

The tank mass and the prime mover mass are evaluated as follows:

$$m_{\text{tank}}^{\text{C-FCEV}} = m_{\text{fuel}}^{\text{C-FCEV}}\, \alpha_{H_2}, \tag{18}$$

and:

$$m_{\text{pm}}^{\text{C-FCEV}} = P_{FC}\, \beta_{FC}, \tag{19}$$

The battery size is calculated with the same algorithm described for BEVs, as well as the EM sizing and payload calculations.

Regarding the power efficiency curve of the PEM-FC, we select the one reported in Fig. 3, which is representative of the state-of-the-art characteristic curves for efficient PEM fuel cells. We select a tank density of $\alpha_{H_2} = 12\,\text{kg/kg}_{\text{fuel}}$, which is in the lower end of the density range for hydrogen tanks ($12 \div 24\,\text{kg/kg}_{\text{fuel}}$) [25,39–42].

2.2.4. V-FCEV

While C-FCEVs have a better management of the FC and lower consumption rates, V-FCEVs manage to reduce the size of the powertrain and of the buffer battery, thus reducing capitals costs associated with their purchase. In fact, the fuel cell can adjust its power output based on driving conditions, to meet the specific demands of the vehicle (see Eq. (9)). The battery still assists in providing extra power during acceleration or during demand pikes. When the vehicle's requirements during the driving cycle change consistently, the V-FCEV allows the fuel cell to operate more efficiently because it can adjust its output to match the exact vehicle's requirements. At the same time, V-FCEV adds complexity, both structural and electronic, to the powertrain design.

For powertrain and battery sizing, the difference with C-FCHEV is that the power of the FC follows the load of the driving cycle, whereas the characteristic curve is assumed equal to that of the C-FCEV (see Fig. 3).

The power of the FC is calibrated to cover 95 per cent of the power spectrum required during the driving cycle, i.e., the highest 5 per cent of the power required during the cycle is covered by the battery.

2.3. Cost analysis

The TCO analysis aims to provide a comprehensive perspective on the costs associated with a particular vehicle throughout its lifespan. The TCO is calculated by summing all costs incurred over the vehicle's lifetime, including purchase costs, fuel costs, insurance, maintenance, taxes, and other expenses. The cost analysis is conducted assuming the current scenario (as of 2025) for all cost entries. Moreover, to add generality to the work, we consider the historical cost range for electricity between 2008 and 2024 and for diesel fuel cost between 2005 and 2025. For electricity cost, we also evaluate values associated to fast-charging applications (see Sub Section 2.3.2). Also, we select the hydrogen cost assuming the current expectations and estimates from the EU Commission [44,45], i.e. an average hydrogen cost of 5 €/kg. However, to generalize the work, we have considered a cost range also for hydrogen (see Sub Section 2.3.2).

The major cost components include vehicle purchase cost, fuel cost, insurance, maintenance and repair costs, taxes and fees, and road tolls.

The TCO is defined as follows [27,46]:

$$\text{TCO} = \sum_{j=1}^{J} \frac{G_j}{(1+i)^j}, \tag{20}$$

where G_j (in €) is the total cash flow of the jth year, i (in %) the discount rate and J is the final year of the analysis. We assume the discount rate i to be equal to 7%. The total yearly cash flow G_j can be determined by summing all the costs incurred in the year jth, considering both fixed costs $G_{\text{fixed},j}$ (in €) and variable costs $G_{\text{var},j}$ (in €/km, depending on the yearly mileage) of the jth year:

$$G_j = G_{\text{fixed},j} + D_j\, G_{\text{var},j}, \tag{21}$$

where D_j is equal to the kilometers traveled by the vehicle in the jth year.

Since we are analyzing commercial vehicles, the payload plays a key role in defining the performance of a powertrain. Therefore, we also define the Levelized cost of transportation [27,47]:

$$\text{LCOT} = \frac{\text{TCO}}{\sum_{j=1}^{J} \frac{D_j\, TW}{(1+i)^j}}. \tag{22}$$

TW is the transported weight per year. The LCOT is expressed in €/(km·kg) and is amortized over the distance driven throughout the vehicle's life. For all cases discussed in this work, we assumed that the truck travels five days/week and 50 weeks/year. This assumptions are subjected to variations depending on the country's legislation and companies policy [48].

2.3.1. Capital costs

The Total Purchase Cost (TPC) of the vehicle is defined as follows:

$$\text{TPC} = G_{\text{purchase}}\, (\text{RPE} + \text{VAT}), \tag{23}$$

where G_{purchase} is the direct purchase cost, RPE is Retail Price Equivalent factor, assumed equal to 1.36 [27], and VAT = 0.2 is the Value Added Tax. The RPE is used to take indirect costs and net profit into account, when only direct costs are available, as in our case. The direct costs can be assumed as the sum of the components of the vehicle, where the powertrain represents the larger fraction. A summary of all the components' costs for traditional ICE vehicles is displayed in Table 6, while BEV and FCEV costs are retrieved from [27], where the breakdown into the main components is performed. We assume only day cabs, thus disregarding energy demands and costs associated with sleeper cabs.

We assume a 5-year financing, with an interest rate of 5%. We also assume that the vehicle be sold in the second-hand market after it has been used, and we evaluate the revenue RV according to the following formulation:

$$\text{RV} = \text{TPC}\, e^{(X\, x + Y\, y)}, \tag{24}$$

Table 6
Specific cost of vehicles' main components for each drivetrain analyzed, with reference. Symbols C_x are for grouping: Chassis and structure comprise the costs G_1 and G_2 from Table 6; Battery, EM and management comprise the costs G_{3-10} and G_{16-17}; FC and H_2 storage comprise the costs G_{11} and G_{12}.

	Component	Cost	Unit	Reference
G_1	Cab, cooling modules, chassis & driveline	19,150	€	[28,49]
G_2	Electrical & wires, HVAC, air brakes	6380	€	[49]
G_3	Battery specific cost	230	€/kWh	[49,50]
G_4	On-board charger	65	€/kW	[28,49]
G_5	DC/DC converter	82	€	[49,51]
G_6	High Voltage distribution	25	€/kW	[28,49]
G_7	Battery/Electronics thermal management	19	€/kW	[28,49]
G_8	Electric drive unit	75	€/kW	[49]
G_9	Air compressor	1360	€/kW	[28,49]
G_{10}	Steering pump system	273	€/kW	[28,49]
G_{11}	FC specific cost	430	€/kW	[52]
G_{12}	Hydrogen storage	1435	€/kg	[49,53]
G_{13}	Internal Combustion Engine	55	€/kW	[54,55]
G_{14}	Aftertreatment unit	0.71	€/t	[54]
G_{15}	Transmission	5320	€	[54]

where x is the vehicle age (in years) at the end of the analysis, y is the cumulative mileage (in km), and X and Y are coefficients defined as: $\exp(X) = 0.911$ and $\exp(Y) = 0.999$.

2.3.2. Fuel costs

We estimate the energy consumption EC by performing the integral of the power profiles of the cycles.

The assumed hydrogen cost range varies between 2 €/kg and 8 €/kg. Such range has been retrieved from the latest available estimates and projections of the European Commission [44,45]. These values take into consideration possible reductions of the cost of hydrogen technologies and also variable renewable energy prices. Up to now it is not clear how hydrogen will be subject to taxation, however, the assumed range is broad enough to eventually consider also the after tax cost.

The electricity cost range lies between 0.214 €/kWh and 0.9 €/kWh. The lower value is the average European electricity price between 2008 and 2024 [56,57] and represents the case in which slow charging mode is adopted. Vice versa, the higher value represents the cost for fast charging [58]. Therefore, the analyzed range can cover the whole spectrum of electricity vehicle usage. The assumed values are considered after taxation.

The diesel fuel cost range goes from a minimum of 0.984 €/l to a maximum of 2.034 €/l representing the historical average European price between 2008 and 2024 after tax [59].

2.3.3. Maintenance and repair

The costs of maintenance and repair over the course of a vehicle's life depend upon the vehicle weight class and powertrain technology. From [60] it is possible to infer the sum of maintenance and repair costs (i.e., $G^{M\&R}$) for the five typologies of powertrain studied in this work. Subsequently:

$$\mathrm{TCO}_{M\&R} = \sum_{j=1}^{J} \frac{G^{M\&R}}{(1+i)^j}. \tag{25}$$

In particular, the cost of replacing the vehicle main propulsion components entirely or in part because of deterioration are included in the midlife overhaul costs. In the case of BEVs, midlife costs include battery pack replacement. We assume a battery is deemed unsuitable for vehicle use as soon as its capacity falls below 80% (see for instance [61]). The battery lifetime in this study is set at 500,000 kilometers; if this mileage is not reached in ten years, it is expected that the battery will need to be replaced in the tenth year (see for instance [27]). The replaced battery is given a residual value that is equivalent to 15% of the original purchase price.

As for the fuel cells, we assume that the efficiency becomes too low for mobile applications after a lifetime of 15,000 h is reached [62]. The residual value of the fuel cell stack is set at 25% of its initial value, and like batteries, it can be sold on the second-hand market and used for stationary applications.

2.3.4. Other fixed costs

We neglect the costs derived from road tolls, fees, and drivers' salaries. In fact, the main purpose of this work is to compare different technologies and such costs would have the exact same impact on each. Also, we assume that electric vehicle charging takes place during mandatory driver stops. Such assumption, besides being reasonable, is also conservative towards the thesis of the paper to show the economic feasibility of hydrogen vehicles. In fact, considering that the driver has to be paid also during charging process would disadvantage economic figures of the electric vehicles.

Specific costs are reported in Table 6, which are used to find the total capital cost per powertrain.

3. Results and discussion

The results of the sizing procedure are first discussed. We then comment the comparison between all the drivetrains in terms of costs and competitiveness in the road freight transportation market.

3.1. Powertrain sizing

The results of the sizing procedure for the V-FCEV vehicles are shown in Fig. 4.

While the categories 3.5 t and 5.2 t exhibit a denser presence of the lower power ranges (< 50 kW), vehicles in the range 18 t to 44 t have a much smoother distribution in the power spectrum. This is due to the different cycles adopted in the two cases (CARB-HHDDT for light-duty, FIGE for heavy-duty trucks). The rise in power is strongly non-linear, since it increases from 57.6 kW to 275.5 kW when shifting from a 3.5 t vehicle to a 44 t tractor trailer. For C-FCEVs, the FC power is constant. Its nominal value is such to guarantee the energy equilibrium with the buffer battery and the requested power. Therefore, P_{FC} is 10.9 kW for 3.5t, 14.3 kW for 5.2t, 45.1 kW for 18 t, and 90.8 kW for 44 t.

Following the results of such sizing procedure, we are able to calculate the payload for each drivetrain configuration (see Table 7).

Conventional ICEs require a larger installed power than FCEVs due to the absence of a buffer battery, i.e., the engine covers the whole power spectrum. Similarly to FCEVs, the power size does not scale linearly with the weight class, since it ranges from 67.4 kW to 391.9 kW (a factor of ≈ 6), while the weight increases by a factor of 12.5.

The capacity of the battery stacks on-board BEVs increases significantly with the driving range, since they store the energy required to cover the mileage. Such capacity can be up to twelve times larger than that of a C-FCEVs for $DR = 700$ km, irrespective of the weight class. On average, V-FCVEs reduce the capacity of the buffer battery by 56.2% compared to C-FCEVs, thanks to the load-following mode of the FC.

The payload of all configurations is very similar, except for the BEVs, which especially at high daily mileage, present a relevantly lower payload, due to the high specific weight of on-board batteries. At lower weight classes (i.e. 3.5 t) this aspect is even more relevant making the payload null for daily mileage of 300 km, since all the storage mass is occupied by the battery. Such result suggests that light-duty commercial vehicles can be hardly decarbonized by BEVs. In the rest of the paper we do not represent such zero-payload configurations that would lead to infinite LCOT values. For BEVs, the cargo space utilization efficiency (payload/total weight) ranges between 27% ÷ 74%, when $DR = 100$ km and $DR = 700$ km, respectively. For all the other powertrains, it ranges between 34% and 78%.

At the same time, BEVs have a lower energy consumption thanks to higher drivetrain efficiencies (there are less mechanical components

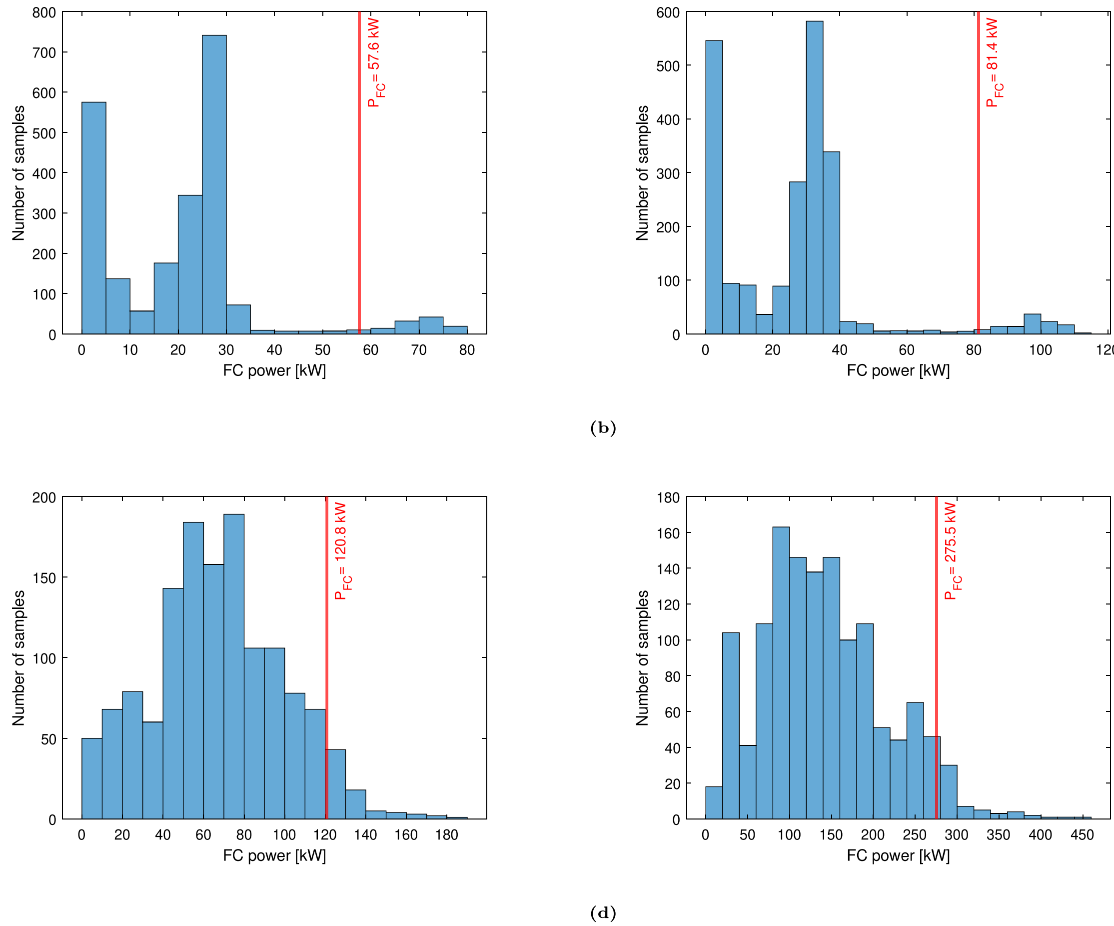

Fig. 4. Results of the sizing procedure of V-FCEVs for (a) 3.5 ton, (b) 5.2 ton, (c) 18 ton, and (d) 44 ton. For each sub-figure the horizontal axis represents the required power from the vehicle, while the vertical axis represents the number of time-steps in the driving cycle at which such power is required. By analyzing the represented distributions we can design the fuel cell nominal power for each weight class. The red vertical line represents the selected nominal power. The buffer battery will be used in parallel to the fuel cell when the required power is higher than the nominal power. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 7
Sizing results of the C-FCEVs. Nominal power refers to the internal combustion engine power for ICE and H_2-ICE cases, to electric motor power for BEV case, and to FC power for C-FCEV and V-FCEV cases. *low value for $DR = 100$ km, high value for $DR = 700$ km; † low value for $DR = 100$ km, high value for $DR = 300$ km.

		Rated Power [kW]	Capacity [kWh]	Payload* [kg]	En. Consumption* [$\frac{kWh}{km \cdot t}$]	Fuel mass* [kg]
ICE	3.5t	67.4	–	1,446–1365	1.13–1.19	11.4–79.6
	5.2t	94.7	–	3,031–2945	0.56–0.58	12.0–83.8
	18t	161.9	–	14,410–14,218	0.26–0.27	26.7–187.0
	44t	391.9	–	36,200–35,900	0.16–0.17	41.7–291.9
BEV	3.5t	75.6	54.9–342.9*	1258–573 †	0.29–0.63 †	–
	5.2t	106.1	61.7–432.1*	2849–204	0.16–2.25	–
	18t	181.5	130.3–905.3*	13,780–8243	0.07–0.12	–
	44t	439.3	260.6–1,797*	35,100–24,126	0.05–0.08	–
C-FCEV	3.5t	30.4	28.7	1348–1222	1.02–1.12	1.61–11.3
	5.2t	38.6	39.4	2886–2727	0.60–0.64	2.04–14.3
	18t	65.7	63.0	14,034–13,664	0.29–0.29	4.74–33.2
	44t	121.8	149.6	35,463–34,717	0.23–0.23	9.57–66.97
V-FCEV	3.5t	57.6	13.7	1530–1397	0.95–1.04	1.71–11.96
	5.2t	81.4	13.7	3164–2993	0.59–0.62	2.18–15.30
	18t	120.6	28.5	14,440–14,034	0.30–0.31	5.09–35.6
	44t	275.5	70.9	36,321–35,520	0.24–0.25	10.3–71.9
H2-ICE	3.5t	67.4	–	1402–1052	2.72–3.62	4.5–31.4
	5.2t	94.7	–	2,984–2616	1.34–1.53	4.7–33.0
	18t	161.9	–	14,305–13,483	0.63–0.66	10.5–73.7
	44t	391.9	–	36,036–34,753	0.39–0.40	16.4–115.1

in the energy transmission chain). This is an indication of the high efficiencies of EMs and battery packs. Such result finds validation in literature, in fact a detailed report was drawn to quantify a comparison between BEVs and H_2-fueled vehicles by Wallington et al. [63], which shows that electric heavy-duty trucks can be 3 to 4 times more efficient than H_2 alternatives. They also comment that heavy-duty BEVs face significant challenges as for the payload efficiency and the overall weight of the battery pack. Conventional ICEs and FCEVs have similar consumption rates, and both can be slightly more convenient than each other depending on the truck weight. C-FCEVs and V-FCEVs exhibits very similar consumption rates, though C-FCEVs present slightly lower values, except for 100 km. Finally, H2-ICE present the highest energy consumption due to the lower efficiencies of the hydrogen thermal engines, also with respect to fuel cells, which directly convert the chemical energy of hydrogen into electric energy. We comment that energy consumptions decrease with the weight of the vehicle, as expected, for all drivetrain configurations (see Table 4 for primary consumption rates and emission factors).

Conventional and H_2 ICEs store different amounts of fuel on board the truck, due to the huge difference in the fuel weight (liquid diesel and gaseous hydrogen).

3.2. Purchase costs

Purchase costs for BEVs, C-FCEVs, and V-FCEVs and four weight categories are shown in Fig. 5. The *Chassis and structure* costs are constant in all cases, since it includes common components of the vehicle assembly in all configurations and does not depend on the driving range (namely, G_1 and G_2). *Battery, EM and management* includes the electric/electronic components, on-board charger, the battery pack and its thermal management/cooling systems, as well as the converter unit (namely G_{3-10} and G_{16-17}). As such, this cost is constant for FCEVs since the FC is the only component growing with the driving range, whereas it increases with the driving range in the BEVs. *FC and H_2 storage* comprises of the fuel cell system and hydrogen on-board storage tank (namely, G_{11} and G_{12}).

The driving range affects the costs directly being proportional to the energy to be stored on-board, either in the battery or in the hydrogen tank. BEVs appear to have the lowest purchase costs at lower driving ranges, due to the absence of the hydrogen and Fuel Cell-related costs. However, when the driving distance is greater than or equal to 300 km in the 3.5 t category, the payload is completely occupied by the battery, whose energy density is much smaller than that of hydrogen. This implies that FCEVs are more competitive at greater distances. This remains true for all of the four categories, albeit the percentage advantage is lower at higher weights. In fact, for $DR = 700$ km, the purchase cost of a 44 t BEV is 32.3% more onerous than a V-FCEV, while a 5.2 t BEV is 47.8% more onerous than a V-FCEV. Such advantage is indeed mitigated for lower driving ranges. In fact, for $DR = 300$ km, a 3.5 t BEV is 30.3% more expensive than a V-FCEV, while it is 4.4% more convenient in the 44 t class.

V-FCEVs are slightly less onerous than C-FCEVs. This is due to a smaller battery pack, whose cost is relevant. Conversely, hydrogen storage and FC weight slightly more than in the C-FCEV configuration, due to the higher fuel consumptions. Nonetheless, even for a driving range of 700 km, V-FCEVs are 6.6% less expensive in the 3.5 t category, and 3.7% less expensive in the 44 t category.

In all cases, BEVs purchase cost present a sharp increase with the driving range, due to an ever-increasingly big battery stack.

3.3. TCO and LCOT

The TCO of the four vehicles weight categories, broken down into powertrain configurations and driving range, is shown in Fig. 6. In the BEV case, *fuel* refers to the electric energy. In such figure we represent the variation of the TCO due to the fuel costs ranges described in Sub Section 2.3.2 with a black interval bar overlapping the fuel cost bar. Considering average fuel costs, BEVs present a less competitive TCO than FCEVs for all weight classes. The TCO gap becomes larger for longer driving ranges. Also, for driving ranges from 500 km and upward the FCEVs with maximum hydrogen cost (i.e 8 €/kg) are less costly than BEVs with minimum electricity cost (i.e. 0.214 €/kWh). Particularly significant is the *midlife* cost for BEVs, especially at increasing driving ranges, due to the battery stack replacement. This item is much less relevant for FCEVs, where the dominant entry is the *maintenance*, which also increases with the driving range.

The TCO increases with the weight of the vehicle, due to the increase of both CAPEX and OPEX. It also increases with the driving range, which is primarily due to the increase in the battery pack/fuel costs and to maintenance costs. Overall, V-FCEVs appear to be more expensive than C-FCEVs in all weight classes, due to higher fuel costs, whereas CAPEX costs are slightly lower thanks to lower battery costs. In fact, considering the average hydrogen cost, TCO for V-FCEVs is 7.4% higher than for C-FCEVs on average (the gap is 5.6% for 3.5 t vehicles, and 10.9% for 44 t vehicles).

Considering heavy-duty trucks, for which we can compare the technologies over the entire driving ranges, at $DR = 100$ km BEVs are 14.4% more expensive than V-FCEVs for a 18 t truck, while 4.9% more expensive for a 44 t truck, with average fuel costs. Whereas, for $DR = 700$ km, BEVs are 52.6% more expensive than V-FCEVs for a 18 t truck, while 52.9% more expensive for a 44 t truck, with average fuel costs. This confirms that the gap between BEVs and FCEVs increase with the daily mileage, due to expenses associated with the battery pack. We also note that, considering 44 t weight class for $DR = 700$ km the BEV TCO with minimum electricity cost is 18.6% higher than the V-FCEV TCO with maximum hydrogen cost. Proving that fuel costs variability does not compensate for structural cost increases due to battery and midlife.

The LCOT of the four vehicles' categories is shown in Fig. 7. Also in this figure we represent the variation of the LCOT due to the fuel costs ranges described in Sub Section 2.3.2 with a black interval bar overlapping the fuel cost bar. For all weight classes, the LCOT of BEVs is more competitive than that of FCEVs for very short driving ranges (e.g., 100 km) and only considering minimum electricity cost and maximum hydrogen price. For longer driving ranges FCEVs become less expensive with the advantage augmenting with increasing driving ranges. This is mainly due to the very high costs associated with the purchase and replacement of the battery stack (CAPEX and midlife, respectively). In fact, BEVs costs are impaired by midlife interventions, which are negligible for FCEVs. Furthermore, the LCOT decreases with increasing driving ranges for FCEVs, since the increase in costs is overcompensated with a longer transport distance. This is not the case for BEVs, whose LCOT increases exponentially for light-duty vehicles while presenting a quadratic trend for heavy-duty vehicles. In fact, LCOT of BEVs present a minimum at 300 km for 18 t and 44 t weight classes. V-FCEVs are slightly more competitive than C-FCEVs thanks to a better management of the FC and a smaller battery stack, whose cost is significant in the C-FCEVs. However, we comment that the gap is negligible especially for heavy-duty trucks. For the 5.2 t class, the BEVs exhibit a sharp increase in the LCOT as the driving range approaches 7500 km, due to the cost of the battery (both first purchase and future midlife replacement) and to the sharp decrease of the payload. For this reason, we decided not to represent the value in Fig. 7 to not affect the overall graph proportions. With regards to heavy-duty vehicles (18 t and 44 t), costs are significantly smaller than for light-duty vehicles, thanks to a relevantly bigger payload. This over-compensates the increase in costs. In this case, there is no clear linear behavior for the LCOT profile of BEVs. However, V-FCEVs are more competitive than C-FCEVs for light-duty vehicles, irrespective of the driving range. Conversely, C-FCEVs are slightly less expensive than V-FCEVs only in the heavy-duty class (i.e., 18 t and 44 t), with the two configurations yielding very similar LCOTs for lower weight classes.

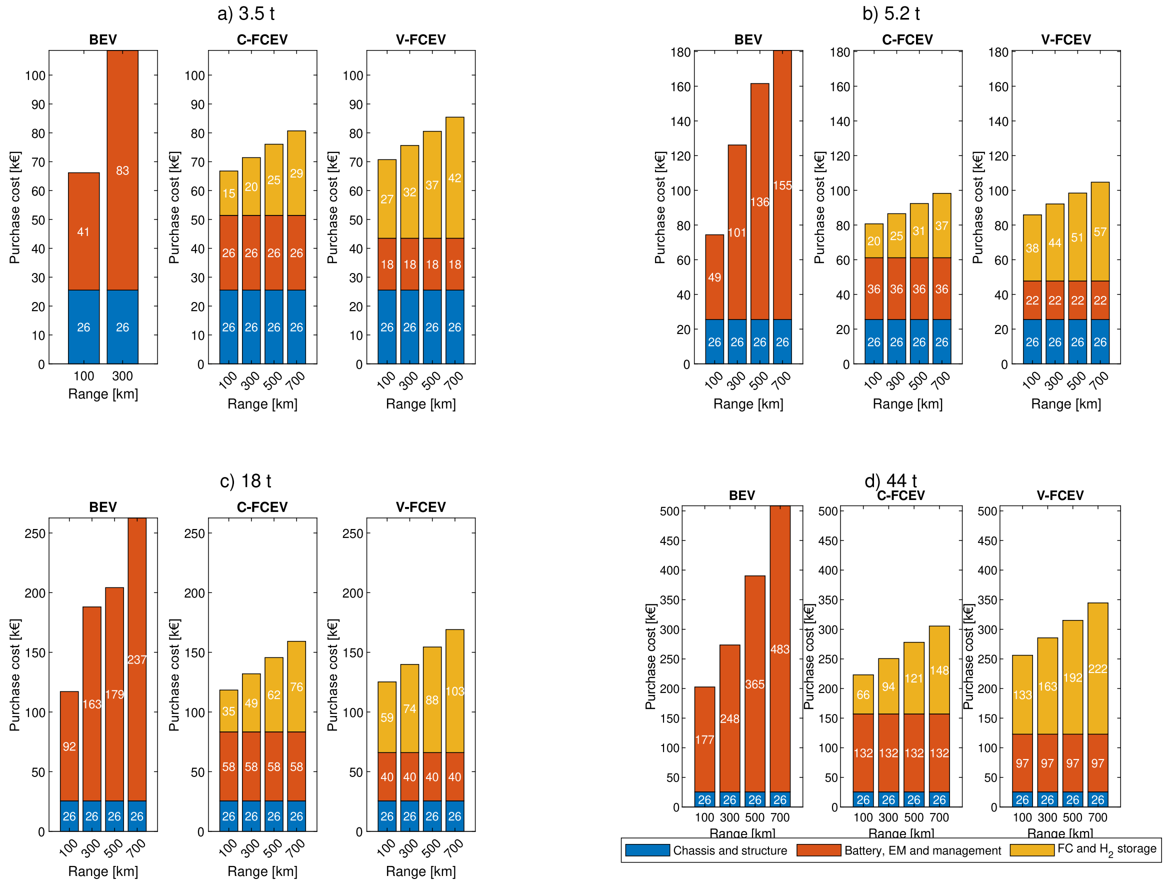

Fig. 5. Purchase cost breakdown for (a) 3.5 ton, (b) 5.2 ton, (c) 18 ton, and (d) 44 ton for three different vehicles' powertrains. Chassis and structure comprise the costs G_1 and G_2 from Table 6; Battery, EM and management comprise the costs G_{3-10} and G_{16-17}; FC and H_2 storage comprise the costs G_{11} and G_{12}.

For light-duty vehicles and $DR = 300$ km (since BEVs are not practicable at higher driving ranges), BEVs are 69.1% more expensive on average (i.e., 3.5 t and 5.2 t). For heavy-duty vehicle (i.e., 18 t and 44 t) at the same driving range, BEVs are 43% more expensive on average. This confirms the trend commented for the purchase cost, namely that the gap between BEVs and FCEVs reduce with the weight of the vehicle. Nonetheless, it remains significant. However, for heavy-duty trucks and $DR = 700$ km, BEVs are 70.2% more expensive on average (i.e., 18 t and 44 t), i.e., the gap between BEVs and FCEVs increases with the driving range.

3.4. Discussion

The results obtained in this paper are compared with other relevant works available in literature [25,27] to be validated. Considering the same categories of vehicles and driving cycles reported in [25] results show good agreement. For instance, the power sizing of ICE trucks is 2.9% different on average (i.e., in the four weight classes), with a standard deviation of 1.2 kW. Though it is not possible to compare BEVs and FCEVs since the authors do not differentiate in the driving range value, the payload is 0.9% different on average in the ICE category, confirming the substantial soundness of the methodology here presented.

Energy consumption contributes to the definition of the LCOT, since a higher value corresponds to lower efficiency and, thus, a higher LCOT. Lombardi et al. [25] present a consumption of 1.05 kWh/(km t) and 0.55 kWh/(km t) for ICEs at 3.5 t and 5.2 t, respectively. Furthermore, the authors claim an energy consumption of 1.05 kWh/(km t) and 0.60 kWh/(km t) for V-FCEVs at 3.5t and 5.2t, respectively. Overall, the average difference between our energy consumptions and those of [25] is 6.8% for light-duty vehicles and 3.4% for heavy-duty vehicles. Thus, our data agree well, in light of the fact that Lombardi et al. [25] only present data for a driving range of 250 km, which has been approximated to 300 km.

Compared to [27], our LCOT of V-FCEVs is 2.5% higher on average for 18 t trucks, for a driving range between 300 and 700 km, which is of interest for commercial trucks. Considering the different assumptions made, the gap is considered acceptable. Furthermore, a higher LCOT for FCEVs allows to draw more conservative conclusions when comparing with traditional ICEs or BEVs. Despite the general agreement on the numerical results, the conclusions of this work are different. In fact, the results suggest that H2-ICEs are not economically viable alternatives to FCEVs or BEVs, not even for very high daily mileages, where the LCOTs of H2-ICEs and FCEVs are very close to each other, as shown with the following analysis.

Such analysis consists in applying the methodology to two additional configurations, which do not need substantial technological or infrastructural modifications, namely conventional diesel ICE and non-conventional H_2 ICE. Fig. 8a shows the LCOT for the traditional Diesel ICE powertrain. The LCOT decreases with the driving range and weight of the vehicle, and fuel is the more impactful cost entry, followed by maintenance costs. This is a major difference with the other 3 powertrain technologies considered in this study. Considering average fuel prices and comparing Fig. 7 with Fig. 8a traditional ICE (Diesel) is the cost-optimal solution in almost any case, accordingly to what expected. However, the FCEVs are a competitive solution at middle to high mileages (i.e $\geq$ 300 km) and for low to middle class weight (i.e 3.5 t, 5.2 t, and 18 t), while also achieving zero emissions. However, the V-FCEVs is 20% more expensive than ICE at 44 t weight class for 700 km range. Therefore, FCEVs can be considered competitive,

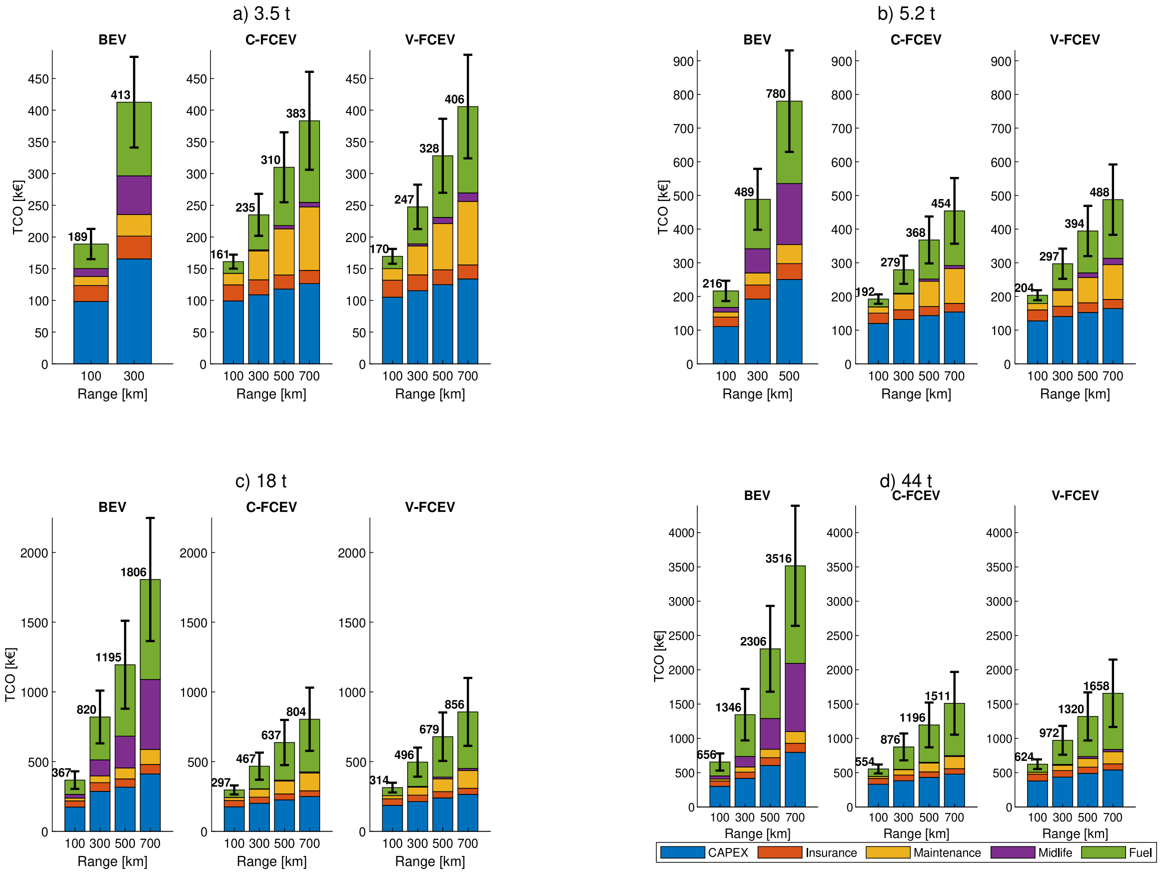

Fig. 6. TCO of BEVs and FCEVs for (a) 3.5 ton, (b) 5.2 ton, (c) 18 ton, and (d) 44 ton. The interval bars represent the fuel cost ranges discussed in Sub Section 2.3.2 for diesel, electricity, and hydrogen.

also aiming at the possible improvements that fuel cell and hydrogen technologies can still achieve. While BEVs and FCEVs are zero-emission vehicles, conventional diesel ICEs yield specific emissions between 0.311 $g_{CO_2}/(\mathrm{km\ t})$ and 0.044 $g_{CO_2}/(\mathrm{km\ t})$ when weight increases from 3.5 t to 44 t.

Diesel and hydrogen costs greatly influence the final LCOT, so great care must be taken when retrieving updated data from the energy market. In fact, selecting 44 ton class weight and 700 km range as most representative of heavy duty transportation, the ICE LCOT goes from 7.1 c€/kmt to 12.9 c€/kmt according to assumed fuel costs, while V-FCEVs goes from 8.5 c€/kmt to 15.5 c€/kmt, showing a wide overlapping region where the convenience of a technology over the other is not clearly detectable. The cost of the FC is set at a rather optimistic value (see Table 6), although retrieved from specialized literature. Similarly, the average hydrogen cost of 5 €/kg is quite low, but the future outlook confirms a descending trend for electricity [64] and hydrogen price [65]. Moreover, although current price levels for hydrogen could be higher than 5 €/kg, it is realistic to assume policies to reduce it, or additional taxation for fossil fuels [66,67]. Meanwhile, conventional ICEs are either expected to be phased out legally for environmental reasons or to be replaced by a high demand towards EVs [68].

Hydrogen-fueled Internal combustion engines were also analyzed in terms of LCOT. However, this technology is not yet ready for commercialization and it does not constitute a zero-emissions vehicle, since nitrogen oxides are released during operation [69]. Furthermore, the comparison of Fig. 7 with Fig. 8b shows that, considering average hydrogen price, the percentage difference between LCOTs of V-FCEVs and H2-ICEs goes from +1% to −116% as a function of the driving range for the 3.5 t truck. The same comparison for the 44 t truck reads values from +43% to −8%. Such figures suggest that the FCEVs are more convenient at middle to high mileages and for low to middle class weight. Therefore, similar trends to those comparing ICEs and FCEVs can be observed but with overall closer values showing weaker advantage of the H2-ICEs. In fact, despite the CAPEX is much lower for H2-ICEs, the advantage is over-compensated at high driving ranges by the higher hydrogen consumptions, i.e., by the lower efficiency of the H_2 ICE with respect to that of the FC.

Hunter et al. [70] also showed that heavy-duty trucks powered with batteries or fuel cells can be economically competitive with diesel trucks under specific conditions. In particular, the authors studied the TCO of 6 different powertrains (conventional diesel, diesel hybrid-electric, plug-in hybrid electric, compressed natural gas, fuel cell, and battery electric vehicles). FCEVs are estimated to reach parity with conventional powertrains if a hydrogen price of 4 $/kg is assumed for the ultimate technology year (2050). In fact, fuel costs are found to have the most significant impact on the final TCO. Nonetheless, the authors also conclude that BEVs may be best for short-range applications, while FCEVs perform better (economy-wise) for longer ranges.

To add generality to the results, this study also evaluates the LCOT of BEVs, FCEVs, and ICEs at higher driving ranges (i.e., 1000 km) as well (see Table 8). This scenario is more suitable for extra-European contexts, e.g., North America, where the distance between refueling stations is larger and it is often not possible to refill the tank within a working shift. Therefore, larger driving ranges are necessary to ensure operational continuity.

Moreover, the BEV LCOT increases with the driving range (see 8). Specifically, for the 44 t weight class going from 700 km to 1000 km range, the LCOT increase is 43%. Conversely, the LCOT of FCEVs and ICEs decreases on average of 4% and 6% for the 3.5 t and 44 t respectively, when the driving range goes from 700 km to 1000 km. The trend of the levelized cost is thus essentially confirmed, further

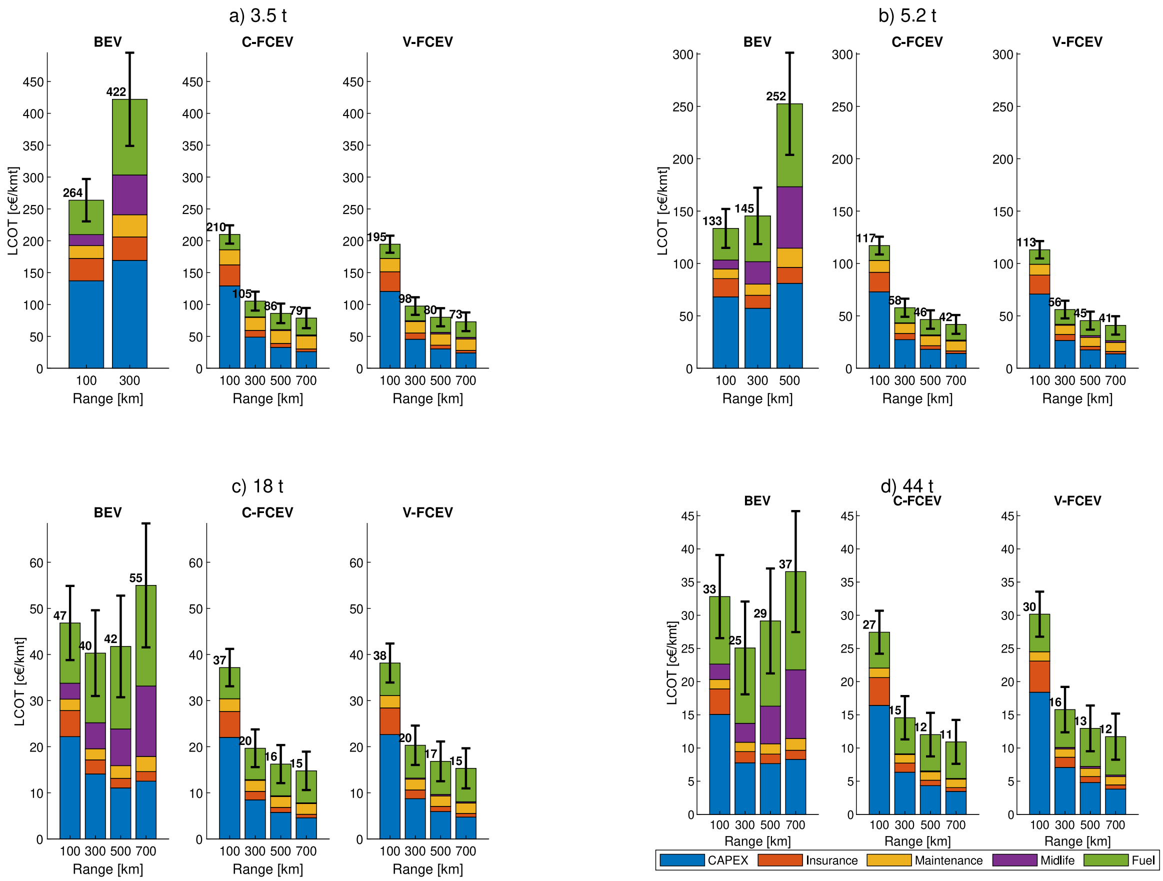

Fig. 7. LCOT of BEVs and FCEVs for (a) 3.5 ton, (b) 5.2 ton, (c) 18 ton, and (d) 44 ton. The interval bars represent the fuel cost ranges discussed in Sub Section 2.3.2 for diesel, electricity, and hydrogen.

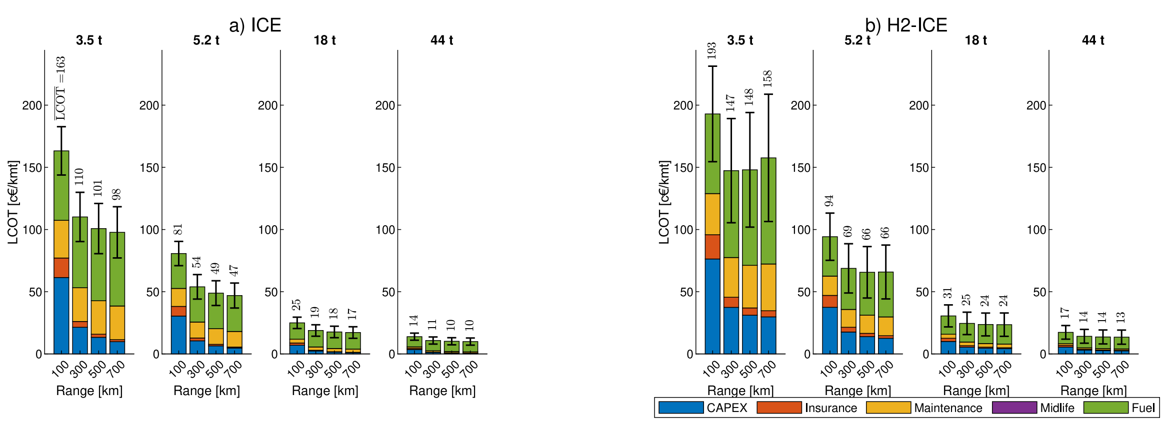

Fig. 8. LCOT of traditional Diesel ICE (a) and H_2 fueled ICE (b), categorized by driving range and weight class. The interval bars represent the fuel cost ranges discussed in Sub Section 2.3.2 for diesel and hydrogen.

suggesting that a driving range of 700 km is representative of the transportation costs at long distances.

4. Conclusions

A comprehensive study was conducted to evaluate the specific energy consumption and total costs of five distinct heavy-duty and light-duty vehicle powertrains:

- Diesel Internal Combustion Engine (ICE)
- Hydrogen Internal Combustion Engine (H_2-ICE)
- Battery Electric Vehicle (BEV)

Table 8
LCOT of BEVs, FCEVs, and ICEs evaluated at 1,000 km driving range considering average fuel prices.

	LCOT [c€/km t]			
	BEV	C-FCEV	V-FCEV	ICE
3.5 t	/	74.8	69.2	96.8
5.2 t	/	38.8	38.0	68.5
18 t	92.9	13.8	14.4	16.9
44 t	53.0	10.2	10.9	9.7

- Constant Power Fuel Cell Electric Vehicle (C-FCEV)
- Variable Power Fuel Cell Electric Vehicle (V-FCEV)

The analysis focused on two primary economic metrics: Total Cost of Ownership (TCO) and Levelized Cost of Transportation (LCOT). These metrics were evaluated across four different driving ranges (DR = 100 km, 300 km, 500 km, and 700 km) and four distinct tonnages divided into two weight classes:

- Light-Duty: 3.5 t and 5.2 t
- Heavy-Duty: 18 t and 44 t

Fuel costs were analyzed over realistic operational ranges.

Results demonstrate that the hydrogen is a promising solution for decarbonizing the freight transports. In fact, for a driving range larger than 100 km hydrogen powered vehicles have lower TCO and LCOT for all the weight classes among the zero-emissions alternatives. Notably, for the 3.5 t vehicles, BEV driving range is limited to 300 km while hydrogen vehicles do not have any range limitation. Also, FCEVs offer promising alternatives to traditional ICE trucks, but their competitiveness varies significantly based on driving range and vehicle weight. In detail, the main key findings are:

- For TCO considering heavy-duty trucks, at $DR = 100$ km BEVs are 14.4% more expensive than V-FCEVs for a 18 t truck, while 4.9% more expensive for a 44 t truck, with average fuel costs. Whereas, for $DR = 700$ km, BEVs are 52.6% more expensive than V-FCEVs for a 18 t truck, while 52.9% more expensive for a 44 t truck, with average fuel costs. This shows that BEVs are more expensive than FCEVs with a variable gap influenced by daily mileage and weight class
- For all weight classes, the LCOT of BEVs is more competitive than that of FCEVs for very short driving ranges (e.g., 100 km) and only considering minimum electricity cost and maximum hydrogen price. For longer driving ranges FCEVs become less expensive with the advantage augmenting with increasing driving ranges. This is mainly due to the very high costs associated with the purchase and replacement of the battery stack (CAPEX and midlife, respectively)
- Heavy-duty vehicles exhibit a lower LCOT than light-duty vehicles, irrespective of the powertrain technology, thanks to a bigger payload
- Traditional ICE (Diesel) is the cost-optimal solution in almost any case. However, the FCEVs are a competitive solution at middle to high mileages (i.e ≥ 300 km) and for low to middle class weight (i.e 3.5 t, 5.2 t, and 18 t), while also achieving zero emissions. Non-conventional ICEs (hydrogen) have similar economics to FCEVs while still emitting pollutants such as nitrogen oxides
- BEVs have the lowest energy consumption thanks to the high efficiencies of batteries and electric motors, but they present the lowest payload especially at higher driving ranges. The on-board battery stack can be up to 12 times larger than the buffer battery of C-FCEVs, while V-FCEVs reduce such size by 56.2% thanks to the following mode of the FC

In conclusion, the work suggests that politic support to zero emission freight road transportation vehicles should lean towards fuel cell electric vehicles instead of battery electric vehicles. Moreover, the topic seems to be relatively in early stages and future studies should evaluate the techno-economic parameters of the road freight transportation on real measured missions. Moreover, a broader scenario analysis could be conducted involving hydrogen production and supply for truck transportation.

CRediT authorship contribution statement

Marco Maggini: Writing – original draft, Visualization, Validation, Methodology. **Gabriele Loreti:** Writing – original draft, Visualization, Validation, Software, Methodology, Conceptualization. **Francesca Santoni:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Andrea L. Facci:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Stefano Ubertini:** Writing – review & editing, Resources. **Viviana Cigolotti:** Writing – review & editing, Resources, Funding acquisition. **Giulia Monteleone:** Writing – review & editing, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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