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Evaluation of opportunities arising from hydrogen retrofitting of commercial vehicles in urban areas: a case study

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Executive Summary

The automotive industry has undergone a complex transition from internal combustion engine (ICE) systems to electric propulsion due to environmental and regulatory pressures. Urbanization and the growth of e-commerce have increased the demand for sustainable commercial vehicles, especially in urban centers. Battery electric vehicles (BEVs) face range limitations for urban freight transportation, making fuel cell electric vehicles (FCEVs) and fuel cell hybrid electric vehicles (FCHEVs) more viable for zero-emission solutions due to their range and rapid refueling. This study explores the retrofitting of diesel vehicles to FCHEVs as a transitional solution through a case study in Rome, Italy, assessing the technical feasibility of vehicle retrofitting using commercially available components. Representative urban routes have been analyzed to design an effective FCHEV architecture. Impact assessment metrics highlight the potential environmental and operational benefits of retrofitting for urban freight transportation in large cities.

Keywords: Fuel Cell Electric Vehicles; Retrofitting EVs; Fuel Cell Systems, Environmental impact, Sustainable Energy

1 Introduction

Logistics issues are high on the agenda of both cities and companies. Local authorities must ensure a good quality of life while providing citizens with easy access to services and goods. Companies are committed to making their processes more efficient with a view to increasing profits and respecting increasingly stringent environmental constraints. In recent years the freight distribution system in urban areas has undergone strong fragmentation. The birth of numerous small operators and the exponential growth of home delivery make coordination and reorganization by those who govern the territory more complex. The negative impacts of this phenomenon are particularly evident in the urban centers of large cities which, however, can support this transition by encouraging the use of ecological vehicles and the introduction of new distribution models [1], [2], [3], [4], [5], [6]. In Europe, the path to reducing greenhouse gases and decarbonizing the economy has received a decisive boost with the 2020 strategy of the European Commission, through the Green Deal with the aim of achieving climate neutrality in the EU by 2050. In implementation of the Green Deal, the European Climate Law was approved, which aims to ensure that all economic sectors and sectors of society contribute to the goal of net-zero emissions by 2050 and outlines a framework for evaluating progress made in this direction. It also proposes a new EU target of a net emissions reduction of at least 55% by 2030 compared to 1990 levels. In 2019, the European Union approved the regulation (EU) 2019/1242, which established the CO_2 emission standards for heavy-duty vehicles until 2030 and in 2023, the Commission proposed a revision of the same regulation [7], [8]. These CO_2 standards are a fundamental part of a broader objective which is to contribute to the target of cutting transport emissions by 90% by 2050, as set out in the European Green Deal, while allowing the EU single market to continue growing [9], [10]. To achieve carbon neutrality goals, European governments are pushing for the development of EVs in urban logistics through incentive policies, since they can have advantages such as zero emissions and lower costs of use compared to conventional fuel vehicles [11], [12], [13]. Today there are several further potential measures linked to the ability to reduce emissions, already adopted by some logistics operators, including modal shift, digitalization, the adoption of cargo bikes, transition models that pay attention to the right sizing of the propulsion system with respect to the mission of use. For example, using large trucks for the entire delivery cycle and in urban areas is certainly an element of great inefficiency even if the vehicles used are zero emissions. For a correct analysis of the impact of electric mobility in the logistics sector, it is also important to correctly evaluate the energy consumption of Battery Electric Vehicles (BEVs) which, even if they do not emit locally, could be powered by energy produced with fossil fuels and would, in the latter case is just a tool to relocate the problem [14], [15]. Among the possible technological decarbonization solutions for vans and heavy transport, in addition to BEVs, there are those powered by fuel cells, the so-called Fuel Cell Electric Vehicles (FCEVs). These systems transform the energy potential of the hydrogen carrier into electricity. If technically the latter are, in fact, EVs (traction is guaranteed by an electric motor), the propulsion system, the charging infrastructure and the production and distribution of hydrogen make them a radically different solution from BEVs [16], [17], [18], [19], [20], [21], [22]. However, the higher technological investment costs on board the vehicle together with the costs associated with the production of green hydrogen and the lack of an infrastructure network currently make the use of hydrogen in urban areas inconvenient except in some specific cases or where it is impossible to decarbonize through the exclusive use of batteries (hard to abate sectors) [23]. Light commercial vehicle (LCV) dominate urban freight transport. LCV is designed and built exclusively or mainly for the transport of goods with a maximum mass not exceeding 3.5 tons (N1 category). LCVs include vehicles such as vans, pickup trucks and three-wheeled motor vehicles and represent the most widespread category for the transport of freight in urban areas. In 2022, the sales volume in Europe was approximately 1.62 million units overall, highlighting how LCVs are a key player in urban logistics [24]. In 2022, electric LCV sales worldwide increased nearly double compared to 2021, totaling more than 310,000 vehicles. Globally, electric LCVs account for 3.6% of the total share of LCVs sales [25]. For the first time, the increase in the share of electric LCVs exceeded that of electric cars (Figure 1).

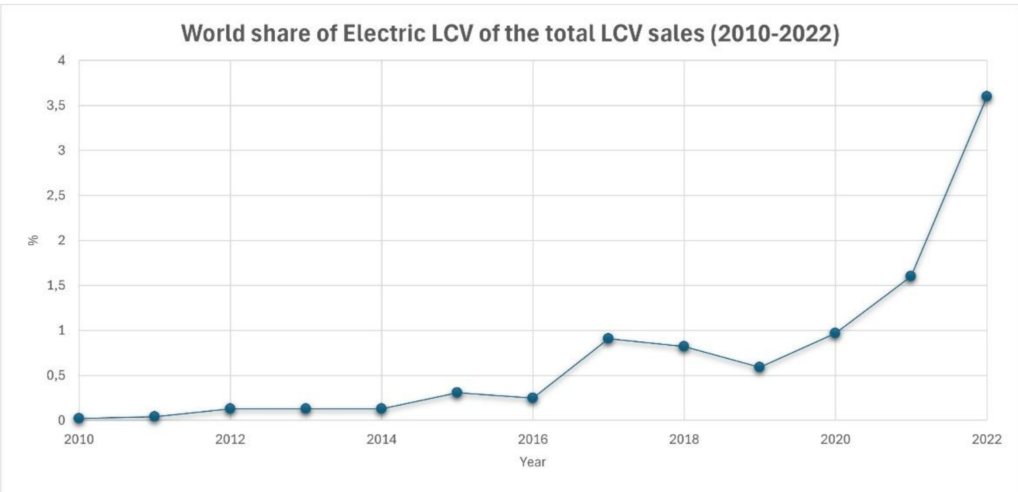

Figure 1 World Share of electric LCVs of the Total LCVs Sales

Electric powertrains not only allow the use of vehicles without direct emissions of CO2 and air pollutants, but also have fewer design constraints than conventional vehicles. Although traction batteries still offer an energy density much lower than petrol, electric motors can generally express higher torque and power and allow flexible integration into the vehicle chassis [26], [27], [28], [29], [30], [31]. Today the electrification of logistics companies' vehicle fleets is one of the main initiatives aimed at improving the sustainability of transport operations[32]. The economic and financial benefits to using electric vehicle as an alternative to engine-powered vehicles for the last-mile distribution have been studied from different perspectives. In [33] the authors calculate a reduction of up to 25% in external costs with the introduction of electric vehicles in urban logistics activities, as well as a 73% reduction in CO_2 emissions. One example, showed up to 25% of reductions in external costs introducing EVs in urban logistic activities, as well as 73% reductions in CO2 emissions and a fleet replacement threshold of 10% of electric LCV. The optimization of vehicle routing and scheduling specificities remains limited due to the importance of operational cost savings for freight EVs [34], [35]. Even if, from a technical point of view, BEVs are suitable as delivery vehicles thanks to the performance comparable to vehicles with Internal Combustion Engines (ICE), their autonomy generally being sufficient for urban missions of use (in this case, it does not represent a critical factor) and silence, there are currently few models of battery electric LCVs available on the market and their price is even higher than ICE vehicles. It is necessary to recognize, from this point of view, that despite being subject to common climate targets, the options, and preferences for the composition of the fleet of companies depend greatly on the local conditions linked to incentive policies which vary widely from one state to another and even from one city to another [36]. In addition to costs, the availability of charging infrastructure, the size of the city and the main logistics operators operating there and their location, the indications deriving from any Sustainable Urban Logistics Plans (SULP) are all factors with which fleet managers find themselves having to deal with the electrification process of the fleet [18], [37], [38]. A necessary evaluation on the use of EVs is also the connection to the so-called environmental sustainability. It is certain that EVs improve air quality compared to petrol and diesel vehicles, but it is necessary to consider that their simple use does not completely solve the problem. Firstly, because non-exhaust emissions are still significant [39]. Then it is necessary to look at the production phases of the vehicle and the result of the comparison is less favorable for EVs if we consider the current impacts of their production on ecosystems and the toxicity of the materials involved [40]. Finally, whether it is certain that a full EV does not pollute locally, the overall share of emissions depends on the method of producing the electrical energy used for its propulsion. For this reason, calculating the amount of energy used is relevant for the purposes of an environmental sustainability analysis [41], [42], [43]. Energy consumption is clearly variable and depends on a series of external factors such as traffic, road topology and driving style [44].

The range of LCVs powered by batteries varies significantly depending on battery capacity, payload weight, and operational conditions. Current European market models offer advertised ranges between 150 and 300 km per charge under optimal conditions. However, real-world tests indicate that actual range, particularly in urban environments with frequent stop-and-go driving and heavy cargo loads, is often significantly lower. The energy consumption of an electric LCV ranges between 20 and 30 kWh per 100 km, with real-world range potentially dropping to 150-200 km, especially in cold weather or heavy traffic conditions [45]. This is substantially lower than diesel vehicles, which can exceed 600 km on a single tank. Another major challenge is charging time, which directly impacts fleet operations. Charging via an alternating current (AC) charging station with a power output of 11-22 kW takes between 6 and 10 hours for a 75 kWh battery, requiring prolonged vehicle downtime. Fast-charging infrastructure using direct current (DC) with power levels between 50 and 150 kW can enable an 80% charge in approximately 45-60 minutes. However, access to these stations remains limited, particularly in congested urban areas. Additionally, frequent use of fast charging accelerates battery degradation, progressively reducing range and increasing long-term maintenance costs [46]. These factors make BEVs a viable solution for urban freight transport only in specific operational contexts, such as short-range deliveries and fleets with carefully planned daily routes. However, for logistics operations requiring greater flexibility and extended range, alternative solutions are emerging, including hydrogen fuel cell electric vehicles (FCEVs), which could better address medium- and long-distance urban freight transport needs. In this article, through a real case study in the city of Rome, the opportunities of using hydrogen carrier for the freight distribution in urban areas are evaluated. In particular, two market solutions with a fuel cell hybrid electric vehicles (FCHEV) architecture created through retrofitting of the propulsion system are compared.

2 Hydrogen opportunities in Urban Freight Transport

Hydrogen is emerging as a key energy carrier for road transport, particularly for heavy-duty applications where battery-electric solutions face limitations. While BEVs are well-suited for passenger cars and short-range urban transport, they struggle with range, charging time, and payload capacity in sectors like freight transport and public transit. Hydrogen-powered FCEVs offer extended range and faster refueling, making them a viable alternative for long-haul trucks, buses, and high-utilization urban fleets [47], [48] (Figure 2).

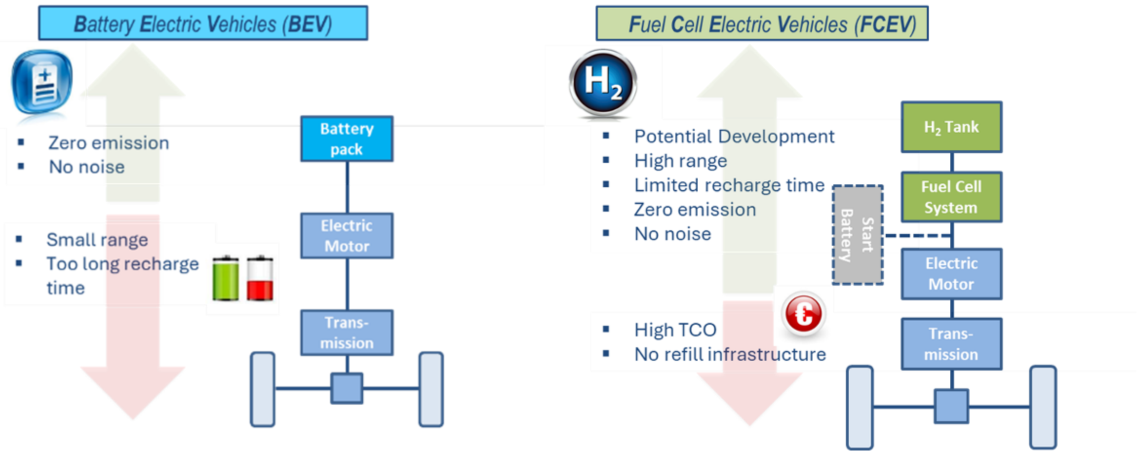

Figure 2 BEV and FCEV

The logistics sector, especially long-distance freight transport, stands to benefit significantly from hydrogen due to its ability to support continuous operation without lengthy recharging stops. In urban settings, hydrogen presents opportunities where daily mileage requirements exceed typical battery ranges or where operational flexibility is crucial, such as in public buses, municipal service vehicles, and last-mile delivery fleets operating in large urban areas. However, widespread hydrogen adoption faces challenges, including the high cost of green hydrogen production, the need for extensive refueling infrastructure, and energy efficiency concerns compared to direct electrification. Despite these barriers, public and private sector investments are driving advancements in hydrogen mobility, with policy incentives and infrastructure expansion playing a crucial role in determining its long-term viability in road transport. To address these challenges, the concept of Fuel Cell Hybrid Electric Vehicles (FCHEVs) has emerged as a promising middle ground. FCHEVs combine batteries and fuel cells, leveraging the strengths of both technologies. This hybrid configuration extends vehicle range, reduces refueling time, and mitigates some of the limitations associated with relying solely on batteries. The synergy between fuel cells and batteries enables FCHEVs to handle demanding use cases, such as heavy freight transport and fleet operations in urban and suburban environments [22], [23], [48] (Figure 3).

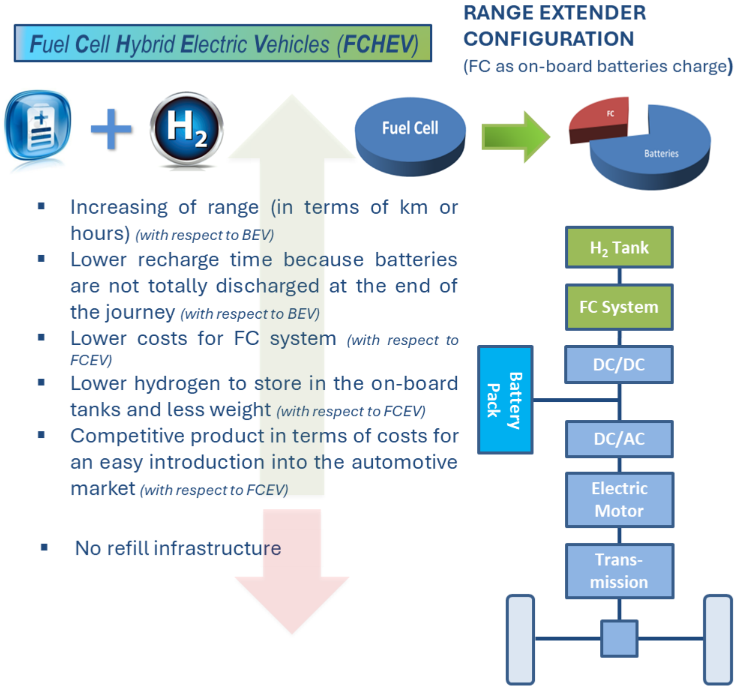

Figure 3 FCHEV

Hydrogen-powered LCV represent a promising technology for sustainable freight transport, but their market penetration remains extremely limited. Unlike BEV, which offer a wide range of available models, fuel cell solutions remain a marginal option, with very few offerings from automotive manufacturers. Currently, only a handful of producers have begun commercializing hydrogen LCVs, often in limited numbers and primarily intended for pilot programs or selected corporate clients. This situation makes large-scale adoption challenging, especially for logistics companies that require readily available vehicles and a well-developed support infrastructure. Given the slow pace of developing a robust hydrogen supply chain, that would lower technology costs, retrofitting ICE vehicles into FCHEVs is proposed as an interim solution [22], [23], [49], [50]. Retrofitting involves replacing the traditional propulsion system with a hybrid powertrain consisting of fuel cells and batteries. This approach allows for the reuse of existing vehicle structures, reducing the environmental impact associated with manufacturing entirely new vehicles. It also offers an economically feasible pathway for fleet operators to transition to zero-emission vehicles [51]. Retrofitting conventional commercial vehicles to run on hydrogen thus emerges as a cost-effective and scalable solution for achieving emissions reductions without the immediate need for fleet renewal. Retrofitting, the process of upgrading existing ICE vehicles with alternative propulsion systems such as battery-electric or hydrogen fuel cell technology, presents significant advantages in terms of cost-effectiveness, environmental sustainability, and accelerating the transition to low-emission mobility. Studies have shown that retrofitting can substantially reduce lifecycle costs compared to purchasing new zero-emission vehicles. This economic advantage is particularly crucial for fleet operators and municipalities that must comply with emissions regulations while managing budget constraints. From an environmental perspective, retrofitting contributes significantly to emissions reduction by converting older ICE vehicles into battery-electric or hydrogen-powered alternatives, thereby cutting CO_2, NOx, and particulate matter emissions [53]. Furthermore, the approach aligns with circular economy principles, as it reduces the need for raw materials used in new vehicle production and minimizes industrial waste. Additionally, retrofitting accelerates the transition to clean mobility without waiting for new vehicle production to scale up. This is particularly relevant in urban areas where regulations and low-emission zones (LEZs) are driving the demand for zero-emission vehicles. Retrofitting allows cities and companies to meet emissions regulations faster by converting existing fleets instead of facing delays in procuring new models. However, challenges remain in terms of regulatory approvals and standardization, which require coordinated efforts from policymakers and industry stakeholders [54].

3 The Case Study of Rome

The paper’s case study focuses on Rome, a city with several logistical challenges due to its extensive urban area, dense population and a very ancient road network. These factors necessitate vehicles with high autonomy, compact dimensions, and adequate load capacity to navigate narrow streets and deliver freight efficiently. First of all, the needs of an important logistics operator were collected which shared three different distribution routes in an urban area (Figure 4).

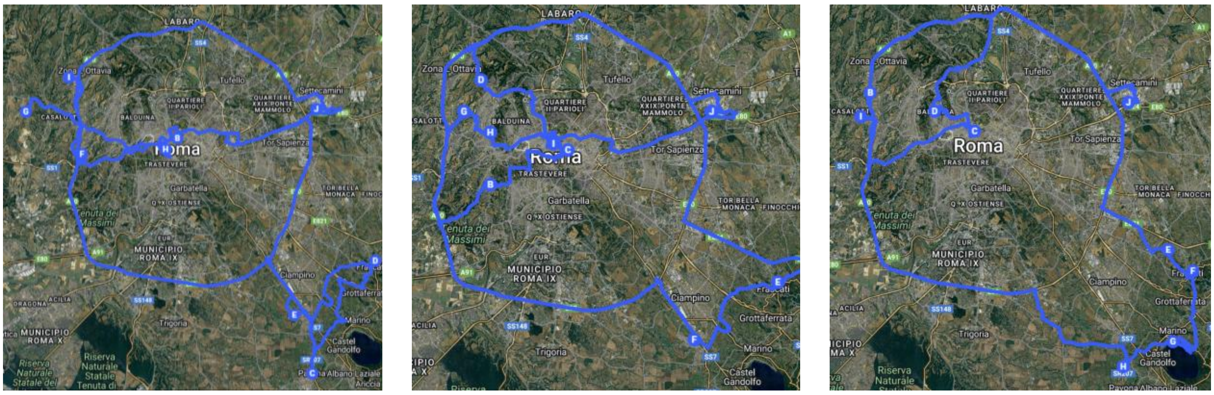

Figure 4 Distribution of goods in the urban area of Rome (Italy). Route 1 on the left: 203 km; Route 2 in the middle: 192 km; Route 3 on the right: 199 km

After an appropriate analysis of the data acquired by the detection systems, it was found that the required autonomy is in the range 192÷203 km [55], [56], [57], [58]. Since no hydrogen-powered LCV is currently actually available in the Italian distribution network of commercial vehicle manufacturers, with the aim of verifying the possibilities offered by electric vehicles, in this work an LCV was selected from the market, offering two types of propulsion system with ICE and electric motor (BEV). Among the manufacturer's vehicle configurations, a version with a large loading compartment was chosen to ensure the delivery of even bulkier goods (Figure 5). The mechanical characteristics of the LCV such as size, weight, type of wheels and loading volume are shown in Table1. Table 2 highlights the technical specifications of the ICE version while Table 3 shows those of the BEV version [59]. In the latter case the battery is Lithium-based with Nickel – Manganese – Cobalt chemistry (NMC).

Figure 5 LCV selected on the market and whose characteristics are used in the analysis

Table1. LCV mechanical characteristics

Vehicle Type	LCV
Length	4,1 m
Width	2,15 m
Height	2,2 m
Cargo Volume	19.6 m^3
Curb weight	2114 kg

Table 2. ICE LCV Technical specifications

Vehicle Type	ICE LCV
Engine type	ICE
Engine Power	81 kW
Engine Torque	330 Nm
Fuel consumption	9.8 l/100 km
CO_2 emissions	256 g/km

Table 3. Electric LCV (BEV) Technical specifications

Vehicle Type	Electric LCV (BEV)
Motor type	SSM – Magnetless
Motor Power	57 kW
Motor Torque	225 Nm
Battery type	NMC
Battery Energy	52 kWh
Battery Voltage	348 V
Battery weight	350 kg
Autonomy	147÷176

It should be taken into account that the energy available for traction, reported in Table 3, is usually equal to 80% of that of the battery. For the vehicle in question, it is therefore corresponding to 41.6 kWh. Based on the autonomy declared by the manufacturer, energy consumption is in the range 236÷283 Wh/km. It is evident that the vehicle's autonomy is not sufficient to cover the needs of any of the planned routes (Table 4)Table 3. Table 3 in fact shows that the declared autonomy, which is in line with the commercial proposals of other manufacturers that do not offer higher autonomy, is lower than the needs. It is also recognized in literature that the autonomy declared by electric vehicle manufacturers is often lower than that verified on the road [60], [61]. Table 4 also reports the estimated energy consumption value calculated by extending the autonomy proportionally to the consumption declared by the manufacturer. As a precaution, the highest consumption value has been taken into consideration.

Table 4. Parameters and Estimated Energy Consumption for the three routes

	Route 1	Route 2	Route 3
Distance traveled [Km]	203	192	199
Estimated energy consumption [kWh]*	57,45	54,33	56,31

**Calculation derived from the vehicle datasheet*

Currently, the commercial vehicle market for models exceeding 3.5 tons does not offer electric options with the necessary range and performance to meet urban logistics distribution needs, particularly in contexts requiring high autonomy. This is the main motivation behind the subsequent analyses aimed at evaluating the opportunities offered by retrofitting. Italy has one of the oldest vehicle fleets on the continent; the oldest vehicles in circulation and registered for over ten years reach over 85%. By replacing, through retrofit actions, only the parts related to the functioning of the internal combustion engine, the circulation of a new zero-emission FCHEV vehicle will coincide with the elimination of a polluting vehicle. Rome’s logistical demands make it an ideal setting for exploring the feasibility of retrofitting vehicles into hydrogen power vehicles. These factors highlight the potential advantages of hydrogen as an energy carrier for freight transport. The Italian decree of October 23, 2018, permits hydrogen storage at 700 bar and provides regulatory guidelines for the construction of hydrogen refueling stations (HRS) for automotive applications. Given these considerations, the study explored the feasibility of retrofitting an internal combustion engine (ICE) vehicle into a FCHEV for urban freight distribution. In this configuration, propulsion energy is supplied by a battery pack or Battery Energy Storage (BES) system in combination with a Fuel Cell System (FCS), which work synergistically. In order to appropriately size the key components suitable for the proposed operational scenarios, a preliminary design phase has been conducted. Taking into account the energy consumption necessary to satisfy the analysed routes, the minimum energy content was set at 60 kWh which will represent 80% of the final one equal to 75 kWh. After a selection of commercial systems based on the compatibility of voltage levels, device weight and overall technical characteristics, a BES (Energy: 35 kWh) and a FCS (Nominal power of 45 kW) have been identified whose combined use can satisfy the required technical specifications required on the vehicle taken into consideration. One of the advantages of using FCS is that of being able to separately size the energy content that will go into the appropriate tanks. For the storage system, a tank containing 3.5 kg of hydrogen compressed at 350 bar was considered. Using the lower calorific value, the energy thus available is equal to 116 kWh. Considering an FCS efficiency of 48% (cautiously slightly lower than declared by the manufacturer), the total usable energy will be equal to approximately 55 kWh. The energy content on board will therefore be equal to 83 kWh. Always considering a consumption of 283 Wh/km, the estimated final autonomy will thus be equal to approximately 293 km (Table 5).

Table 5 BES, FCS and H_2 Storage System configurations

BES Energy [kWh]	H2 Energy (3,5 kg @350 bar) [kWh]	FCS Nominal Power [kW]	Energy available for traction [kWh]	Estimated Autonomy [km]
35 kWh	116	45	83	293

The autonomy value obtained is certainly suitable to satisfy the requirements requested in the case study analysed even in the case in which the maximum consumption value declared by the manufacturer is, in practice, actually even higher. The advantages deriving from the use of hydrogen are also those related to the management of a fleet composed of similar vehicles which, being able to refuel in comparable times to combustion vehicles, could be composed of a lower number of vehicles than a analogous BEV fleet. The main challenges clearly concern the cost analysis compared to a new vehicle and in proportion to scalability, the operating costs related to the use of green hydrogen that guarantees an entire zero-emission supply chain, the presence of refueling stations. The authors are currently analysing these aspects with the aim of formalizing a metric for impact assessment. From an environmental point of view, the first results obtained also by the authors with an approach based on LCA applied to a comparable cases are encouraging [23] [62].

4 Conclusion

This study evaluated the potential of retrofitting internal combustion engine (ICE) light commercial vehicles (LCVs) into fuel cell hybrid electric vehicles (FCHEVs) for urban freight transport. Through a detailed case study in the city of Rome, the analysis demonstrated that retrofitting can offer a concrete and sustainable alternative to the full replacement of vehicle fleets with new battery electric vehicles (BEVs) or hydrogen-powered models. The results show that a properly designed configuration combining a fuel cell system, a battery energy storage system, and hydrogen storage can meet the energy requirements of urban delivery routes exceeding 190 km, achieving an estimated range of approximately 290 km. This confirms that FCHEV technology can overcome key limitations associated with BEVs, particularly regarding range, recharging time, and operational flexibility. From an environmental standpoint, the retrofit approach presents advantages in terms of life cycle assessment (LCA), reducing the impacts linked to new vehicle manufacturing and aligning with circular economy principles. Furthermore, reusing existing vehicle platforms facilitates a faster and more cost-effective transition for fleet operators, particularly in a regulatory context that increasingly demands rapid decarbonization of the transport sector. Nevertheless, challenges remain concerning regulatory frameworks, hydrogen refueling infrastructure, and the current costs of green hydrogen. These aspects require further investigation and strong collaboration among policymakers, industry stakeholders, and research institutions. In conclusion, FCHEV retrofitting represents an effective, scalable, and sustainable strategy to support the ecological transition of urban freight transport, contributing meaningfully to the achievement of climate neutrality targets set by European directives.

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