World Electric Vehicle Journal

MDPI

Article

An Evaluation of Opportunities Arising from Hydrogen Retrofitting of Commercial Vehicles in Urban Areas: A Case Study

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Abstract

This article investigates the feasibility of hydrogen-based retrofitting solutions for light commercial vehicles operating in urban freight transport. The analysis is based on a mission-driven methodology applied to a representative urban case study in the city of Rome, using synthetic route profiles and vehicle specifications derived from manufacturer datasheets. Three representative urban delivery missions are defined, characterised by cumulative daily distances of approximately 190–200 km and associated energy requirements in the range of 54–57 kWh. These mission profiles are first used to assess a commercially representative battery electric vehicle configuration, for which the usable onboard battery energy is estimated at 41.6 kWh. The results show that, under the considered operating conditions, the battery electric configuration is not able to complete the planned routes without intermediate recharging. On this basis, a fuel cell hybrid electric vehicle retrofit configuration is evaluated, combining a 35 kWh battery, a 45 kW fuel cell system and 3.5 kg of onboard hydrogen storage at 350 bar. The resulting estimated driving range is approximately 293 km, which is sufficient to satisfy the defined mission requirements. This study is framed as a technical feasibility assessment and does not aim to provide optimisation or experimental validation. The proposed methodology can be applied to other urban contexts by adapting route characteristics and daily mileage requirements.

Keywords: fuel cell electric vehicles; retrofitting EVs; fuel cell systems; environmental impact; sustainable energy

Academic Editor: Michael Fowler

Received: 22 November 2025
Revised: 3 February 2026
Accepted: 5 February 2026
Published: 11 February 2026

1. Introduction

Logistics and freight distribution play a central role in the functioning of modern cities, but they also represent a major source of energy consumption, air pollution, and greenhouse gas emissions. Local authorities are increasingly required to balance the growing demand for goods and services with the need to improve urban livability and environmental quality. At the same time, logistics operators face strong pressure to improve efficiency while complying with progressively stricter environmental regulations. In recent years, urban freight systems have become increasingly fragmented due to the proliferation of small operators and the rapid growth of e-commerce and home delivery services, making coordination and planning more complex, especially in large metropolitan areas [1–5].

Within the European context, the decarbonisation of transport has received a decisive boost through the European Green Deal and the subsequent European Climate Law, which set the objective of achieving climate neutrality by 2050 and a net reduction in greenhouse gas emissions of at least 55% by 2030 compared to 1990 levels [6,7]. These targets are supported by specific regulatory measures addressing road transport emissions, including CO_2 standards for heavy-duty vehicles and broader strategies aimed at reducing transport-related emissions by up to 90% by mid-century [8,9]. In this framework, urban freight transport has been identified as a priority sector for the deployment of low- and zero-emission vehicle technologies.

Electric vehicles (EVs) are widely regarded as a key solution for reducing local emissions in urban logistics. Compared to vehicles powered by internal combustion engines (ICEs), EVs offer advantages such as zero tailpipe emissions, reduced noise, and lower operational energy costs [10–13]. However, a correct assessment of their environmental and operational benefits requires a system-level perspective. Although BEVs do not produce local emissions, their overall environmental impact depends on the electricity generation mix and on vehicle energy consumption under real operating conditions [14–16]. Moreover, the electrification of freight fleets is influenced by multiple factors, including vehicle availability, charging infrastructure, incentive schemes, city size, logistics hub locations, and the presence of Sustainable Urban Logistics Plans (SULPs), which vary significantly across regions and cities [17–28].

From an operational perspective, BEVs are generally well suited for short-range urban delivery missions, but they still present limitations when applied to high-utilisation freight services. Real-world driving range is strongly affected by payload, traffic conditions, driving style, and ambient temperature, often resulting in values significantly lower than those declared by manufacturers [29,30]. In addition, long charging times and limited access to high-power charging infrastructure can increase vehicle downtime and reduce operational flexibility, particularly for logistics operators managing intensive daily routes. Despite these constraints, the growing penetration of battery electric LCVs in the global market reflects the increasing interest in electrified solutions for urban freight transport, as shown in Figure 1 [31,32].

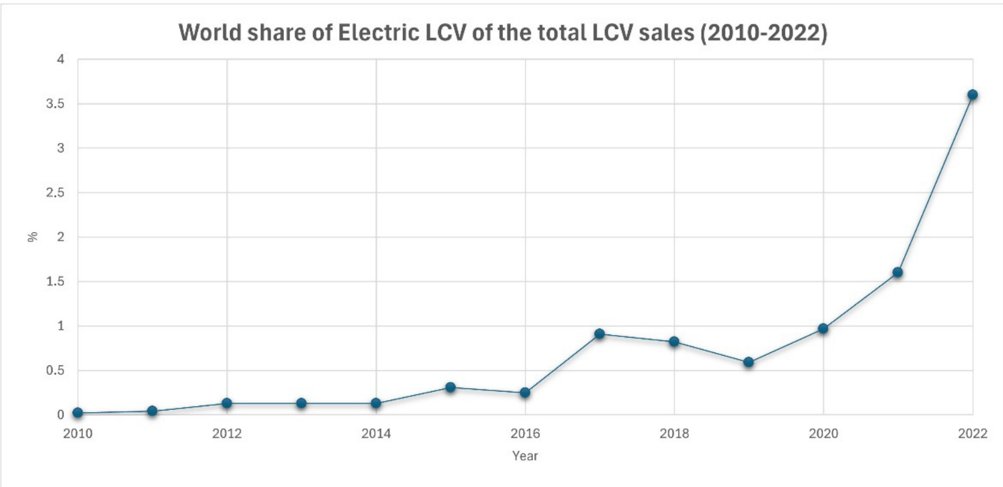


Figure 1. World Share of electric LCVs of the Total LCVs Sales.

Among alternative zero-emission solutions, hydrogen-powered fuel cell electric vehicles (FCEVs) have attracted growing attention, particularly for applications where battery-based solutions face intrinsic limitations. Fuel cell systems convert the chemical energy of hydrogen into electricity, enabling longer driving ranges and faster refuelling compared to BEVs, while maintaining electric traction. The fundamental differences between battery-based and hydrogen-based electric vehicle architectures, in terms of onboard energy storage, energy conversion, and refuelling strategies, are schematically illustrated in Figure 2 [33,34]. Hydrogen refuelling times for LCV's are typically of the order of a few minutes, generally ranging between approximately 180 and 300 s, depending on storage pressure and the refuelling protocol. By contrast, BEVs require substantially longer recharging times, which, even under fast-charging conditions, typically range from several tens of minutes to more than one hour, depending on battery capacity and charging power [35]. These characteristics make hydrogen-based solutions potentially attractive for freight transport missions requiring extended range and high vehicle availability.

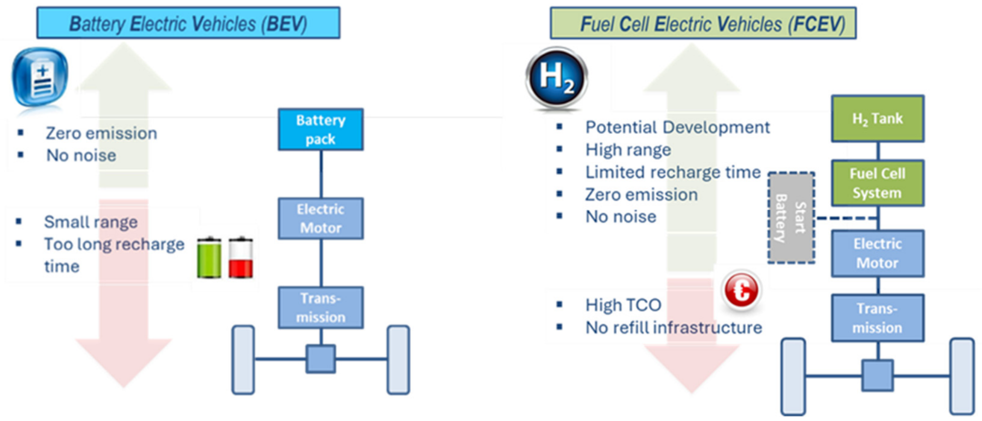


Figure 2. Comparative architectures of Battery Electric Vehicle (BEV) and Fuel Cell Electric Vehicle (FCEV). The green arrow lists the main advantages, the red arrow lists the disadvantages.

FCHEVs represent a further evolution of hydrogen-based electric propulsion by combining a fuel cell system with a battery energy storage system. In this configuration, the fuel cell primarily acts as an energy converter, while the battery supports peak power demand and regenerative braking, enabling improved efficiency and power management under variable load conditions. A schematic layout of the FCHEV powertrain architecture is shown in Figure 3 [29,34,36,37]. Despite these advantages, the adoption of hydrogen-based vehicles in urban freight transport remains limited due to high vehicle costs, the current price of green hydrogen, and the still sparse refuelling infrastructure [25,38].

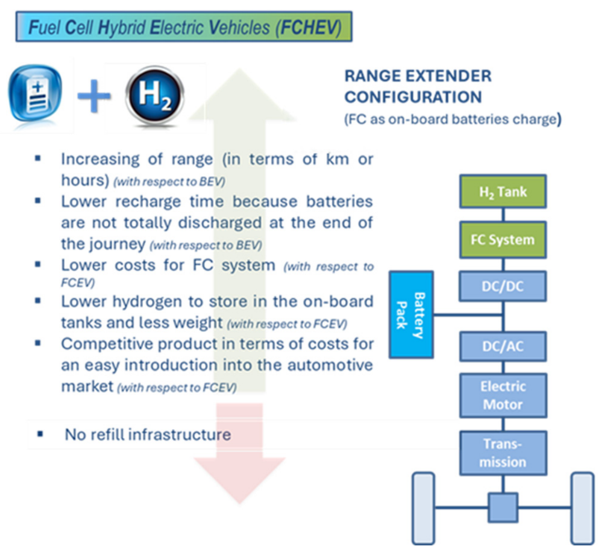


Figure 3. Schematic layout of the Fuel Cell Hybrid Electric Vehicle (FCHEV) powertrain. The green arrow lists the main advantages, the red arrow lists the disadvantages.

From a system-integration perspective, the suitability of hydrogen-based powertrains for urban freight transport is closely linked to the specific operational characteristics of LCVs. These vehicles are typically required to combine relatively high daily mileage, frequent stop-and-go cycles, variable payloads, and limited tolerance for operational downtime. In this context, hybrid architectures that decouple energy storage from power delivery can offer relevant advantages, allowing the fuel cell system to operate closer to favourable efficiency regions while the battery manages transient power demands. These features make FCHEVs particularly well aligned with urban logistics missions where flexibility, availability, and mission-completion reliability are critical performance indicators. An additional barrier to widespread deployment is the very limited availability of hydrogen-powered LCVs on the commercial market. Unlike BEVs, which are offered in multiple configurations by most manufacturers, fuel cell solutions for the LCV segment are generally restricted to small production volumes, pilot projects, or selected corporate fleets [29,36,39,40]. Examples include hydrogen-powered derivatives of mid-size vans introduced by major automotive manufacturers, such as the Opel Vivaro-e HYDROGEN and equivalent models within the Stellantis LCV platform family, as well as pilot deployments of hydrogen versions of large vans developed for professional use. These vehicles typically combine compressed hydrogen storage with a fuel cell system to extend the driving range and enable fast refuelling but remain produced in limited volumes and targeted to specific fleet applications [41–43]. As a result, large-scale fleet renewal based on new hydrogen vehicles is currently difficult to achieve, especially in countries characterised by an ageing vehicle fleet. In this context, retrofitting existing ICE vehicles with alternative powertrains has emerged as a potential transitional strategy, offering the possibility to reduce emissions while extending vehicle lifetime and supporting circular-economy principles [29,36,39,40,44–46]. Retrofitting conventional commercial vehicles into battery electric or fuel cell hybrid configurations can significantly reduce lifecycle emissions by avoiding the environmental impacts associated with the production of new vehicles while enabling faster compliance with low-emission and zero-emission zone requirements [47,48]. Several studies have highlighted the potential benefits of retrofit solutions in terms of cost-effectiveness, environmental performance, and accelerated deployment of clean mobility technologies, particularly in urban contexts [44,48–53]. However, the technical feasibility and operational suitability of fuel cell hybrid retrofits for urban freight applications remain underexplored, especially when real mission requirements and route characteristics are considered. Against this background, this study investigates the opportunities offered by hydrogen-based retrofitting of LCVs for urban freight transport. Through a real-world case study in the city of Rome, representative delivery routes are analysed to define energy demand and operational constraints. A system-level methodology is then applied to design and size an FCHEV powertrain using commercially available components, with the aim of assessing the technical feasibility and potential benefits of hydrogen-based retrofits as a transitional solution toward zero-emission urban logistics.

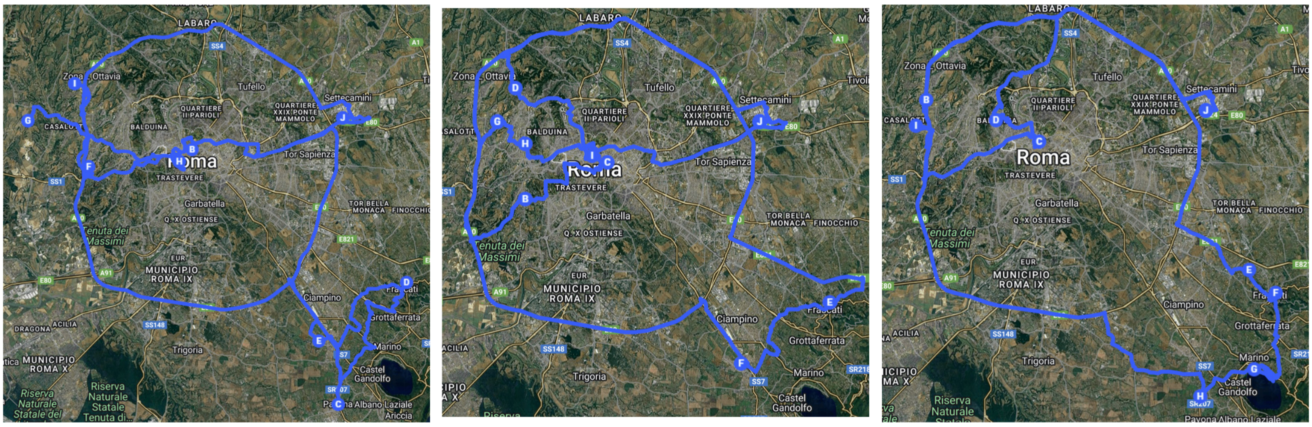
2. Materials and Methods

2.1. The Case Study of Rome

The city of Rome (Italy) was selected as a case study to investigate the feasibility of hydrogen-based retrofitting solutions for urban freight transport. As one of the largest metropolitan areas in Europe, Rome is characterised by a complex urban structure, a high density of commercial activities, and a heterogeneous road network combining modern arterial roads with historical streets originally designed for non-motorised traffic. These characteristics make urban freight operations particularly challenging and provide a meaningful context for assessing alternative powertrain solutions.

Urban logistics activities in Rome are predominantly carried out by LCVs and are characterised by operating conditions that differ significantly from those of inter-urban or long-haul freight transport. Typical missions involve frequent stop-and-go driving, variable payloads, restricted access windows in central areas, and significant levels of traffic congestion, which strongly influence vehicle utilisation patterns and energy demand. These features are well documented for urban freight transport in large European cities and represent a key driver for data management and powertrain selection and sizing [54–57].

To represent these operating conditions, three representative urban delivery routes were defined within the metropolitan area of Rome. The selected routes were chosen to reflect different urban contexts, including central areas characterised by dense traffic and access restrictions, mixed residential and commercial districts, and more peripheral zones with longer travel distances. The spatial distribution of the selected routes is shown in Figure 4.



(**a**) (**b**) (**c**)

Figure 4. Distribution of goods in the urban area of Rome (Italy). (**a**) Route 1: 203 km; (**b**) Route 2: 192 km; (**c**) Route 3: 199 km. Map data ©2025 Google.

The route profiles were defined using a synthetic dataset developed to represent typical urban freight missions rather than to reproduce measurements from a specific vehicle or fleet. Key parameters such as route length, travel time, average speed, and stop frequency were specified based on characteristic urban traffic conditions and commonly reported logistics practices. In this framework, the three routes illustrated in Figure 4 should be interpreted as aggregated daily mission profiles rather than as individual continuous trips. The synthetic route profiles were validated against operational mission data provided by a major logistics operator active in the Rome metropolitan area, ensuring representativeness of daily mileage, mission duration, and stop-and-go characteristics. Each route represents the cumulative distance travelled over a working day, resulting from multiple delivery or service operations distributed within the urban area. This interpretation is adopted to ensure consistency with the system-level scope of the analysis, which focuses on daily operating requirements rather than on the detailed temporal structure of individual trips. This approach enables the definition of transparent, repeatable, and internally consistent mission scenarios that are suitable for system-level feasibility analyses and preliminary powertrain sizing.

Beyond its demographic density and historical urban fabric, the Rome metropolitan area is characterised by operational conditions that are particularly demanding for urban freight vehicles. The synthetic routes reported in Figure 4 reflect typical service missions developed within a complex road network, where limited road width, frequent intersections, traffic congestion, and regulated access zones lead to low average driving speeds and a high frequency of stop-and-go events. Although detailed kinematic parameters are not explicitly modelled, the route structure implicitly represents operating conditions associated with frequent acceleration phases, variable payload utilisation, and extended daily driving periods. These factors are known to increase the effective energy demand of battery electric vehicles and to reduce the usable driving range compared to nominal values declared under standard test conditions. In this context, altitude variations and local topography, even when moderate, may further contribute to transient power peaks and additional energy demand during repeated acceleration cycles. While such effects can be partially mitigated through regenerative braking, their cumulative impact over long daily missions remains non-negligible for battery-only solutions. Conversely, the FCHEV architecture benefits from a decoupling between instantaneous power demand and onboard energy availability. The presence of a fuel cell system operating as a range extender enables sustained energy supply over extended missions, reducing sensitivity to cumulative route characteristics such as stop frequency and mission length. This makes hydrogen-based hybridisation particularly suitable for urban freight contexts characterised by long cumulative mileage and limited flexibility for intermediate charging.

Although the defined routes differ in length and urban context, they share common operational features such as repeated acceleration and deceleration phases, extended idling periods, and limited opportunities for continuous driving. From a powertrain design perspective, the relevance of these routes does not lie solely in their individual length, but in the cumulative distance and operational continuity required over a typical working day. Urban freight operations performed by LCVs are generally composed of multiple consecutive missions, often separated by short dwell times associated with loading, unloading, or service activities. As a result, daily mileage requirements emerge as a critical parameter for powertrain sizing, as they determine both the total onboard energy demand and the operational flexibility needed to complete missions without disruptive interruptions.

In the present case study, the defined route profiles were therefore used to derive representative daily mileage requirements by aggregating multiple missions within a typical working day. These cumulative distance requirements form the basis for the subsequent design and sizing of the fuel cell hybrid electric powertrain, ensuring that the analysis reflects realistic operational demands rather than idealised single-trip scenarios. While the analysis refers to the specific context of Rome, the proposed mission-driven methodology is not city-dependent and can be directly applied to other urban environments by adapting route profiles and daily mileage requirements to local operating conditions. For the purpose of the present analysis, it is assumed that the reference vehicle operates within a captive fleet framework and departs from a private logistics depot. The depot is assumed to be equipped with a dedicated hydrogen refuelling station, enabling daily refuelling operations without relying on publicly accessible hydrogen infrastructure.

As a consequence, the availability and spatial distribution of public hydrogen refuelling stations within the urban area are not considered in the present study. This assumption is consistent with typical early-stage hydrogen deployment scenarios for commercial fleets, where vehicles operate on predefined routes with scheduled return-to-base operations and centralised refuelling infrastructure.

2.2. Vehicle Selection and Specifications

The vehicle selected as the reference platform for the retrofit analysis belongs to the light commercial vehicle (LCV) segment typically employed in urban freight and service operations. This vehicle class represents a significant share of last-mile delivery fleets and is widely recognised as a key enabler of logistics activities in metropolitan areas. The selection of the reference platform was guided by representativeness rather than optimisation, with the objective of analysing a configuration that reflects common characteristics of LCVs currently operating in urban contexts [58]. The adopted reference platform is shown in Figure 5.

Figure 5. Light Commercial Vehicle (LCV) selected as the reference platform for retrofit analysis.

The mechanical and dimensional characteristics of the selected LCV platform are summarised in Table 1. These parameters define the baseline constraints relevant to the retrofit study, including mass-related limits and geometric boundaries that influence the feasibility of integrating alternative powertrain components while preserving vehicle functionality and compliance with operational requirements. As the analysis focuses on powertrain substitution while maintaining the same vehicle platform, the characteristics reported in Table 1 are common to all configurations considered in this study.

Table 1. LCV mechanical characteristics [59].

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

Starting from the selected platform, two powertrain configurations are analysed: the original internal combustion engine (ICE) configuration and a battery electric vehicle (BEV) configuration used as a reference for comparison. Their powertrain-specific characteristics are reported in Table 2, which enables a direct comparison while keeping the vehicle platform characteristics common to both configurations in Table 1.

Table 2. Comparison between ICE and BEV powertrain configurations for the selected LCV platform [59].

Parameter	ICE LCV	Electric LCV (BEV)
Powertrain type	ICE	Electric
Rated Power	81 kW	57 kW
Rated Torque	330 Nm	225 Nm
Energy Storage	Diesel fuel	Battery (NMC)
Fuel/battery energy	9.8 L/100 km	52 kWh
Driving range	-	147–176 km
Energy consumption (kWh/100 km)	98.0 (fuel energy input, LHV-based)	23.6–28.3 (derived)
Operating cost (€/100 km)	16.3 (diesel)	6.6–7.9 (electricity)
Vehicle price (indicative)	~€35,000	~€55,900

In practical applications, the energy available for traction for the BEV configuration is typically lower than the nominal battery capacity due to state-of-charge operating windows, power reserve requirements, and battery degradation considerations. For this reason, it is common to assume that approximately 80% of the nominal battery energy is usable for traction, as widely adopted in vehicle energy modelling [59,60].

For the ICE configuration, fuel consumption expressed in L/100 km is converted into energy input using the lower heating value of diesel, assumed equal to 36 MJ/L (approximately 10 kWh/L), in order to allow a consistent energy-based comparison between the two powertrain systems.

Indicative operating costs expressed in €/100 km are also reported in Table 2 based on explicitly stated reference energy prices, namely diesel fuel priced at 1.66 €/L and electricity priced at 0.2797 €/kWh, representative of Italian reference values. Vehicle mass is not repeated in the comparative table, as it refers to the common platform characteristics already reported in Table 1, while vehicle prices are provided as indicative list values, acknowledging that they may vary depending on configuration and market conditions.

To facilitate visual comparison between the reference powertrain configurations, a bar chart representation of the energy consumption values reported in Table 2 is provided in Figure 6. The figure highlights the substantial difference in energy demand between the ICE and BEV (average value) configurations when expressed on an energy-equivalent basis.

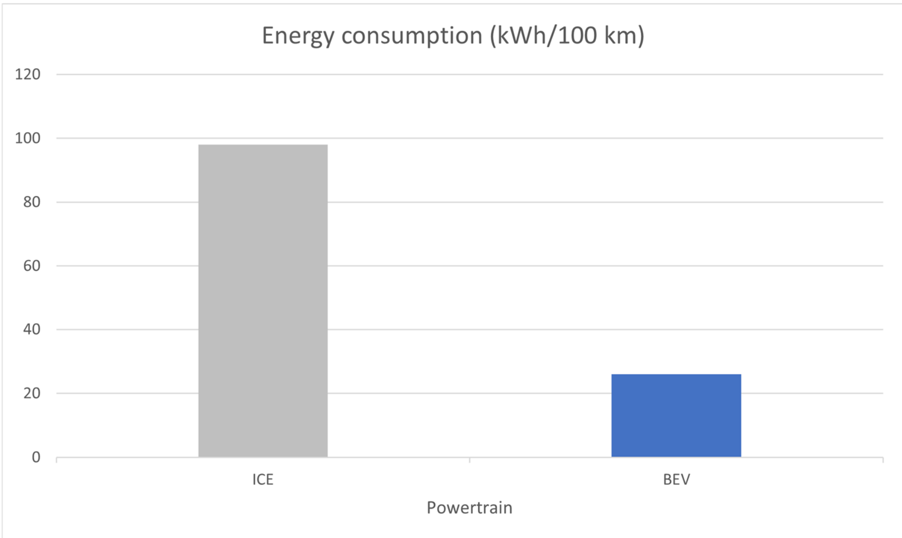


Figure 6. Comparison of energy consumption between ICE and BEV reference configurations.

Overall, Figure 5, Tables 1 and 2 provide the complete set of baseline inputs required for the subsequent methodological steps. The selected vehicle platform, its mechanical constraints, and the comparative characterisation of the ICE and BEV powertrain configurations jointly define the boundary conditions for the energy assessment and powertrain sizing analysis presented in Section 2.3.

2.3. Methodology for FCHEV Powertrain Design

The methodology adopted in this study aims to assess the technical feasibility of retrofitting the selected LCV platform with a fuel cell hybrid electric powertrain under representative urban freight operating conditions. The approach is mission-driven and ensures consistency between the route profiles defined in Section 2.1, the vehicle characteristics reported in Section 2.2, and the energy and power requirements used for powertrain sizing. The analysis is based on synthetic mission data and manufacturer-declared vehicle specifications and does not rely on experimental measurements from a specific vehicle or fleet.

As a first step, the energy demand associated with the BEV reference configuration is evaluated in order to verify its suitability with respect to the mission requirements derived from the Rome case study. It should be taken into account that the energy available for traction for the BEV configuration reported in Table 3 corresponds to a fraction of the nominal battery capacity. In line with common practice, the usable energy is assumed to be equal to 80% of the installed battery capacity, which for the selected vehicle results in 41.6 kWh [58]. Based on the driving range declared by the manufacturer, the corresponding specific energy consumption falls within the range of 236–283 Wh/km.

Table 3. 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.

When these values are compared with the length of the representative urban routes considered in this study, it becomes evident that the declared vehicle autonomy is not sufficient to cover the energy requirements of any of the planned missions. Table 3 shows that the declared autonomy of the selected BEV platform, which is in line with the commercial proposals of other manufacturers operating in the same vehicle segment, remains lower than the cumulative distance requirements associated with the defined routes. This mismatch highlights a structural limitation of the BEV configuration when applied to the mission profiles identified in Section 2.1.

It is also recognised in the literature that the driving range declared by electric vehicle manufacturers is often higher than the range verified under real operating conditions, particularly in urban contexts characterised by stop-and-go driving, frequent accelerations and decelerations, and variable payload conditions [61,62]. For this reason, an additional estimation of energy consumption is carried out by proportionally extending the declared autonomy according to the manufacturer-reported consumption figures. As a precautionary assumption, the highest value within the declared specific consumption range is considered in the subsequent analysis.

The parameters adopted for the estimation and the resulting energy consumption values for the three representative routes are reported in Table 3, together with the corresponding route lengths and cumulative distance requirements. As indicated in the table, the calculations are derived from the vehicle datasheet and are intended to provide a conservative estimate of energy demand under the considered operating conditions.

The results reported in Table 4 confirm that, even under conservative assumptions, the BEV configuration does not provide sufficient usable energy to complete the planned routes without intermediate recharging. This limitation becomes more pronounced when considering cumulative daily mileage requirements, which are representative of typical urban freight operations performed by LCVs. These findings motivate the adoption of a hybrid electrified architecture capable of decoupling onboard energy storage from instantaneous power delivery.

Table 4. Mass contribution of onboard energy storage subsystems.

Configuration	Energy Carrier/Storage	Assumption	Mass Contribution
ICE	Diesel fuel	80 L; density 0.83 kg/L	66 kg
BEV	Battery pack	Declared battery mass	350 kg
FCHEV retrofit	Hydrogen (usable)	3.5 kg @ 350 bar	3.5 kg
FCHEV retrofit	H_2 storage system (incl. H_2)	350 bar system gravimetric capacity ~5.5 wt%	~64 kg

The present analysis does not explicitly model the influence of external driving conditions such as ambient temperature, precipitation, or day–night operation. Energy consumption is therefore evaluated under nominal operating conditions, consistently with manufacturer-declared specifications and with the system-level scope of the study.

While it is well recognised that environmental and operating conditions can affect real-world vehicle energy consumption, their explicit inclusion would require high-resolution operational and climatic data that are beyond the objectives of the present feasibility-oriented assessment.

On this basis, the FCHEV powertrain architecture is considered, combining a fuel cell system with a battery energy storage system. Within this architecture, the fuel cell primarily acts as an energy converter supplying the average power demand associated with the mission profiles, while the battery is used to buffer transient power peaks and to recover energy during regenerative braking. This functional decoupling allows the fuel cell to operate closer to favourable efficiency conditions, while maintaining sufficient flexibility to accommodate the stop-and-go nature of urban freight missions.

The sizing of the fuel cell system is therefore driven by average power demand rather than peak traction requirements, whereas the battery system is sized to manage power transients and to support regenerative energy recovery without imposing excessive mass penalties. Hydrogen storage capacity is defined to satisfy the cumulative daily energy demand derived from the route analysis, with the objective of enabling completion of a typical working day without intermediate refuelling.

To address the mass implications of different propulsion systems, a simplified comparison of the onboard energy storage subsystems is provided. For the ICE configuration, the fuel mass is calculated assuming an 80 L diesel tank and a typical EN 590 diesel density at 15 °C of approximately 0.83 kg/L, resulting in a fuel mass of about 66 kg.

For the BEV configuration, the battery mass is taken from manufacturer-declared specifications (350 kg). For the FCHEV retrofit configuration, the hydrogen mass is 3.5 kg (350 bar storage), and the corresponding compressed hydrogen tank system mass can be estimated using representative gravimetric capacity values for 350-bar storage systems. In particular, a nominal usable gravimetric capacity of about 5.5 wt% is reported for 350-bar compressed tank systems, leading to an overall hydrogen storage system mass of approximately 64 kg for 3.5 kg of usable hydrogen (including the hydrogen mass).

The resulting comparison highlights that, while diesel fuel mass for a full tank is limited (tens of kilograms), the BEV battery pack introduces a substantially higher mass contribution, whereas the hydrogen storage subsystem remains comparatively low. It is noted that the mass of the diesel tank hardware depends on design and material; therefore, this simplified analysis focuses primarily on the energy carrier mass and the main storage system mass contributions. Table 4 provides a simplified comparison of the mass contribution of the onboard energy storage subsystems for the different propulsion configurations considered. The gravimetric storage capacity (wt%) represents the ratio between the stored hydrogen mass and the total mass of the storage system.

The overall assessment is carried out using a quasi-static, backward-facing calculation approach, in which traction energy demand derived from the mission profiles is propagated through the drivetrain to estimate component-level energy requirements. The objective of this methodology is not to optimise component sizes or energy management strategies, but to verify the internal consistency and technical plausibility of the proposed FCHEV retrofit configuration under representative urban freight operating conditions. The outcomes of the sizing process and the implications for vehicle autonomy and energy use are discussed in the following section.

To clarify the rationale behind the selected FCHEV retrofit configuration, a concise comparative assessment of alternative sizing options was performed. Table 5 reports three representative combinations of fuel cell system nominal power and battery energy storage capacity, selected to reflect realistic lower- and higher-bound design options rather than to perform a full optimisation exercise. A lower-power configuration would reduce system mass and cost but would limit the capability to sustain long cumulative missions, particularly under repeated stop-and-go operation. Conversely, increasing both fuel cell power and battery capacity would improve peak power availability but at the expense of significantly higher mass and cost, with limited additional benefits in terms of daily mission completion. The selected configuration therefore represents a balanced compromise between energy availability, system mass, and expected operational flexibility, consistent with the feasibility-oriented scope of the present study.

Table 5. Comparative assessment of alternative FCHEV retrofit configurations.

Configuration	FCS Nominal Power	BES Capacity	Indicative Mass Impact	Indicative Cost Impact	Expected Operational Capability
A—low-power	30 kW	25 kWh	Low	Medium	Limited support under long missions
B—balanced (selected)	45 kW	35 kWh	Moderate	Moderate	Suitable for full daily missions
C—high-power	65 kW	50 kWh	High	High	Marginal benefit vs. added mass

The present study does not include experimental testing on a real vehicle driving the defined routes. Energy and fuel consumption values are therefore derived from manufacturer-declared specifications and consistent modelling assumptions. While this approach is subject to uncertainty with respect to real-world operation, it is intentionally adopted to support a preliminary feasibility assessment and to identify boundary conditions for powertrain sizing prior to experimental validation. To complement the energy feasibility assessment, a simplified mass balance of the energy storage subsystems is provided. The comparison focuses on the mass contribution associated with onboard energy storage (fuel, battery, and hydrogen storage), as this is the component directly affected by powertrain electrification and retrofit choices. The platform-level vehicle characteristics are common (Table 1); therefore, the analysis is presented in terms of relative mass changes in the storage subsystems rather than absolute vehicle curb weight, which would require a full component-level bill of materials.

To complement the energy-based comparison, an indicative operating cost per 100 km is estimated for the propulsion systems analysed, and the resulting values are reported in Table 6. The cost assessment is based on consistent energy-equivalent assumptions and on the consumption values adopted throughout the study, combined with explicitly stated reference energy prices. For the ICE configuration, the operating cost is calculated from the declared fuel consumption (9.8 L/100 km) and the Italian average diesel price for self-service refuelling, assumed equal to 1.686 €/L (2026). For the BEV configuration, the cost is derived from the electrical energy demand associated with the reference vehicle, expressed as a consumption range of 23.6–28.3 kWh/100 km, and from the ARERA reference electricity price of 0.2797 €/kWh (2026). For the FCHEV retrofit configuration, the operating cost is estimated using an energy-equivalent approach. In particular, the same traction energy demand identified for the BEV reference configuration is assumed, while the corresponding hydrogen consumption is obtained by converting the required energy into equivalent hydrogen input on a lower heating value basis. A representative hydrogen price of 13.7 €/kg is adopted to derive the indicative cost per unit distance. The hydrogen price considered in the present analysis refers to green hydrogen produced via renewable electricity-based electrolysis, consistently with the decarbonisation scope of the study. The resulting values are intended to provide an order-of-magnitude comparison between the analysed propulsion systems, as both energy prices and real-world consumption may vary depending on operating conditions and supply arrangements, such as depot-based refuelling strategies typically adopted in captive fleet applications.

Table 6. Indicative operating cost per 100 km for the analysed propulsion systems.

Configuration	Energy Basis	Price Assumption	Cost [€/100 km]
ICE	9.8 L/100 km	Diesel price (reference)	16.5
BEV	23.6–28.3 kWh/100 km	Electricity price (reference)	6.6–7.9
FCHEV retrofit	Same traction energy as BEV	Hydrogen price (reference)	15–17

3. Results and Discussion

The results are presented by discussing the implications of the methodology described in Section 2.3 in relation to the mission requirements derived from the Rome case study. In particular, the analysis focuses on the ability of different electrified powertrain configurations to satisfy cumulative daily mileage requirements under representative urban freight operating conditions.

The quantitative assessment carried out in Section 2.3 shows that the usable traction energy available in the BEV reference configuration is not sufficient to complete the planned routes without intermediate recharging. This outcome is a direct consequence of the mismatch between the cumulative distance associated with the selected missions and the usable onboard battery energy derived from manufacturer-declared specifications. Such a limitation is particularly critical in urban freight operations, where stop-and-go driving, frequent payload variations, and restricted charging opportunities reduce the effective autonomy compared to nominal range declarations.

This finding is consistent with evidence reported in the literature, where the driving range declared by electric vehicle manufacturers is often higher than that verified under real urban operating conditions, especially for commercial vehicles engaged in intensive delivery and service missions [61,62]. As a result, BEV configurations that are nominally suitable for urban use may encounter operational constraints when applied to routes characterised by long cumulative mileage and limited flexibility for mid-day charging. The adoption of the FCHEV architecture should therefore be interpreted as a response to route-specific energy constraints rather than as a general preference for hydrogen-based solutions.

To address this limitation, the FCHEV retrofit configuration described in Section 2.3 is considered. The battery energy capacity and FCS nominal power adopted in the proposed FCHEV configuration are derived from commercially available vehicle platforms and components. In particular, the battery capacity value is based on manufacturer specifications reported for a representative 3.5 t battery electric van platform [58], while the FCS nominal power is selected in line with commercially available automotive FCS suitable for LCV applications, as documented in the literature [63]. At the same time, it is recognized that the long-term durability and reliability of the fuel cell system represent a critical challenge for FCHEV applications under dynamic urban operating conditions. Recent studies have shown that adaptive health status monitoring and temperature sensitivity management can significantly mitigate performance degradation of PEMFC systems subjected to frequent start–stop cycles and fluctuating thermal conditions, thereby improving their operational robustness in urban freight applications [64]. Further evidence from the literature confirms that degradation phenomena in PEMFC systems are strongly influenced by coupled thermal, electrochemical, and mass transport effects, including gas diffusion layer aging, water management instability, and material fatigue under variable load profiles, which are particularly relevant for vehicle applications characterised by transient operating conditions [65–69]. The resulting system configuration and the corresponding estimated driving range are reported in Table 7. Under the adopted assumptions, the available onboard energy provided by the combination of hydrogen storage, fuel cell system, and battery buffer enables an estimated autonomy of approximately 293 km, which is sufficient to cover all the representative routes defined in the case study while maintaining an operational margin compatible with daily freight activities.

Table 7. BES, FCS and H2 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	116	45	83	293

The driving range estimate is obtained by assuming the same traction energy demand per unit distance as the BEV reference configuration, without applying FCHEV-specific simulations or experimental corrections. In particular, the upper-bound BEV consumption value (283 Wh/km) is adopted as a conservative assumption to convert the available traction energy of the FCHEV configuration into an estimated driving range. In addition to the route-based energy comparison, the BEV reference configuration and the FCHEV retrofit configuration are compared using the technical specifications reported in Tables 1 and 2 and the sizing outcomes in Table 4. This allows discussing feasibility not only in terms of mission completion capability (range/energy), but also with respect to vehicle constraints relevant to urban freight operations such as mass and payload limits. Charging and refuelling times are not quantified in this study, as they depend on infrastructure-specific conditions and would require additional assumptions and data beyond the scope of the present feasibility-oriented framework.

The comparison between the BEV reference configuration and the FCHEV retrofit solution highlights a key feasibility outcome. While the BEV configuration reflects current commercial offerings in the same vehicle segment, its usable energy content limits mission completion capability under the considered operating conditions. In contrast, the FCHEV retrofit configuration can satisfy the same mission requirements without intermediate recharging, suggesting that hydrogen-based hybridisation can effectively decouple daily mileage capability from battery-only constraints in urban freight applications.

These results should be interpreted within the scope of a feasibility study. The analysis does not aim to optimise component sizing or energy management strategies, nor does it provide experimental validation of on-road performance. Instead, it demonstrates the internal consistency and technical plausibility of a retrofit-oriented FCHEV configuration when applied to realistic urban mission profiles. The conclusions therefore depend on the adopted assumptions and input parameters, but the methodological approach is transferable to other urban contexts by adapting mission characteristics and vehicle specifications.

From a broader perspective, the proposed retrofit solution also offers potential advantages in terms of fleet transition pathways, as it allows existing vehicles to be repurposed rather than replaced. While a detailed environmental assessment is beyond the scope of this study, the existing literature suggests that retrofit strategies may contribute to emission reductions when combined with low-carbon hydrogen supply pathways [29,70].

4. Conclusions

This study investigated the opportunities offered by hydrogen-based retrofitting of light commercial vehicles for urban freight transport, with the objective of assessing technical feasibility under representative operating conditions rather than providing an optimised or experimentally validated solution. The analysis was grounded in a real urban context, using the city of Rome as a case study, and combined synthetic mission profiles with vehicle specifications derived from manufacturer datasheets.

The results highlight a key operational aspect of urban freight transport that is often underestimated when assessing electrification strategies. Although battery electric vehicles are widely recognised as a suitable solution for short-range urban applications, the cumulative daily mileage associated with intensive delivery and service missions can exceed the usable onboard battery energy of commercially representative BEV configurations. The quantitative assessment carried out in this study shows that, under the considered mission profiles, the BEV reference configuration is not able to complete the planned routes without intermediate recharging, even when conservative assumptions are adopted.

On this basis, a fuel cell hybrid electric vehicle retrofit configuration was analysed as an alternative electrification pathway. By decoupling onboard energy availability from battery-only constraints, the FCHEV architecture enables greater operational flexibility and allows the completion of the same missions without intermediate charging. The analysis demonstrates that, under the adopted assumptions, the hybrid configuration can satisfy cumulative daily mileage requirements that exceed the effective autonomy of the BEV reference, thereby addressing a structural limitation observed in battery-only solutions for route-based urban freight applications.

From a quantitative perspective, the analysis highlights clear differences between the analysed propulsion systems. The BEV reference configuration, characterised by a nominal battery capacity of 52 kWh and a usable traction energy of approximately 41.6 kWh, results in an energy consumption range of 23.6–28.3 kWh/100 km. Under these conditions, cumulative daily missions exceeding approximately 190–200 km cannot be completed without intermediate recharging, even under conservative assumptions.

In contrast, the FCHEV retrofit configuration, based on 3.5 kg of hydrogen storage at 350 bar combined with a battery buffer, provides a substantially higher usable onboard energy content, enabling the completion of the same daily missions without mid-day charging requirements. This difference directly reflects the higher specific energy associated with hydrogen compared to battery-based storage, which allows operational autonomy to be extended without proportionally increasing vehicle mass.

The mass comparison further supports this outcome. While the BEV configuration requires a battery pack with a mass of approximately 350 kg, the hydrogen storage system associated with the FCHEV retrofit is estimated at around 64 kg (including stored hydrogen), compared to approximately 66 kg of diesel fuel for a full 80 L tank in the ICE configuration. These values underline the fundamentally different mass–energy trade-offs of the analysed powertrain solutions.

Finally, the indicative operating cost analysis shows values in the range of approximately 6.6–7.9 €/100 km for the BEV configuration, around 16.5 €/100 km for the ICE reference vehicle, and comparable values for the FCHEV retrofit under current hydrogen price assumptions. Although strongly dependent on energy prices and supply conditions, these figures provide an additional quantitative perspective on the trade-offs associated with different electrification pathways. From an economic perspective, the feasibility of hydrogen-based retrofitting is primarily influenced by two external variables: the price of green hydrogen and the organisation of refuelling infrastructure. In the case of captive or semi-captive fleets operating from private logistics depots, on-site hydrogen refuelling can mitigate infrastructure constraints, shifting economic feasibility mainly towards hydrogen procurement costs.

The contribution of this work lies in the adoption of a structured, mission-driven methodology that links route characteristics, vehicle constraints, and powertrain sizing in a consistent framework. Rather than focusing on performance optimisation, this study provides a transparent feasibility assessment that can support decision-making for fleet transition strategies, particularly in contexts where vehicle replacement is constrained by economic, operational, or availability considerations. In this sense, hydrogen-based retrofitting emerges as a potential transitional option to complement battery electrification in specific use cases characterised by long cumulative mileage and limited charging flexibility.

Several limitations of this study should be acknowledged. The analysis relies on synthetic route profiles and on consumption values derived from manufacturer-declared specifications and does not include experimental validation or dynamic energy management optimisation. In addition, infrastructure availability, hydrogen supply pathways, and detailed life cycle environmental impacts were not explicitly modelled and may significantly influence the overall sustainability of retrofit solutions. Despite the technical feasibility highlighted by the present analysis, several challenges currently limit the large-scale deployment of hydrogen-based retrofit solutions. Key barriers include the high cost of green hydrogen under present market conditions, the limited availability of refuelling infrastructure outside captive fleet scenarios, and the additional system complexity introduced by hybrid powertrain architectures. Further challenges are related to regulatory approval procedures for vehicle retrofitting, certification requirements, and the integration of hydrogen systems within existing vehicle platforms originally designed for conventional powertrains. These aspects may significantly affect implementation timelines and overall economic viability. Finally, uncertainties associated with long-term hydrogen supply chains, component cost reduction trajectories, and standardisation of retrofit solutions remain open issues that must be addressed to enable broader adoption. In this context, long-term operational stability of fuel cell systems represents a key enabling factor for the practical deployment of retrofit solutions in commercial vehicle fleets. Urban freight applications are characterised by frequent start–stop events and highly variable load profiles, which may accelerate fuel cell degradation and progressively affect both driving range and operational efficiency over time. Hybrid fuel cell electric vehicle architectures offer a partial mitigation of these degradation mechanisms by enabling operating strategies in which the fuel cell system is maintained closer to quasi-constant power conditions, while transient power demands are managed by the battery. As discussed in previous work [21], this decoupling of energy storage and power delivery can reduce electrochemical and thermal stress on the fuel cell stack, potentially contributing to an extension of its useful lifetime under urban operating conditions. In this perspective, degradation-aware operating strategies and health monitoring approaches are increasingly recognised as key enablers for the long-term feasibility of FCHEV retrofit solutions.

Recent research has demonstrated that advanced online health state estimation methods can provide effective tools for monitoring fuel cell degradation under real operating conditions. In particular, approaches based on the quantitative decoupling of activation, ohmic, and concentration losses, combined with the analysis of open-circuit voltage transients, enable real-time estimation of key internal parameters such as electrochemical active area and internal resistance. These methods offer a feasible pathway to support predictive maintenance strategies, enhance long-term system reliability, and ultimately contribute to stable fleet operation and commercial viability when evaluating hydrogen-based conversion opportunities [71].

Future work will focus on extending the proposed framework through experimental validation on representative vehicles, refinement of energy consumption modelling under real driving conditions, and the integration of environmental and techno-economic assessments, including retrofit cost structures and comparative lifecycle perspectives. These developments will be essential to further quantify the role of hydrogen-based retrofitting within broader strategies for the decarbonisation of urban freight transport.

Author Contributions: Conceptualization, G.N. and S.M.; methodology, G.N.; validation, G.N. and S.M.; formal analysis, G.N.; investigation, G.N. and S.M.; resources, G.N., A.S.S., L.C. and S.M.; data curation, G.N., A.S.S., L.C. and S.M.; writing—original draft preparation, G.N.; writing—review and editing, G.N., A.S.S., L.C. and S.M.; visualization; S.M.; supervision, G.N.; project administration, G.N.; funding acquisition, G.N. and S.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the European Union—NextGeneration EU —and the Italian Ministry of Environment and Energy Security (POR H2 AdP MMES/ENEA), along with involvement from the CNR and RSE: PNRR—Mission 2, Component 2, and Investment 3.5 "Ricerca e sviluppo sull'idrogeno" and CUP: B93C22000630006.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors gratefully acknowledge DACHSER & FERCAM Italia for their valuable collaboration in validating the operational assumptions and synthetic datasets used in this study.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BEV	Battery Electric Vehicle
BES	Battery Energy Storage
CO_2	Carbon Dioxide
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCHEV	Fuel Cell Hybrid Electric Vehicle
FCS	Fuel Cell System
HRS	Hydrogen Refueling Station
ICE	Internal Combustion Engine
LCV	Light Commercial Vehicle
NMC	Nickel–Manganese–Cobalt (battery chemistry)
SULP	Sustainable Urban Logistics Plan

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