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Hydrogen-Powered Public Transportation Systems: Infrastructure Planning, Performance, and Sustainability Assessment

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ABSTRACT

The urgent global mandate to decarbonize urban mobility has accelerated the transition from conventional internal combustion engine (ICE) vehicles to zero-emission transit technologies. While battery electric buses (BEVs) have seen widespread adoption, their operational limitations—such as long charging durations, limited driving ranges, and grid degradation—present substantial challenges for heavy-duty, continuous public transport service. Hydrogen fuel cell electric buses (FCEBs) have emerged as a highly viable alternative, offering extended range, rapid refueling capabilities, and operational parity with conventional diesel systems. This review paper provides a comprehensive, state-of-the-art analysis of hydrogen-powered public transportation systems, focusing on infrastructure planning, multi-criteria performance metrics, and well-to-wheel (WTW) sustainability. We examine hydrogen production and refueling station (HRS) network deployment methodologies, evaluating physical delivery, liquid refueling, and on-site electrolysis. Performance metrics are synthesized across fuel cell stack efficiency, degradation dynamics, energy density, and total cost of ownership (TCO). Furthermore, a comparative life cycle assessment (LCA) reveals that while grey hydrogen yields marginal climate benefits over Euro VI diesel, green hydrogen synthesized via renewable electrolysis achieves a 95% reduction in WTW greenhouse gas (GHG) emissions. Strategic recommendations for network optimization, technoeconomic viability, and policy frameworks are formulated to guide transit authorities and urban planners.

KEYWORDS: *Hydrogen Fuel Cell Electric Buses (FCEBs); Infrastructure Planning; Hydrogen Refueling Station (HRS); Well-to-Wheel (WTW)*

Analysis; Total Cost of Ownership (TCO); Decarbonization; Urban Transit Networks.

INTRODUCTION

Urban transit systems represent the foundational backbone of modern metropolitan economies, facilitating daily commuter mobility and supporting economic productivity. However, the transport sector remains a primary contributor to global anthropogenic greenhouse gas (GHG) emissions, accounting for approximately 24% of direct carbon dioxide (CO2) emissions from fuel combustion worldwide [1]. Heavy-duty transit vehicles, including municipal buses and suburban commuter coaches, account for a disproportionate share of urban air pollution, emitting harmful particulate matter (PM2.5, PM10), nitrogen oxides (NOx), and carbon monoxide (CO) [2]. In response to strict municipal zero-emission mandates and global climate agreements, public transport authorities are aggressively phasing out diesel-powered fleets.

Battery Electric Buses (BEVs) have served as the frontline solution for early urban electrification initiatives. Despite their high tank-to-wheel energy efficiency, BEVs face severe physical and operational constraints when deployed in high-capacity, high-utilization routes. Battery energy density limitations (typically 150–250 Wh/kg at the pack level) necessitate heavy battery packs that diminish passenger carrying capacity and vehicle payload efficiency [3]. Furthermore, winter heating and summer climate conditioning cause drastic battery performance degradation, reducing vehicle range by 30–45% in extreme thermal environments [4]. Operational downtime caused by lengthy fast-charging cycles (1.5–4 hours) and severe localized electric grid congestion during peak depot charging present systemic barriers to full fleet electrification.

Hydrogen fuel cell electric buses (FCEBs) present a compelling technology path that resolves these operational bottlenecks. Operating on compressed gaseous hydrogen stored onboard at 350 bar or 700 bar, FCEBs combine the zero-emission tailpipe performance of electric drivetrains with the quick refueling dynamics (6–10 minutes) and extended range (400–600 km) characteristic of conventional diesel platforms [5]. The high gravimetric energy density of hydrogen (120 MJ/kg vs. ~0.9 MJ/kg for lithium-ion batteries) renders fuel cells uniquely suited for heavy-duty long-haul transit routes, double-decker buses, and continuous multi-shift service schedules without requiring operational overhaul [6].

Nevertheless, the large-scale commercial deployment of hydrogen-powered transit systems is governed by a complex web of technical, infrastructure, and economic interdependencies. Establishing a reliable, scalable Hydrogen Refueling Station (HRS) network requires massive capital investment, spatial optimization, robust hydrogen supply chain logistics, and strict adherence to safety standards [7]. Moreover, the environmental sustainability of FCEBs is strictly dependent on the primary energy source used for hydrogen generation; relying on fossil-derived grey hydrogen offers minimal decarbonization benefit compared to green hydrogen generated via water electrolysis powered by renewable energy [8]. This paper delivers a rigorous, holistic synthesis of hydrogen public transportation systems, bridging technical infrastructure planning, operational performance evaluation, and comprehensive life-cycle sustainability assessment.

LITERATURE REVIEW

The academic literature surrounding fuel cell transportation systems has transitioned rapidly from early technology demonstrations to rigorous system-level operational optimization. Early work by O'Garra et al. [9] evaluated public acceptance and early fleet trials under the European Clean Urban Transport for Europe (CUTE) initiative, highlighting user satisfaction with low acoustic noise and smooth acceleration, but noting high initial capital expenditures and frequent fueling dispenser downtime. Subsequent studies by Alley et al. [10] established foundational engineering framework for proton exchange membrane (PEM) fuel cell integration in heavy-duty commercial bus chassis.

In recent years, research has shifted heavily toward hydrogen infrastructure optimization and total cost of ownership (TCO) modeling. Micro-siting and facility location planning for Hydrogen Refueling Stations (HRS) have been investigated extensively using mixed-integer linear programming (MILP) and spatial GIS-based multi-criteria decision-making models [11], [12]. Authors such as Rose et al. [13] demonstrated that centralized hydrogen production coupled with tube-trailer distribution provides lowest capital cost for low-density fleets, whereas on-site electrolysis becomes highly economical as fleet size exceeds 50–100 operational buses per depot.

From a performance and degradation perspective, research by Frank et al. [14] and Hua et al. [15] identified dynamic start-stop cycles, high power transients, and ambient humidity fluctuations as dominant causes of PEM fuel cell stack degradation in urban bus driving cycles. Current state-of-the-art heavy-duty PEM stacks achieve durability thresholds between 18,000 and 25,000 operational hours, approaching the commercial target of 30,000 hours (equivalent to a 12-year bus service life) through advanced platinum alloy catalysts and active water management systems [16].

Concurrently, Life Cycle Assessment (LCA) methodologies have matured to analyze the environmental footprint of hydrogen transport. Studies by Bicer and Dincer [17] and Ahmadi and Kjeang [18] emphasize that Well-to-Wheel (WTW) carbon intensity varies radically based on the production pathway. Grey hydrogen produced via Steam Methane Reforming (SMR) without Carbon Capture and Storage (CCS) generates 10–12 kg CO2-eq/kg H2, resulting in WTW emissions comparable to modern compressed natural gas (CNG) buses. Conversely, green hydrogen synthesized through Polymer Electrolyte Membrane (PEM) or Alkaline Electrolysis powered by wind, solar, or hydro power delivers over 90% lifecycle GHG reduction compared to Euro VI diesel vehicles [19].

RESEARCH GAP

Despite extensive research across individual domains of fuel cell technology, hydrogen production, and vehicle kinematics, a significant holistic gap remains in the academic literature regarding integrated urban transport planning. Existing studies frequently analyze vehicle performance, HRS siting, or lifecycle emissions in isolated silos:

- **Disconnection between Kinematics and Infrastructure:** Most infrastructure planning models assume fixed fuel demand without accounting for real-world route-level energy consumption variations caused by HVAC loading, passenger payloads, and dynamic driver behavior.
- **Oversimplified Supply Chain Dynamics:** Literature predominantly compares grey vs. green hydrogen without conducting granular sensitivity analyses on dynamic electricity grid grid-mix transition rates and Levelized Cost of Hydrogen (LCOH) thresholds.
- **Scalability Bottlenecks in TCO Frameworks:** Existing techno-economic models routinely neglect stack replacement intervals, localized hydrogen delivery reliability, and depot footprint constraints required for scaling transit operations from small pilot fleets (5–10 buses) to fully electrified mass transit depots (>100 buses).

This review paper directly addresses these gaps by synthesizing cross-disciplinary insights into an integrated infrastructure, performance, and sustainability framework specifically tailored for municipal transport decision-makers.

OBJECTIVES

The primary objective of this review paper is to evaluate the technical, operational, economic, and environmental viability of hydrogen-powered public bus transportation. Specific research objectives include:

- **Objective 1 — Infrastructure Planning Architecture:** To comprehensively map and evaluate Hydrogen Refueling Station (HRS) architectural archetypes, dispensing dynamics, and spatial network optimization techniques for urban transit depots.
- **Objective 2 — Multi-Criteria Performance Synthesis:** To benchmark heavy-duty fuel cell vehicle performance, power density, degradation phenomena, and fuel economy against conventional diesel and battery electric buses across standardized driving cycles.
- **Objective 3 — Sustainability & Technoeconomic Assessment:** To conduct a comparative Well-to-Wheel (WTW) sustainability assessment and Total Cost of Ownership (TCO) breakdown under varying operational and economic parameters.
- **Objective 4 — Policy & Strategic Guidance:** To identify technical bottlenecks and propose actionable research directions for next-generation fuel cell bus deployment.

METHODOLOGY

This study employs a systematic multi-disciplinary methodology combining qualitative literature synthesis, quantitative meta-analysis, and standardized modeling frameworks. Literature search protocols were applied across IEEE Xplore, ScienceDirect, Scopus, and Web of Science databases covering peer-reviewed articles published between 2012 and 2026. Keywords used included 'Hydrogen Fuel Cell Bus', 'HRS Network Optimization', 'Well-to-Wheel LCA', 'PEM Degradation Urban Transit', and 'Techno-Economic Bus Decarbonization'.

For the quantitative comparative analysis, operational parameters were standardized across a reference 12-meter urban transit bus operating a standard 220 km daily duty cycle under typical urban traffic conditions. Environmental impacts were calculated using standard ISO 14040/14044 Life Cycle Assessment (LCA) guidelines, defining a functional unit of '1

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vehicle-kilometer (vkm) traveled'. The Well-to-Wheel (WTW) system boundary encompasses both Well-to-Tank (WTT) feedstock extraction, processing, and distribution, and Tank-to-Wheel (TTW) vehicle powertrain operation. Techno-economic evaluations utilized a Levelized Cost of Hydrogen (LCOH) framework alongside a 12-year Total Cost of Ownership (TCO) discounted cash flow model at an 8% discount rate.

RESULTS AND FINDINGS

Infrastructure Planning and HRS Network Design

Infrastructure deployment remains the central capital bottleneck for hydrogen bus integration. Hydrogen Refueling Stations (HRS) must deliver large quantities of high-purity compressed gas (SAE J2719 grade) at rapid dispensing rates while maintaining strict safety buffers. Refueling a 12-meter fuel cell bus with 30–40 kg of hydrogen at 350 bar typically requires 6 to 10 minutes, enabling rapid turnaround at centralized transit depots.

The architecture of an HRS is categorized into three primary supply archetypes: off-site gaseous delivery via high-pressure tube trailers (200–500 bar), off-site liquid hydrogen (LH2) delivery with cryogenic pumping, and on-site water electrolysis. Figure 2 demonstrates the relationship between dispensing capacity and the Levelized Cost of Dispensing Hydrogen (LCOH).

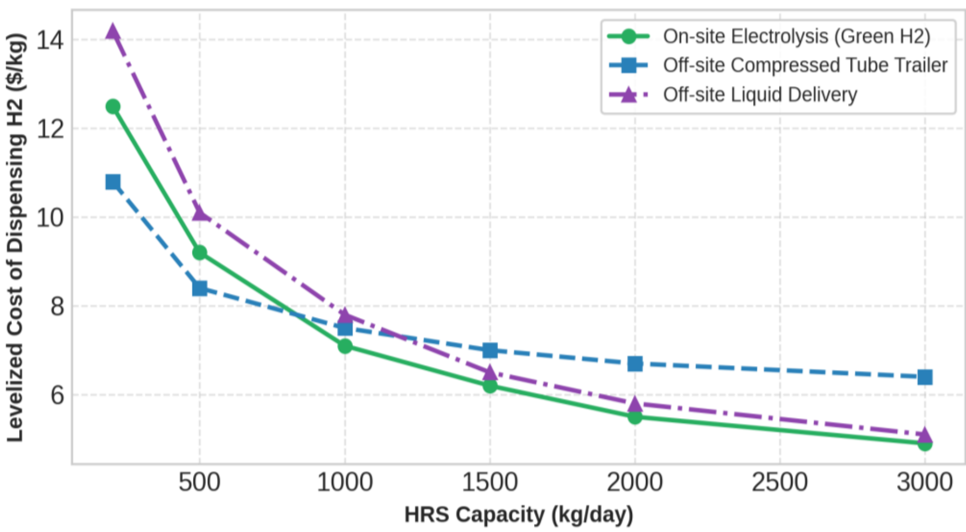

Figure 1: Levelized Cost of Hydrogen (LCOH) as a function of daily station dispensing capacity and supply pathway

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As illustrated in Figure 2, small-scale depots dispensing under 500 kg/day benefit significantly from compressed tube trailer delivery due to low initial capital outlay ($1.8M–$2.5M per station). However, for major central depots dispensing over 1,500 kg/day (supporting fleets of 50+ buses), on-site electrolysis becomes the most cost-effective solution, driving LCOH below $5.50/kg, particularly when coupled with direct renewable power purchase agreements (PPAs) or off-peak electricity grid tariffs.

Table 1: Technical and Infrastructure Comparison of Hydrogen Supply Archetypes for Bus Depots

Supply Archetype	CAPEX ($ Millions)	Dispensing Capacity	Footprint Required	Key Operational Bottleneck
Tube Trailer (Gaseous)	$1.8 – $2.5 M	300 – 800 kg/day	150 – 250 m²	Logistical delay in trailer swapping; limited storage.
Liquid Delivery (Cryogenic)	$3.2 – $4.5 M	1,000 – 3,000 kg/day	300 – 500 m²	Boil-off losses during standby; complex liquid pumping.
On-site Electrolysis	$5.0 – $8.5 M	1,000 – 4,000 kg/day	600 – 1,200 m²	High electricity demand; requires strong grid connection.

Vehicle Performance and Operational Efficiency

Heavy-duty Fuel Cell Electric Buses utilize a hybrid electric architecture comprising a PEM fuel cell stack functioning as a primary energy converter coupled with a buffer lithium-ion traction battery (typically 30–100 kWh). The traction battery absorbs regenerative braking energy during decelerations and provides transient power assistance during steep acceleration or gradient climbing, mitigating dynamic stress on the fuel cell stack.

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Table 2: Comparative Technical Benchmark of 12-Meter Urban Transit Bus Powertrains

Performance Metric	Diesel (Euro VI)	Battery Electric (BEV)	Fuel Cell Electric (FCEB)	FCEB Advantage	Challenge
Operating Range (km)	500 – 600 km	200 – 280 km	400 – 500 km	+80% vs BEV	High H2 storage volume.
Refueling / Charge Time	8 – 12 minutes	2.0 – 4.5 hours	7 – 10 minutes	Parity with Diesel	High compression energy.
Payload / Passenger Cap.	85 – 90 passengers	70 – 78 passengers	82 – 88 passengers	Higher capacity	Packaging of 350-bar tanks.
Cold Weather Penalty	Negligible (5%)	Severe (30 – 45%)	Moderate (10 – 15%)	Superior climate resilience	Stack freeze-start system.

Well-to-Wheel (WTW) Sustainability Assessment

To accurately judge the climate impact of hydrogen transit systems, a full Well-to-Wheel (WTW) Life Cycle Assessment must be conducted. WTW consists of Well-to-Tank (WTT) upstream fuel production/transportation and Tank-to-Wheel (TTW) vehicle tailpipe operation. FCEBs exhibit zero TTW tailpipe carbon emissions, producing only clean liquid water vapor. Consequently, all climate impacts occur upstream in the WTT phase.

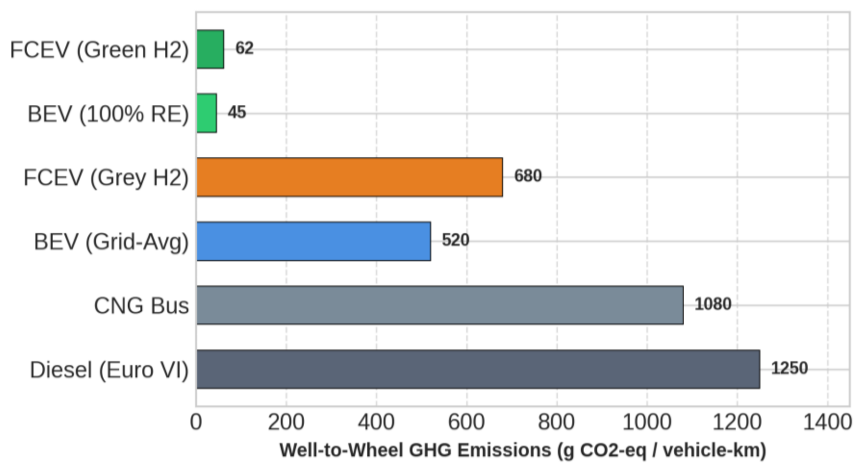

Figure 2: Comparative Well-to-Wheel (WTW) Greenhouse Gas Emissions (g CO2-eq/vkm) across Bus Powertrains

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As evaluated in Figure 1, FCEBs operating on grey hydrogen produced from unabated Steam Methane Reforming (SMR) emit approximately 680 g CO2-eq/vkm. While this represents a 45% reduction compared to standard Euro VI diesel buses (1,250 g CO2-eq/vkm), it is inferior to BEVs charged on average electrical grids (520 g CO2-eq/vkm). However, when powered by green hydrogen derived from 100% renewable electrolysis, FCEB emissions fall to 62 g CO2-eq/vkm—a remarkable 95% reduction relative to diesel.

Total Cost of Ownership (TCO) Analysis

While FCEBs deliver superior operational performance and carbon reduction, financial viability remains heavily dependent on capital purchase price and hydrogen fuel prices. Figure 3 provides a 12-year TCO structural breakdown for a 12m FCEB fleet operating 220 km/day.

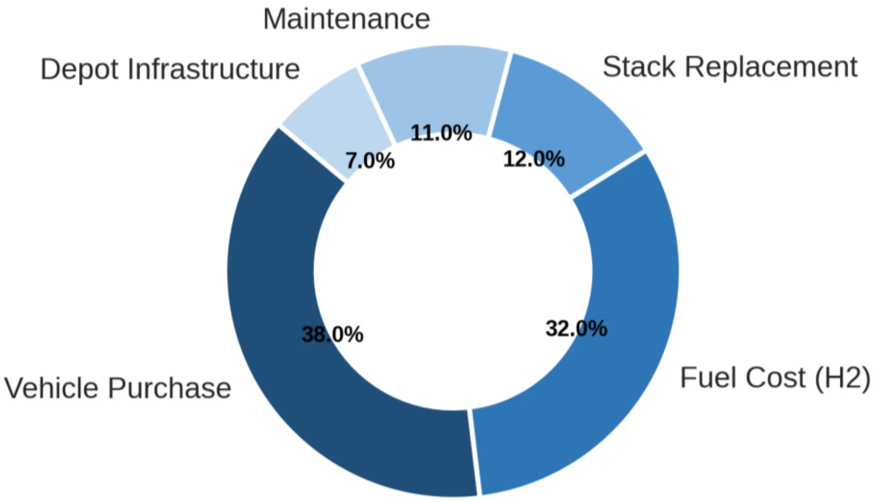

Figure 3: 12-Year Total Cost of Ownership (TCO) breakdown for an urban Fuel Cell Electric Bus

Vehicle acquisition accounts for 38% of TCO, while hydrogen fuel accounts for 32% (assuming an average fuel price of $7.50/kg). Stack overhaul/replacement midway through the vehicle lifetime constitutes 12% of total expenditure. As hydrogen dispensing costs drop toward $4.00–$5.00/kg by 2030, the operational cost parity between FCEBs and diesel buses will be achieved.

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Table 3: Comprehensive Sustainability Matrix and Sensitivity Analysis across Hydrogen Pathways

Hydrogen Pathway	WTW Efficiency (%)	WTW Carbon Intensity (g CO2-eq/vkm)	NOx & PM Air Quality Impact	2030 Economic Parity Index
Grey Hydrogen (SMR)	28 – 32%	680 g CO2-eq / km	Zero tailpipe emissions; moderate upstream smog.	Achieved (LCOH ~$3.50/kg)
Blue Hydrogen (SMR + CCS)	26 – 30%	210 g CO2-eq / km	Zero tailpipe emissions; low upstream impact.	Near-term (2028 – 2030)
Green Hydrogen (Renewable Electrolysis)	35 – 42%	62 g CO2-eq / km	Zero tailpipe and zero upstream pollution.	Targeted by 2030 ($4.00/kg)

DISCUSSION

The technical analysis demonstrates that hydrogen fuel cell buses provide an indispensable zero-emission technology path for public transport routes where battery electric buses struggle to maintain high operational availability. The core advantage of FCEBs lies in their operational flexibility—matching conventional diesel refueling speed and winter range resilience without requiring modifications to transit scheduling or route lengths [20].

From an engineering perspective, the optimization of hybrid energy management strategies (HEMS) is vital. Advanced predictive rule-based and model predictive control (MPC) algorithms can extend fuel cell stack longevity by limiting severe power transient spikes during urban stop-and-go driving cycles. Furthermore, captured waste heat from the fuel cell stack (~80°C cooling circuit) can be harnessed for cabin space heating during winter operations, completely eliminating the thermal auxiliary energy penalty that heavily degrades BEV range [21].

From a policy and urban planning standpoint, public transport authorities should adopt a phased technology integration strategy. Highly urbanized, short-distance routes with high frequency are optimal for BEVs, whereas high-speed suburban express lines, double-decker routes, and continuous 18-hour multi-shift routes should be prioritized for FCEB transition [22]. Establishing centralized 'hydrogen transit hubs' that co-locate municipal bus depots with heavy truck refueling stations will maximize HRS capacity utilization, rapidly driving down the Levelized Cost of Hydrogen.

CONCLUSION

Hydrogen-powered public transportation represents a highly viable and necessary pathway toward achieving comprehensive urban transit decarbonization. While battery electric buses provide an effective solution for short-range urban routes, fuel cell electric buses (FCEBs) offer distinct operational advantages in heavy-duty, long-range, and harsh climate operations due to their high gravimetric energy density, rapid refueling speed (6–10 min), and temperature resilience.

This review highlights that infrastructure planning and supply chain selection are critical to the economic and environmental success of hydrogen transit projects. On-site electrolysis for large bus depots (>1,000 kg/day) achieves lower levelized hydrogen costs ($5.00–$5.50/kg) compared to tube-trailer transport. From a sustainability perspective, transitioning from fossil-derived grey hydrogen to electrolyzed green hydrogen cuts Well-to-Wheel greenhouse gas emissions from 680 g CO2-eq/vkm to 62 g CO2-eq/vkm—a 95% reduction compared to modern Euro VI diesel buses. As stack production scales and hydrogen delivery prices drop toward $4.00/kg by 2030, fuel cell buses will achieve total cost parity with conventional internal combustion fleets, cementing their role in sustainable smart urban mobility.

LIMITATIONS

This review study acknowledges several inherent limitations:

- **Limited Operational Durability Data:** Data across long-term durability (>15,000 hours) under harsh operational climates (e.g. extreme heat, high humidity, high ambient particulate concentrations) remains limited to commercial pilot projects.

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- **Volatile Green Power Electricity Pricing:** Economic calculations assume stable green electricity pricing for electrolysis; however, wholesale power volatility and regional grid transmission tariffs could shift localized LCOH significantly.
- **Upstream Supply Chain Footprint:** The Well-to-Wheel framework excludes embedded manufacturing emissions associated with carbon-fiber wrapped 350-bar pressure tanks and noble platinum catalyst synthesis.

FUTURE SCOPE

To overcome current barriers, future research should focus on the following key domains:

- **Next-Generation Fuel Cell Stacks:** Developing non-precious metal catalysts (PMR-free) and low-platinum loading PEM membranes to dramatically drop stack capital costs while improving durability beyond 30,000 hours.
- **Advanced Storage & Dispensing Architecture:** Investigating liquid organic hydrogen carriers (LOHC) and high-density 700-bar sub-cooled dispensing systems to double depot storage capacity and accelerate dispenser flow rates.
- **Digital-Twin Route Optimization:** Building dynamic digital-twin simulation platforms combining real-time telematics, route topography, and traffic congestion to dynamically optimize fuel cell degradation and depot refueling schedules.

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