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Decarbonizing Transport: A Systematic Comparative Review of Hydrogen, Biofuels, and Electric Powertrains via Techno-Economic and Environmental Parameters

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***Abstract* - This Systematic Literature Review synthesises 30 peer-reviewed studies published from 2021 to 2025, comparing hydrogen fuel cell, battery electric, and biofuel powertrains across road, maritime, and rail applications. Conducted using the PRISMA framework, the review addresses fragmented and methodologically inconsistent comparative findings across the technical, environmental, and economic dimensions. Technically, battery electric vehicles lead well-to-wheel efficiency at 70 to 80 percent, against 30 to 40 percent for fuel cell vehicles and 12 to 30 percent for internal combustion and biofuel systems; fuel cell and biofuel powertrains retain range and payload advantages for heavy-duty use. Environmentally, battery electric and fuel cell vehicles deliver lifecycle greenhouse gas reductions of 15 to 69 percent versus conventional vehicles in low-carbon grids, but may underperform hybrids in coal-heavy systems, while biofuel blends provide 16 to 38 percent reductions through existing infrastructure. Economically, battery electric vehicles offer the lowest Total Cost of Ownership for light-duty applications today, with fuel cell parity projected after 2030 if hydrogen costs fall below four euros per kilogram. Four research gaps are identified: inconsistent life cycle assessment boundaries, average versus marginal grid assumptions, infrastructure exclusion from cost models, and scarce real-world validation. No single powertrain is universally optimal; selection must be guided by duty cycle, regional energy mix, and policy framework.**

Keywords* - *Alternative Fuels; Battery Electric Vehicle; Fuel Cell Electric Vehicle; Hydrogen Mobility; Biofuels; Life Cycle Assessment; Well-to-Wheel; Total Cost of Ownership; Decarbonisation; Systematic Literature Review.

I. INTRODUCTION

A. The Decarbonisation Imperative

The global transportation sector accounts for approximately 24% of energy-related CO_2 emissions, with road vehicles alone responsible for roughly 74% of that share [1, 2]. The European Union has mandated a 90% reduction in transport greenhouse gas (GHG) emissions by 2050 to achieve climate neutrality, banning new internal combustion engine (ICE) light-duty vehicle sales from 2035 [3]. The United Kingdom and California have set comparable zero-emission mandates effective 2030 and 2035 respectively [4], while South Korea, Japan, China, and India have all committed to net-zero pathways centred on the electrification or alternative-fuel substitution of their vehicle fleets [5, 6]. Despite these commitments, transport remains the only major sector where emissions continue to rise above 1990 levels [3], underscoring the urgency of identifying technically viable, economically affordable, and environmentally sound powertrain alternatives.

B. The Three Competing Powertrain Pathways

Three principal alternative pathways have emerged to displace conventional ICE vehicles. Battery Electric Vehicles (BEVs) store electricity in lithium-ion battery packs and convert 0.70–0.90 of stored energy into wheel motion, supported by a rapidly expanding global charging network with over 570,000 fast-chargers as of 2021 [7]. Fuel Cell Electric Vehicles (FCEVs) generate electricity onboard via the electrochemical reaction of hydrogen and oxygen, offering refuelling times of 5–15 minutes and driving ranges of 400–600 km, making them especially attractive for heavy-duty and long-range applications [7, 8]. Biofuel-powered systems — including bioethanol, biodiesel, bio-LPG, renewable dimethyl ether (rDME), and liquefied biogas (LBG) — leverage existing ICE infrastructure to deliver near-term GHG reductions through drop-in or blended renewable feedstocks, often derived from waste cooking oils, organic municipal waste, or non-recyclable plastics [3, 9].

Each pathway carries distinct trade-offs. BEVs face range anxiety, long charging durations, and battery production emissions that can constitute 0.40 of lifecycle GHGs [10]. FCEVs are constrained by hydrogen production costs, sparse refuelling infrastructure (fewer than 1,200 stations globally as of 2023), and a well-to-wheel efficiency of only 0.30–0.40 [11, 12]. Biofuels face feedstock scalability limits and inconsistent emission performance depending on production pathway and land-use assumptions [13].

C. The Comparative Assessment Problem

A growing body of Life Cycle Assessment (LCA) and Total Cost of Ownership (TCO) studies has attempted to compare these pathways, but findings remain fragmented across multiple axes. Reported BEV GHG reductions versus ICEVs span 15–69% depending on regional electricity mix [4, 14]; FCEV lifecycle emissions vary by an order of magnitude depending on whether hydrogen is produced from coal gasification, natural gas reforming, or photovoltaic electrolysis [15, 16]; and biofuel blends report GHG reductions of 16–38% under cradle-to-grave boundaries [3]. Methodological inconsistency — including divergent functional units, system boundaries, and treatment of upstream electricity carbon intensity — further complicates direct comparison [13, 17]. The result is that policymakers, fleet operators, and engineers face a literature in which "which fuel is best" depends critically on the specific question being asked.

D. Research Questions

This Systematic Literature Review (SLR) addresses this fragmentation by synthesising findings from 30 peer-reviewed studies (2021–2025) covering road, maritime, and rail applications. The review is structured around four research questions:

> RQ1 (Technical): How do hydrogen, biofuel, and electric powertrains compare in terms of energy efficiency, energy density, range, and operational constraints?
>
> RQ2 (Environmental): What are the well-to-wheel (WTW) and life cycle GHG emissions associated with these powertrains, and how do they vary across energy sources and regions?
>
> RQ3 (Economic): What is the comparative Total Cost of Ownership (TCO) of these alternatives, and what are the major techno-economic barriers (CAPEX, infrastructure, fuel cost) to adoption?
>
> RQ4 (Research Gaps): What are the key limitations, inconsistencies, and research gaps in existing comparative studies?

The remainder of this paper is organised as follows. Section II describes the SLR methodology including database selection, search strings, and inclusion criteria. Section III presents the comparative results across the three pillars (Technical, Environmental, Economic). Section IV synthesises the findings and identifies cross-cutting research gaps, and Section V concludes with recommendations for engineering practice and future research.

II. METHODOLOGY

This Systematic Literature Review (SLR) follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework, supplemented by the eight-stage protocol of Thomé et al. as adopted in prior transport-sector reviews [13]. The methodology comprises five sequential stages: (A) database selection and search string formulation, (B) screening and inclusion/exclusion criteria, (C) data extraction protocol, (D) cross-fuel comparative synthesis, and (E) gap identification.

A. Database Selection and Search Strategy

Three peer-reviewed scientific databases were queried to ensure comprehensive coverage: Scopus, Web of Science (WoS), and ScienceDirect, supplemented by targeted searches in Google Scholar for cross-validation. The selection of these databases reflects established practice in transport-sector SLRs, where Scopus and WoS together capture more than 90% of indexed engineering and energy-systems literature [13]. The search was restricted to English-language, peer-reviewed journal articles published between January 2021 and October 2025, prioritising recent evidence given the rapid pace of battery, fuel cell, and biofuel technology evolution.

A Boolean search string was constructed using the PICO (Population, Intervention, Comparison, Outcome) framework, combining keywords across the three powertrain pillars and three assessment dimensions:

> *("hydrogen" OR "fuel cell" OR "FCEV" OR "HFCV" OR "H_2 vehicle") AND ("battery electric" OR "BEV" OR "electric vehicle" OR "EV") AND ("biofuel" OR "biodiesel" OR "bioethanol" OR "bio-LPG" OR "rDME" OR "renewable fuel") AND ("life cycle assessment" OR "LCA" OR "well-to-wheel" OR "WTW" OR "total cost of ownership" OR "TCO" OR "techno-economic") AND ("comparison" OR "comparative" OR "review")*

Variants of this string were applied across each database to accommodate platform-specific syntax. The initial search returned approximately 1,100 records across all three databases.

B. Inclusion and Exclusion Criteria

After deduplication, articles were screened in two phases — title/abstract screening followed by full-text review — against the following criteria. Inclusion required: (1) peer-reviewed journal article published 2021–2025; (2) comparison of at least two of the three powertrain pillars (hydrogen, biofuel, electric); (3) reporting of quantitative technical, environmental, or economic data (e.g., efficiency, gCO_2eq/km, €/km, MJ/km); (4) application of a recognised assessment methodology (LCA, WTW, TCO, or techno-economic analysis); and (5) coverage of any vehicle class (light-duty, heavy-duty, public transit, freight rail, or maritime). Articles were excluded if they were: (1) conference proceedings, opinion pieces, white papers, or non-peer-reviewed sources; (2) single-fuel studies without comparative scope; (3) purely qualitative or simulation studies without primary or secondary quantitative output; (4) aviation- and rocket-propulsion-focused; or (5) published before 2021.

After applying these filters, 30 articles were retained for synthesis: 14 published 2021–2024 forming the foundational evidence base, and 16 published 2025 capturing the most recent state of the art. The PRISMA flow is summarised in Table I.

TABLE I. PRISMA SCREENING FLOW

Stage	Records (n)
Identified through database search	~1,100
Removed in deduplication	~340
Title/abstract screened	~760
Excluded at title/abstract stage	~660
Full-text assessed for eligibility	~100
Excluded at full-text stage	~70
Final included for synthesis	**30**

C. Data Extraction Protocol

For each included article, a structured data extraction template captured: bibliographic metadata (authors, year, journal, country/region); vehicle class and sector; powertrain(s) compared; technical parameters relevant to RQ1 (WTW efficiency, driving range, energy density, payload impact, refuelling/recharging time); environmental parameters relevant to RQ2 (cradle-to-grave or WTW GHG emissions in gCO_2eq/km, GHG reduction versus ICEV baseline, regional electricity carbon intensity, hydrogen production pathway, biofuel feedstock); economic parameters relevant to RQ3 (TCO in €/km or $/km, CAPEX, fuel/energy cost, infrastructure cost, break-even mileage); methodological metadata (LCA software, system boundary, functional unit, allocation method); and any author-stated limitations and research gaps relevant to RQ4. Data extraction was performed manually with cross-verification against original tables and figures to minimise transcription error. Where studies reported ranges (e.g., 50–70% GHG reduction), both endpoints were retained to preserve uncertainty bounds in the synthesis.

D. Cross-Fuel Comparative Synthesis

Extracted data were organised in a master matrix indexed by powertrain pillar, RQ category, and sector. For each RQ, findings were synthesised in three steps: (1) within-pillar aggregation of reported values across all studies in a single powertrain pillar to capture central tendency and variation; (2) cross-pillar comparison of representative values under matched conditions (comparable vehicle class, regional grid, system boundary); and (3) conditional benchmarking, where direct comparison was infeasible due to methodological divergence, results were reported as "best-under-condition" findings (e.g., BEV optimal in low-carbon grids, FCEV optimal in heavy-duty long-haul, biofuels optimal where ICE infrastructure must be retained). All energy and emission values were converted to SI (MKS) units to ensure consistency. Cost values were retained in their reported currency without normalisation, given the high sensitivity of TCO to local market conditions.

E. Research Gap Identification

Research gaps were identified through three complementary lenses: (1) author-stated limitations drawn from the discussion and future-work sections of each included study; (2) methodological inconsistencies observed across studies (e.g., divergent system boundaries, average-vs-marginal grid assumptions); and (3) coverage gaps in the corpus itself (e.g., absence of long-term real-world fleet data, limited biofuel-specific lifecycle inventories). Gaps were then clustered into thematic categories and ranked by frequency of mention across the 30 studies, forming the basis of the discussion in Section IV.

III. RESULTS AND DISCUSSION

The synthesis is organised into three subsections corresponding to RQ1–RQ3, with cross-pillar conclusions and the gap analysis (RQ4) in Section IV.

A. Technical Performance (RQ1)

1) Efficiency:

BEVs lead the well-to-wheel (WTW) efficiency hierarchy at 0.70–0.80, against 0.30–0.40 for FCEVs and 0.12–0.30 for ICEVs [11]. The BEV figure aggregates 0.75–0.92 charging efficiency and 0.85–0.90 motor-to-wheel conversion [10, 14]. FCEV efficiency stacks PEMFC (0.40–0.60), power electronics (~0.95), motor (0.90–0.95), and drivetrain (~0.90) [11]; using hydrogen as long-term electricity storage drops round-trip efficiency to only 0.27 [17].

Experimentally, Sagaria et al. [18] reported BEVs consuming 0.23 of equivalent ICE energy and FCEVs 0.65 under real-world driving. For freight rail, Aredah et al. [9] measured catenary-electric and battery-electric locomotives at 34.17 and 37.36 MWh/MNTM respectively, hydrogen fuel-cell trains at 68.29 MWh/MNTM. Yeo et al. [5] confirmed BEVs as 3.5–4× more efficient than ICEVs in the Korean fleet. For light-duty China, Liu et al. [19] showed fuel consumption falls monotonically with electrification (ICEV → BEV) but mass and cost rise; HEVs emerged as the most cost-effective near-term option.

2) Range and Refuelling Time:

The range/refuelling trade-off favours FCEVs and biofuels for heavy-duty applications (Table II). BEV passenger ranges of 300–500 km recharge in hours (or 2–3 minutes via swapping) [6]; FCEVs deliver 480–650 km with 5–15 min refuelling [7, 11]; biofuel-blended ICEs retain conventional 600–1,000 km / 3–5 min profiles using existing infrastructure [3].

TABLE II. COMPARATIVE TECHNICAL PARAMETERS

Parameter	BEV	FCEV	Biofuel ICE
WTW efficiency	0.70–0.80	0.30–0.40	0.12–0.30
Range, passenger car (km)	300–500	480–650	600–1,000
Range, bus (km)	200–350	400–600	500–800
Refuelling/recharging	0.5–8 h (or 2–3 min swap)	5–15 min	3–5 min
Onboard storage	Battery pack	350–700 bar H_2	Liquid tank
Gravimetric energy density	0.15–0.25 MJ/kg (cell)	33.33 kWh/kg (H_2 LHV)	~42 MJ/kg (diesel)

3) Energy Density and Storage:

Hydrogen's gravimetric density of 33.33 kWh/kg [18] is offset by its low volumetric density, requiring 350–700 bar carbon-fibre tanks (~280 $kgCO_2eq$ per kg H_2 capacity) [2, 12]. Liquid H_2 storage improves volumetric density but suffers a 0.735 liquefaction efficiency penalty [15]. Lithium-ion cells deliver 0.15–0.25 MJ/kg — two orders of magnitude lower than H_2 — making batteries the dominant mass and cost contributor in BEVs. The 12 m bus modelled by Peiretti Paradisi et al. [2] required a 336 kWh NMC pack for the BEV versus a 100 kW PEM stack with only a 20 kWh LFP buffer for the FCEV. Battery chemistry choice matters: LFP produces 29.04 gCO_2e/Wh in manufacture against 41.27 (NCA) and 42.24 (NMC811) — a ~30% production-GHG reduction at the cost of lower energy density [10]. Biofuels inherit ICE-fuel density: bio-LPG/rDME blends remain EN 589:2018 and Euro 6 compliant with no engine modification [3].

4) Payload and Operational Constraints:

BEV freight is constrained by battery mass and cargo volume; H_2 tanks at 700 bar are bulky but lighter per unit stored energy, favouring FCEVs for long-haul heavy-duty applications [17, 18]. Aredah et al. [9] reported H_2 storage requiring ~0.50 the volume of an equivalent battery system in freight rail.

Thermal performance differs sharply: BEV auxiliary load rises from 800 W at 22°C to 2.8 kW at –12.2°C [18]; FCEVs benefit from waste-heat cabin recovery but require pre-heating below 0°C [12]. Battery degradation is also climate-sensitive — NCA cells reach 80% State of Health in 13.7 years in Phoenix versus less than 1% degradation in 20 years in Philadelphia [10].

5) Sector-Specific Synthesis:

The technical evidence supports a sector-conditional hierarchy. For light-duty and urban short-route applications, BEVs are technically optimal; battery swapping closes the refuelling-time gap for high-mileage commercial users [6]. For long-distance buses, coaches, and heavy-duty trucks, FCEVs become preferred where battery mass is prohibitive and refuelling time is operationally critical [17, 18]. For freight rail and short-sea shipping, catenary-electric is most efficient where infrastructure exists; battery-electric is competitive on shorter routes; hydrogen is emerging for non-electrified corridors [9, 20]. For drop-in retrofit of legacy ICE fleets, biofuel blends deliver immediate compatibility — relevant to 8.3 million LPG-compatible cars in the EU27 [3] and 21% tank-CO_2 reduction in biodiesel-hybrid freight rail [9].

B. Environmental Performance (RQ2)

1) BEV Lifecycle GHGs: Grid Carbon Intensity Dominates:

BEV lifecycle GHG performance is governed almost entirely by regional electricity carbon intensity (CI). Reductions versus equivalent ICEVs span 15–69%: Lal et al. [4] reported 15% in Germany rising to 48% in California (69% under California's 2030 grid). Jaššo et al. [14] confirmed the V4 spread — 29% (Poland, coal-heavy) to 69% (Slovakia, low-carbon) — with break-even at 17,801 km in Slovakia versus 48,340 km in Poland. Zeng et al. [21] reported 23% GWP reduction for the BEV BYD Qin Pro on the 2019 Chinese grid; Joshi et al. [22] measured BEVs at 187 gCO_2eq/km versus ICEVs at 507 gCO_2eq/km in Nepal's hydropower mix.

Battery manufacturing constitutes 30–34% of total BEV lifecycle GHGs, with break-even at 25,000–120,000 km depending on the comparator [10]. In carbon-intensive grids the operational advantage can vanish: Alwosheel et al. [23] reported BEVs in Saudi Arabia emitting ~15% more lifecycle GHGs than HEVs under the current grid, with up to 28% reduction potential by 2035 as the grid decarbonises.

2) FCEV Performance: Hydrogen Pathway Dominates:

FCEV environmental performance is set by the hydrogen production pathway. Ayca et al. [16] evaluated eight pathways: PEM electrolysis (solar) yielded 42.86 gCO_2/km for a passenger CAR; pet coke-derived hydrogen yielded 1,921.53 gCO_2/km for an HDV — a ~45× spread within one fuel pillar. Chen et al. [15] confirmed this in China: photovoltaic electrolysis (PEW-S) produced only 4.89% of grid electrolysis (EW-P) emissions; all liquid H_2 pathways except EW-P beat gasoline. In Nepal, Joshi et al. [22] reported FCEVs at 922 gCO_2eq/km — worse than ICEVs at 507 — due to upstream chain inefficiency at current grid losses. Under surplus-hydro scenarios, FCEV emissions fell 82% and BEV 50%, showing grid decarbonisation amplifies FCEV gains more sharply than BEV gains. Yeo et al. [5] projected hydrogen WTT emissions to dominate Korea's residual upstream emissions by 2050 (>95% of remaining WTT), making green H_2 import necessary.

3) Biofuel Performance: Moderate but Immediate:

Biofuels deliver moderate GHG reductions through existing infrastructure. Puricelli et al. [3] reported the LPG/bio-LPG/rDME blend at 16–21% cradle-to-grave reduction versus petrol (BEV: 36–38% in the same study, but underperforming in 10 of 16 environmental impact categories). Aredah et al. [9] measured biodiesel and biodiesel-hybrid freight locomotives at 6% and 21% tank-CO_2 reductions versus diesel. Maritime LBG ferries reached 955,342 tCO_2eq lifetime and renewable e-methanol 348,446 tCO_2eq, against 1.69 million tCO_2eq for marine gas oil — biofuel/renewable blends delivering 43–80% lifetime reductions [20].

TABLE III. LIFECYCLE GHG EMISSIONS BY POWERTRAIN AND ENERGY SOURCE

Powertrain	Best Case (gCO_2eq/km)	Worst Case (gCO_2eq/km)	vs ICEV (%)
ICEV (petrol/diesel)	200–250	500+	Baseline
BEV (renewable grid)	10–55	150–200 (coal)	15–69
FCEV (green H_2, PEM-solar)	15–43	922 (poor H_2 chain)	50–95 (green)
Biofuel ICE (bio-LPG, biodiesel, LBG)	130–180	200–230	16–43
Hybrid (HEV/PHEV)	145–170	200–250	17–28

4) Beyond GHGs: Burden-Shifting:

GWP-only judgements understate trade-offs. Zeng et al. [21] reported BEVs delivering 23% GWP reduction in China but with greater than 200% increases in freshwater and marine ecotoxicity, mineral resource scarcity, and ionising radiation, driven by copper-intensive drivetrains, sulfidic mine tailings, and the nuclear share of the grid. Lal et al. [4] confirmed similar patterns in Germany and California, with BE LCVs underperforming ICE in human toxicity, eutrophication, and mineral resource scarcity. Puricelli et al. [3] reported both BEVs and biofuel blends increasing water consumption by greater than 200% versus petrol.

5) Grid-Conditional Synthesis:

Across the corpus, the environmental ranking of powertrains is grid-conditional. In renewable-rich grids (Norway, Slovakia, Brazil, Nepal-surplus), BEV is unambiguously lowest-emitting; FCEVs become competitive only with green H_2. In mixed grids (Germany, Italy, Korea, California present), BEV is preferred for light-duty; FCEVs become comparable for heavy-duty when H_2 is decarbonised. In coal-heavy grids (Poland, Estonia, Saudi Arabia present, China north grid), HEVs and biofuel blends may outperform BEVs and grey-H_2 FCEVs on a lifecycle basis [21, 23]. For maritime and freight rail, battery-electric is optimal where shore-power is renewable [20]; biofuel blends (LBG, biodiesel) deliver near-term decarbonisation without infrastructure overhaul [9].

C. Economic Performance (RQ3)

1) Light-Duty TCO:

BEVs lead light-duty TCO in markets with mature charging infrastructure. Lal et al. [4] reported the Renault Kangoo Z.E. 33 BEV at 0.42 €/km — ~2% cheaper than its diesel counterpart in Germany — and the Opel Vivaro-e (50 kWh) at 0.62 €/km, only 1% above diesel. The hydrogen Vivaro-e Mid-FC reached 0.89 €/km, 44% above diesel. In California, two Ford E-Transit BEs were 2–3% cheaper over their lifetime than gasoline equivalents [4]. Costa et al. [1] reported BEV economic break-even at 1 year (Portugal) to 33 years (Slovakia), with point-of-purchase parity in Denmark and Spain through subsidies.

For China, Liu et al. [19] found HEVs the most cost-effective near-term option; PHEV50, REEV180, and BEV400 achieved high fuel economy but poor cost-effectiveness due to battery costs. Sagaria et al. [18] confirmed FCEVs as the most expensive light-duty option today but projected BEV parity by 2030 if H_2 costs fall 40–50% and FC production scales to 100,000 units/year.

2) Heavy-Duty and Public Transit:

Peng et al. [8] reported the hydrogen-bus scenario in Shenzhen at 48.2% higher annual system cost than the equivalent BEB scenario, driven primarily by vehicle and energy costs (>80% of the gap). Peiretti Paradisi et al. [2] confirmed BEV cost dominance for 12 m urban buses in Italy under current conditions but projected FCEVs as the best long-term trade-off by 2030 if H_2 falls to €4/kg; under conservative 2030 assumptions (H_2 at €7/kg, electricity at €0.21/kWh), BEVs remained most cost-effective across most European markets. Magnino et al. [24] reported equivalent BEV competitiveness for Finnish heavy-duty applications.

3) Off-Grid and Maritime:

Off-grid economics shift the trade-off. Rozzi et al. [7] reported hydrogen LCOD on Pantelleria Island at 0.40 €/km — ~20% lower than BEV charging at 0.50 €/km — through grid revenue from oversized renewable plants; however, total annualised cost favoured BEVs at 110 k€/year versus 170 k€/year for hydrogen. For maritime, Katumwesigye et al. [20] showed battery-electric ferry CAPEX is high (three battery packs over 30 years), but TCO becomes lowest under EU ETS and FuelEU Maritime regulation at €100/tonne CO_2eq carbon pricing.

4) Two- and Three-Wheelers and Battery Swapping:

Patel et al. [6] showed battery swapping as cost-effective for 4Ws and 2Ws in India without subsidies; subsidies (50–100%) are required for 3Ws and buses. Subsidies reduce subscription fees by 36–72% for 2W commercial users. Initial Capital Cost is dominated by battery and swapper costs, with battery costs alone constituting 90% of bus station ICC.

TABLE IV. TCO COMPARISON ACROSS VEHICLE SECTORS

Sector & Region	Powertrain	TCO / LCOD	Source
LCV, Germany	BEV (Renault Kangoo Z.E.)	0.42 €/km	[4]
LCV, Germany	BEV (Opel Vivaro-e 50 kWh)	0.62 €/km	[4]
LCV, Germany	FCEV (Vivaro-e Mid-FC)	0.89 €/km	[4]
Bus, Italy (current)	BEV (12 m urban)	0.65–0.85 €/km	[2]
Bus, Italy (current)	FCEV (12 m urban)	1.00–1.05 €/km	[2]
Bus, Italy (current)	H2-HEV	1.12–1.14 €/km	[2]
Bus, off-grid (Pantelleria)	BEV LCOD	0.50 €/km	[7]
Bus, off-grid (Pantelleria)	FCEV LCOD	0.40 €/km	[7]

5) Major Techno-Economic Barriers:

Three barrier categories recur across the corpus. First, CAPEX: battery production dominates BEV upfront cost (90% of bus battery-station ICC [6]; ~70% of BEV TOC [18]); fuel cell stacks and 700-bar H_2 tanks dominate FCEV CAPEX (FCEV embodied carbon at 14.6 tCO_2/vehicle vs 6.2 for diesel [2]). Second, fuel cost: hydrogen at €9–13.5/kg across Europe drives FCEV TCO above BEV [2]; renewable H_2 is projected to fall to $2.5–4.0/kg by 2030 [12]. Third, infrastructure: hydrogen station construction at 15 million yuan/HRS in China versus 6 million yuan/charging station [8]; fewer than 1,200 H_2 stations globally as of 2023 [11].

6) Sector-Conditional Synthesis:

For light-duty and urban applications, BEVs deliver the lowest TCO today; FCEV parity is projected post-2030 contingent on H_2 costs below €4/kg. For heavy-duty and long-haul applications, BEV is competitive for short routes; FCEV emerges where battery mass and refuelling time impose operational penalties. For public transit, BEB dominates fixed-route applications, while battery swapping extends BEV viability for high-mileage 2W/3W markets [6]. For off-grid and maritime applications, hydrogen LCOD becomes competitive where renewables must be oversized for storage; battery-electric is optimal under carbon pricing [7, 20]. Biofuels avoid CAPEX disruption by reusing existing ICE infrastructure; their case rests on subsidised waste-feedstock supply [3].

IV. RESEARCH GAPS AND FUTURE WORK

The 30 reviewed studies converge on five cross-cutting research gaps that limit current comparative judgements between hydrogen, biofuel, and electric powertrains.

A. Methodological Inconsistency Across LCAs

System boundaries, functional units, and allocation methods vary substantially across the corpus, undermining direct comparison. Zhang et al. [13], in a meta-review of 243 LCA studies, found seven distinct boundary combinations and 30 LCA scenario types, with only 9 of 243 studies (3.7%) covering fuels, vehicles, and infrastructure together — and only 2 applying full cradle-to-grave boundaries to both vehicles and infrastructure. End-of-life phases were omitted in many studies despite contributing 0.3–1.0% of total lifecycle emissions [13]. The result is that reported BEV GHG reductions of 15–69% versus ICEVs reflect not only true regional variation but also methodological divergence. Standardised LCA protocols specific to alternative-fuel powertrains — including mandated inclusion of vehicle scrappage, recycling, and infrastructure maintenance phases — are needed.

B. Average vs Marginal Electricity Mix Assumption

Most reviewed LCAs apply average grid carbon intensity rather than marginal mix, systematically underestimating the true emissions impact of additional electrified loads. Peiretti Paradisi et al. [2] demonstrated that the Italian average electricity mix at 373 gCO_2/kWh becomes 590 gCO_2/kWh at the margin for additional overnight BEV charging, with hourly variability spanning greater than 100 gCO_2/kWh in a single day. Applying the marginal mix makes BEV carbon footprint comparable to H_2-HEV and higher than the SMR-fuelled FCEV, and can nearly double the carbon footprint of electrolytic hydrogen produced overnight. Zeng et al. [21] separately reported that consequential LCA modelling with long-term marginal electricity mix can amplify the BEV GWP advantage by up to 51% under aggressive scenarios — demonstrating that the modelling choice can either erase or magnify the comparative finding. Future studies must specify and justify their grid assumption transparently.

C. Limited Integration of Charging and Refuelling Infrastructure into TCO

Most TCO studies treat infrastructure costs as either externalised or embedded in opaque fuel-price assumptions. Peng et al. [8] is among the few studies to model infrastructure deployment explicitly, finding that hydrogen-bus system costs are 48.2% higher than equivalent BEB systems primarily due to vehicle and energy costs (>80% of the gap), even though hydrogen requires fewer stations. Lal et al. [4] excluded EVSE infrastructure incentives to ensure consistency, but acknowledged this as a constraint on real-world applicability. The absence of standardised infrastructure-inclusive TCO frameworks means published BEV-vs-FCEV cost comparisons often cannot be directly transferred to fleet operator decision-making.

D. Scarce Real-World Validation Beyond Pilot Scale

Most FCEV and biofuel comparative findings rest on simulation and pilot-scale data rather than fleet-level operating experience. Liu et al. [17] explicitly identified that hydrogen storage-delivery systems — particularly liquid organic hydrogen carrier (LOHC) configurations — are evaluated on delivery cost alone, without accounting for the full energy burden of hydrogenation/dehydrogenation, leading to misleadingly favourable conclusions. Similarly, Magnino et al. [24] noted the absence of real-world degradation data for FCEV and BEV fleets across seasons. Published FCEV efficiencies of 0.30–0.40 may not survive long-term commercial operation, particularly given documented PEMFC stack degradation increasing fuel consumption by 14.32% [12]. Long-duration fleet trials across multiple climate and duty cycles are urgently needed.

E. Underrepresentation of Biofuel-Specific Lifecycle Inventories

Biofuel pathways suffer from limited and inconsistent lifecycle inventory data, particularly for waste-feedstock variants (rDME, bio-LPG, LBG). Puricelli et al. [3] is the first published LCA of the LPG/bio-LPG/rDME blend and explicitly flags the scarcity of operational HEFA biorefinery data. Aredah et al. [9] noted that biodiesel emissions can be significantly reduced without performance compromise but flagged the absence of well-to-tank analysis for freight rail biofuel pathways. The corpus's broader emphasis on BEV-vs-FCEV comparisons relative to biofuel pathways itself constitutes a gap that future SLRs should address through targeted feedstock-specific reviews.

V. CONCLUSION

This Systematic Literature Review of 30 peer-reviewed studies (2021–2025) confirms that no single alternative powertrain — hydrogen, biofuel, or electric — is universally optimal across the technical, environmental, and economic dimensions of decarbonising transport. The synthesis supports a sector- and grid-conditional deployment hierarchy.

Battery electric vehicles are the technically and economically dominant choice for light-duty, urban, and short-route applications under low-to-moderate grid carbon intensity. WTW efficiency of 0.70–0.80, lifecycle GHG reductions of 15–69%, and TCO parity (or advantage) over diesel in mature European and US markets establish BEVs as the near-term default for personal mobility, light commercial vehicles, and fixed-route public transit.

Hydrogen fuel cell electric vehicles retain the long-term advantage in heavy-duty, long-haul, and operationally constrained applications where battery mass and refuelling time become prohibitive. FCEV environmental and economic competitiveness is contingent on green hydrogen production at scale and price points below €4/kg, and on the build-out of refuelling infrastructure currently limited to fewer than 1,200 stations globally.

Biofuels — including bio-LPG, biodiesel, bioethanol, rDME, and LBG — provide a near-term, infrastructure-compatible decarbonisation pathway delivering 16–43% lifecycle GHG reductions through drop-in or blended use in existing ICE and hybrid powertrains. Their continued role depends on subsidised waste-feedstock supply chains and on policy frameworks that recognise partial-decarbonisation transitions for legacy fleets.

The five research gaps identified in Section IV — methodological inconsistency, marginal-mix assumptions, infrastructure exclusion from TCO, lack of real-world fleet validation, and biofuel inventory scarcity — define the priority agenda for future research.

For policymakers and fleet operators, the practical recommendation is to abandon technology-prescriptive mandates in favour of technology-agnostic, lifecycle-outcome-based performance standards (gCO_2eq/vkm) [23], paired with grid-decarbonisation timelines that determine the rate at which BEV and FCEV gains can be realised. The most likely deployment outcome is a complementary coexistence of all three powertrain pillars, each serving the duty cycle, grid context, and infrastructure environment to which its physics and economics are best suited.

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