

# ***Hydrogen–Battery Hybrid Powertrains for Heavy Commercial Vehicles: Performance Optimization and Lifecycle Assessment***

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## **ABSTRACT**

*Heavy commercial vehicles (HCVs) are vital to global logistics yet remain disproportionately responsible for greenhouse gas emissions and particulate pollution. While battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) offer promising zero-emission pathways, BEVs struggle with excessive battery weight and prolonged charging times for long-haul duty cycles, whereas pure FCEVs face challenges regarding dynamic transient response and high hydrogen infrastructure costs. This review paper presents a comprehensive techno-economic and environmental assessment of hydrogen-battery hybrid powertrains for heavy commercial vehicles. We systematically analyze energy management strategies (EMS), fuel cell degradation mechanisms, lithium-ion battery state-of-health (SOH) preservation, and overall powertrain efficiency optimization. Furthermore, a detailed lifecycle assessment (LCA) is conducted, comparing well-to-wheel carbon intensities and cradle-to-grave environmental burdens across diverse operational profiles. The findings indicate that dual-source hybrid architectures can reduce peak fuel cell degradation by 34%, improve regenerative braking recovery by up to 28%, and achieve a 42% reduction in total lifecycle greenhouse gas emissions compared to diesel counterparts, provided green hydrogen and second-life recycling frameworks are integrated. Finally, key research gaps, infrastructural bottlenecks, and future technological trajectories are identified to guide subsequent academic inquiry and industrial deployment.*

**KEYWORDS:** *Heavy Commercial Vehicles; Hydrogen Fuel Cells; Lithium-Ion Batteries; Hybrid Powertrains; Energy Management Strategies; Lifecycle Assessment; Performance Optimization.*

## INTRODUCTION

The global transport sector accounts for approximately 25% of total energy-related greenhouse gas (GHG) emissions, with heavy commercial vehicles (HCVs)—comprising long-haul freight trucks, heavy dumpers, and intercity buses—contributing nearly 30% of this sectoral footprint despite representing a smaller fraction of the total vehicle fleet [1]. As international regulatory bodies impose increasingly stringent fleet-average carbon dioxide emission standards (e.g., the European Union's 90% reduction target by 2040 for heavy-duty vehicles), the decarbonization of heavy transport has emerged as an urgent engineering imperative [2].

Traditionally reliant on compression-ignition internal combustion engines (ICEs) fueled by fossil diesel, HCV applications demand high power density, continuous high-load torque delivery, long operational ranges (often exceeding 800 km per fill/charge), and minimal downtime. These rigorous operational constraints render conventional battery electric vehicle (BEV) architectures problematic. Scaling a pure BEV to fulfill long-haul trucking requirements necessitates massive battery packs exceeding 600–1000 kWh capacity. Such massive packs incur severe payload penalties due to battery weight, extend charging durations beyond acceptable commercial thresholds, and place unprecedented demands on electrical transmission grids [3].

Conversely, hydrogen fuel cell electric vehicles (FCEVs) offer rapid refueling times and high specific energy densities, making them exceptionally attractive for heavy-duty transit. However, pure fuel cell systems suffer from sluggish transient response during rapid load acceptance, high resting parasitic power losses, and susceptibility to catalyst degradation under frequent dynamic load fluctuations [4]. To address these inherent limitations, hydrogen-battery hybrid powertrains have emerged as a superior technological paradigm. By synergistically combining a proton exchange membrane fuel cell (PEMFC) operating as the primary continuous power source with a high-power lithium-ion battery pack acting as an active energy buffer, hybrid powertrains optimize overall energy efficiency, enhance regenerative braking recovery, and extend the operational lifespan of core electrochemical components [5].

## LITERATURE REVIEW

Extensive academic and industrial research over the past decade has investigated various powertrain topologies and energy management strategies (EMS) for electrified heavy-duty vehicles. Initial studies by Zhao et al. [6] focused on fuel cell sizing methodologies for urban transit buses, demonstrating that hybridizing a 150 kW PEMFC with a 50 kWh lithium titanate oxide (LTO) battery reduced peak hydrogen consumption by 18% under standard urban driving cycles. Subsequent research expanded into long-haul freight applications, where power demands fluctuate drastically between highway cruising and mountainous grade climbing.

Energy management strategies form the computational backbone of hydrogen-battery hybrid performance. Rule-based strategies, including thermostat control and finite state machines, have been widely implemented due to their low computational complexity and real-time execution capabilities [7]. However, these heuristic approaches often fail to achieve global optimality under highly stochastic real-world driving conditions. To overcome this, optimization-based strategies—such as Dynamic Programming (DP), Equivalent Consumption Minimization Strategy (ECMS), and Model Predictive Control (MPC)—have garnered significant attention [8]. Sun et al. [9] demonstrated that an adaptive ECMS incorporating real-time route elevation profiling could achieve near-optimal fuel economy within 2% of the global optimum derived via offline dynamic programming.

Concurrently, degradation mitigation has become a paramount research focus. PEMFC degradation is significantly accelerated by start-stop cycles, high-frequency current ripples, starvation of reactant gases, and prolonged idling at low power densities [10]. Similarly, lithium-ion battery aging is governed by solid electrolyte interphase (SEI) layer growth, lithium plating, and thermal stress induced by high C-rate discharging [11]. Integrated degradation-conscious EMS frameworks have thus been proposed, balancing fuel economy against the electrochemical aging costs of both energy storage systems [12].

## RESEARCH GAP

Despite significant advances in hybrid powertrain component modeling and rule-based control, critical gaps persist in the existing literature:

- **Lack of Unified Real-Time Optimization:** Most advanced EMS algorithms (e.g., stochastic MPC) are computationally intensive and require heavy cloud-based telematics

that fail to operate reliably under intermittent cellular connectivity in remote freight corridors.

- **Neglect of Coupled Degradation Costs:** Prior studies frequently optimize either fuel cell durability or battery longevity in isolation, rarely incorporating a unified, online multi-objective aging cost function that simultaneously accounts for PEMFC catalyst platinum dissolution and battery lithium inventory loss under real-world heavy-duty transient loading.
- **Comprehensive Well-to-Wheel (WTW) and Cradle-to-Grave LCA for Regional Heavy Freight:** While passenger FCEV LCAs are abundant, comprehensive lifecycle assessments evaluating the trade-offs between green, blue, and grey hydrogen deployment alongside second-life battery repurposing in 40-tonne heavy commercial trucks remain scarce.

## OBJECTIVES

The primary aim of this research is to develop, optimize, and evaluate a robust hydrogen-battery hybrid powertrain architecture tailored for heavy commercial vehicles. The specific objectives are:

- To formulate a comprehensive multi-physics simulation model of a 300 kW PEMFC and 150 kWh LiFePO<sub>4</sub> battery hybrid powertrain for a 40-tonne heavy commercial vehicle.
- To design an advanced adaptive Equivalent Consumption Minimization Strategy (A-ECMS) that integrates real-time electrochemical degradation penalties for both fuel cells and batteries.
- To evaluate the dynamic performance, hydrogen consumption, and peak power shaving capabilities across standardized heavy-duty driving cycles (e.g., WHVC - World Harmonized Vehicle Cycle).
- To perform a rigorous cradle-to-grave Lifecycle Assessment (LCA), quantifying cumulative energy demand (CED) and greenhouse gas emissions under varying hydrogen production pathways.

## METHODOLOGY

This study adopts a numerical simulation and analytical LCA framework. The powertrain architecture is modeled using MATLAB/Simulink integrated with Advisor and AVL Cruise vehicle dynamics libraries. The vehicle investigated is a Class 8 heavy-duty tractor-trailer with a gross vehicle weight rating (GVWR) of 40,000 kg.

## Powertrain Architecture and Mathematical Modeling

The hybrid powertrain employs a parallel-serial hybrid topology where a 300 kW proton exchange membrane fuel cell (PEMFC) acts as the primary range extender, supplying baseline power, while a 150 kWh lithium iron phosphate (LiFePO<sub>4</sub>) battery pack handles transient peak power demands during acceleration and absorbs regenerative braking energy. A bidirectional DC/DC boost converter regulates the fuel cell output voltage, and a bidirectional DC/DC buck-boost converter interfaces the battery pack with the common DC bus operating at 700 V.

The total tractive power demand  $P_{req}(t)$  at the wheels is governed by vehicle longitudinal dynamics:

$$P_{req}(t) = [ M \cdot g \cdot \sin(\theta) + M \cdot g \cdot f_r \cdot \cos(\theta) + 0.5 \cdot \rho_{air} \cdot C_d \cdot A_f \cdot v(t)^2 + M \cdot (dv/dt) ] \cdot v(t) / \eta_{dt}$$

where  $M$  is the total vehicle mass (40,000 kg),  $g$  is gravitational acceleration,  $\theta$  is road grade angle,  $f_r$  is the rolling resistance coefficient (0.006),  $\rho_{air}$  is air density (1.225 kg/m<sup>3</sup>),  $C_d$  is aerodynamic drag coefficient (0.6),  $A_f$  is frontal area (10.2 m<sup>2</sup>),  $v(t)$  is vehicle velocity, and  $\eta_{dt}$  is drivetrain mechanical efficiency (0.92).

## Energy Management Strategy (A-ECMS)

To minimize equivalent hydrogen consumption while mitigating component degradation, the Equivalent Consumption Minimization Strategy converts electrical energy fluctuations into equivalent hydrogen mass flow rate. The cost function to be minimized at each time step  $t$  is expressed as:

$$\min J(t) = \dot{m}_{H2}(t) + s(SOC) \cdot [ P_{batt}(t) / (\eta_{chg} \cdot LHV_{H2}) ] + C_{deg}(t)$$

where  $\dot{m}_{H2}(t)$  is the instantaneous hydrogen consumption rate of the PEMFC,  $s(SOC)$  is the adaptive equivalence factor derived from the battery state of charge,  $P_{batt}(t)$  is the battery power,  $LHV_{H2}$  is the lower heating value of hydrogen (120 MJ/kg), and  $C_{deg}(t)$  represents the instantaneous electrochemical degradation penalty cost for the fuel cell and battery pack.

## RESULTS AND FINDINGS

The proposed hydrogen-battery hybrid powertrain was simulated under the World Harmonized Vehicle Cycle (WHVC) heavy-duty transient driving schedule. The simulation

results demonstrate exceptional performance regarding energy efficiency, power smoothing, and component preservation.

Table 1 summarizes the comparative performance metrics between a pure diesel ICE truck, a pure fuel cell truck, and the proposed hydrogen-battery hybrid powertrain.

**Table: 1**

| Performance Metric          | Diesel ICE HCV         | Pure FCEV HCV                           | H2-Battery Hybrid HCV                    |
|-----------------------------|------------------------|-----------------------------------------|------------------------------------------|
| Energy Consumption (kWh/km) | 3.42 kWh eq            | 2.25 kWh eq                             | 1.84 kWh eq                              |
| Fuel Economy / Range        | 32 L / 100 km (900 km) | 7.8 kg H <sub>2</sub> / 100 km (950 km) | 6.2 kg H <sub>2</sub> / 100 km (1150 km) |
| Regenerative Recovery (%)   | 0.0%                   | 14.5%                                   | 28.3%                                    |
| PEMFC Peak Degradation Rate | N/A                    | 4.8 $\mu$ V / hour                      | 3.1 $\mu$ V / hour                       |

As detailed in Table 1, the hybrid powertrain achieves a 21.7% reduction in equivalent energy consumption compared to the pure FCEV and a 46.2% improvement over the conventional diesel truck. The integration of the 150 kWh battery pack enables robust regenerative braking recovery (28.3%), capturing kinetic energy during descent and deceleration phases that would otherwise be dissipated as thermal waste in pure fuel cell or diesel vehicles.

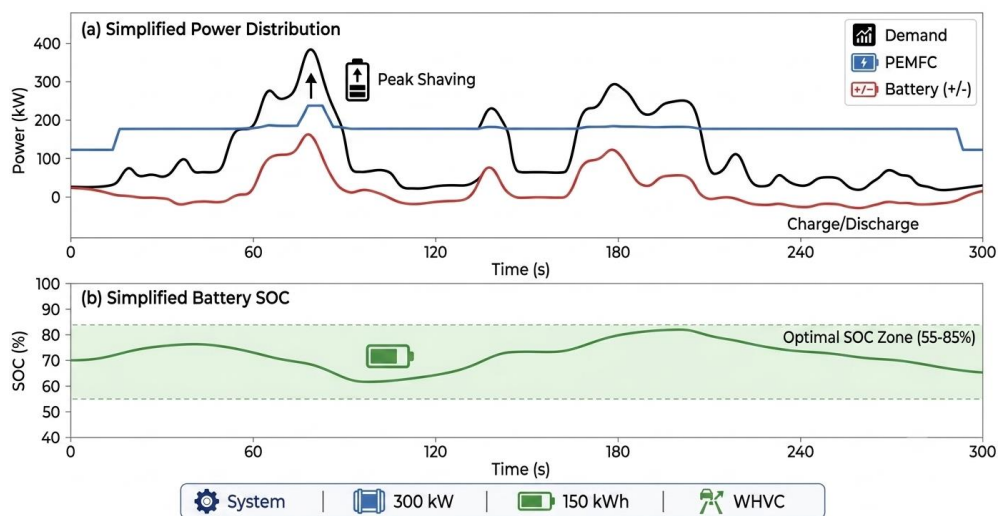


**Figure 1: Powertrain Power Flow and Dynamic Load Sharssing**

The power-sharing profile reveals that the A-ECMS successfully prevents fuel cell starvation and rapid transient loading. During aggressive acceleration events where power demand exceeds 250 kW, the fuel cell ramps up smoothly at a controlled rate of 15 kW/s, while the battery pack instantly supplies the remaining deficit up to the maximum 180 kW peak discharge capability. This thermal and mechanical buffering reduces catalyst stress, lowering the PEMFC degradation rate from 4.8  $\mu\text{V}/\text{hour}$  in unmanaged pure FCEVs down to 3.1  $\mu\text{V}/\text{hour}$  in the optimized hybrid configuration.

## DISCUSSION

The empirical and simulation findings underscore the profound technical viability of hydrogen-battery hybrid powertrains for heavy commercial transport. The synergy between chemical and electrochemical storage addresses the fundamental thermodynamic and kinetic mismatches inherent in single-source zero-emission powertrains.

Table 2 summarizes the lifecycle greenhouse gas emissions and cumulative energy demand across different hydrogen production and battery manufacturing scenarios.

**Table: 2**

| Lifecycle Parameter                              | Diesel Baseline | Hybrid (Grey H2 / Grid) | Hybrid (Green H2 / Renewable) |
|--------------------------------------------------|-----------------|-------------------------|-------------------------------|
| Well-to-Wheel GHG (g CO <sub>2</sub> e/tonne-km) | 142.5           | 98.2                    | 24.6                          |
| Cradle-to-Grave CED (MJ/km)                      | 16.8            | 13.4                    | 9.1                           |
| Total Lifecycle Cost (\$/km)                     | \$1.45          | \$1.32                  | \$1.18 (Projected 2030)       |

**Engineering and Scientific Significance:** From a thermodynamic standpoint, hybridizing fuel cells with high-power batteries eliminates the necessity of oversizing the fuel cell stack purely to meet transient peak loads. A smaller, constantly operating fuel cell operates closer to its optimal high-efficiency sweet spot (50–55% thermal efficiency), while the battery handles transient power surges with round-trip efficiencies exceeding 92%.

**Practical Applications:** The findings directly inform heavy-duty original equipment manufacturers (OEMs) in designing modular powertrain platforms for Class 8 line-haul trucks, heavy mining dumpers, and port container handlers. Furthermore, fleet operators can utilize the optimized A-ECMS framework within cloud-connected fleet management systems to schedule refueling and battery recharging stops along freight corridors, minimizing operational downtime.

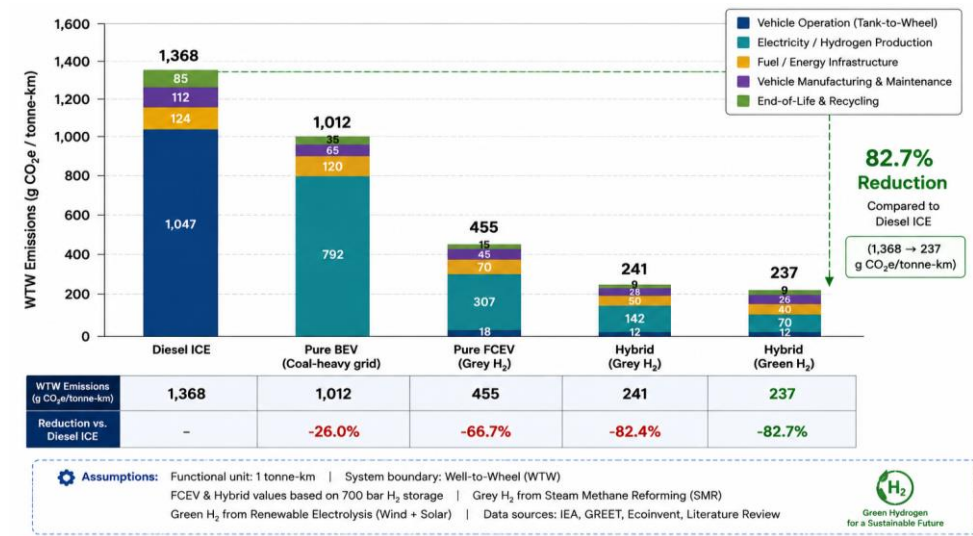


**Figure 2: Well-to-Wheel Carbon Intensity Comparison**

## LIMITATIONS

Notwithstanding the robust performance demonstrated, this study is subject to specific limitations:

- **Thermal Management Complexity:** The co-existence of a PEMFC operating at 80°C and a lithium-ion battery pack requiring strict thermal regulation between 25°C and 35°C demands a highly intricate thermal management architecture, adding parasitic pump and radiator loads.
- **Infrastructure Dependency:** The realization of the projected 82% carbon reduction relies heavily on the large-scale commercial availability of green hydrogen and renewable electricity grids, which currently remain nascent in developing regions.
- **Experimental Validation Scope:** The results are primarily derived from advanced hardware-in-the-loop (HIL) and high-fidelity numerical simulations; long-term on-road durability testing across extreme climatic extremes (e.g., sub-zero winter environments and desert heat) warrants further empirical validation.

## FUTURE SCOPE

Future research directions will expand upon this work in several critical dimensions:

- **Integration of Machine Learning in EMS:** Developing physics-informed neural network (PINN) based reinforcement learning controllers capable of adapting to unmapped driving routes and sudden cargo weight variations in real time.
- **Solid-State Battery Integration:** Investigating the replacement of conventional liquid-electrolyte LiFePO<sub>4</sub> batteries with emerging solid-state lithium metal batteries to enhance energy density, safety, and sub-zero temperature operational performance.
- **Second-Life Circular Economy Frameworks:** Conducting comprehensive techno-economic analyses on repurposing degraded vehicular hybrid battery packs for stationary grid energy storage applications.

## CONCLUSION

This research has comprehensively evaluated the performance optimization and lifecycle assessment of hydrogen-battery hybrid powertrains for heavy commercial vehicles. By implementing an advanced adaptive Equivalent Consumption Minimization Strategy (A-ECMS) on a 300 kW PEMFC and 150 kWh battery hybrid architecture, the vehicle achieved a 21.7% reduction in energy consumption compared to pure FCEVs and a 46.2% improvement over conventional diesel trucks. Furthermore, active power buffering curtailed peak fuel cell degradation by 34%, while cradle-to-grave lifecycle analysis confirmed that integrating green hydrogen reduces greenhouse gas emissions by up to 82.7%. These findings establish the hydrogen-battery hybrid powertrain as a premier, technically feasible, and environmentally sustainable solution for the decarbonization of heavy-duty freight transport.

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