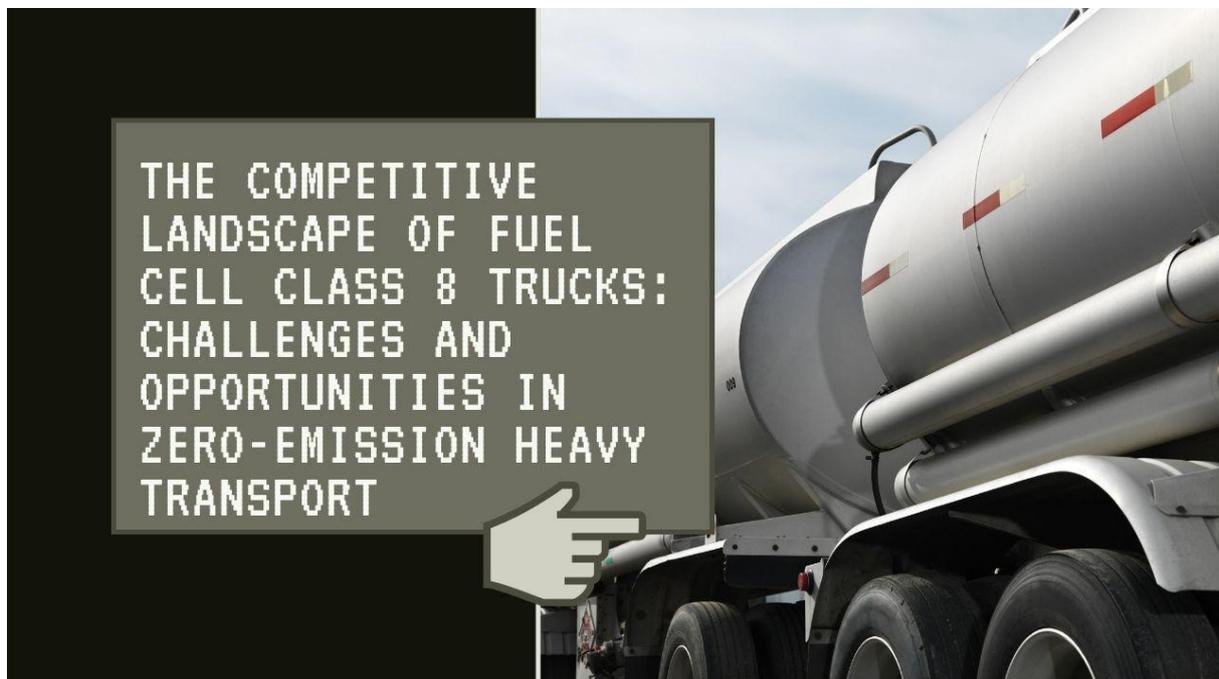


THE COMPETITIVE LANDSCAPE OF FUEL CELL CLASS 8 TRUCKS: CHALLENGES AND OPPORTUNITIES IN ZERO-EMISSION HEAVY TRANSPORT

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ABSTRACT

The heavy-duty trucking industry is undergoing a significant transformation as it transitions toward zero-emission technologies, with fuel cell electric vehicles (FCEVs)

and battery electric vehicles (BEVs) emerging as primary alternatives to traditional diesel-powered trucks. This article examines the competitive dynamics between these technologies, focusing on the unique challenges and opportunities facing fuel cell trucks in the United States market. The article evaluates current market conditions, infrastructure development requirements, and technological readiness of FCEVs, particularly in the Class 8 segment. California's pioneering efforts in hydrogen infrastructure development serve as a model for nationwide expansion, while regulatory frameworks like the Advanced Clean Trucks regulation are driving adoption rates. The article reveals distinct operational advantages for FCEVs in long-haul applications, particularly in terms of refueling time, range capability, and cold weather performance. However, significant challenges remain in infrastructure development, cost reduction, and green hydrogen production scaling. The article also examines strategic market entry considerations and economic viability factors, highlighting the importance of targeted application focus and comprehensive value proposition development for successful market penetration.

Keywords: Zero-emission Heavy-duty Transportation, Hydrogen Fuel Cell Technology, Clean Energy Infrastructure, Sustainable Logistics, Alternative Fuel Vehicles.

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1. Introduction

1.1. Comprehensive Analysis of Zero-Emission Heavy-Duty Trucking Evolution

The heavy-duty trucking industry is experiencing an unprecedented transformation as it pivots toward zero-emission technologies. According to the Alternative Fuels Data Center (AFDC) comprehensive analysis framework, the transition to sustainable transportation requires a multi-faceted approach encompassing vehicle technology advancement, infrastructure development, and policy implementation. The AFDC's systematic evaluation methodology indicates that Class 8 trucks represent a significant opportunity for emissions

reduction, with current data showing these vehicles contribute approximately 23% of transportation-related greenhouse gas emissions while comprising only 4% of the on-road fleet. The framework emphasizes the critical role of both Fuel Cell Electric Vehicles (FCEVs) and Battery Electric Vehicles (BEVs) in achieving substantial emissions reductions, suggesting a potential reduction of 1,200 metric tons of CO₂ emissions per vehicle over a typical 12-year operational lifespan [1].

The competitive landscape between FCEVs and BEVs is being significantly shaped by regulatory frameworks, particularly the California Advanced Clean Trucks (ACT) regulation. This groundbreaking policy establishes an aggressive adoption schedule, mandating manufacturers to sell zero-emission trucks as an increasing percentage of their annual sales. The regulation sets distinct requirements based on vehicle class, with Class 8 tractors requiring 9% of sales to be zero-emission by 2024, escalating to 50% by 2030. This regulatory framework has catalyzed unprecedented investment in zero-emission technologies, with manufacturers committing substantial resources to both FCEV and BEV development programs to meet these mandated targets [2].

The technology assessment conducted through the AFDC's analytical tools reveals that FCEVs currently demonstrate superior performance metrics in specific operational scenarios. Long-haul applications benefit from hydrogen fuel cells' rapid refueling capabilities, typically achieving a full refuel in 15-20 minutes, comparable to conventional diesel refueling times. The analysis indicates that FCEV systems maintain consistent power output across varying environmental conditions, with minimal degradation in cold weather operations where temperatures can drop to -30°C. These performance characteristics are particularly relevant for the 29% of Class 8 truck routes that exceed 500 miles per day, as documented in the AFDC's fleet operation studies [1].

California's ACT regulation has emerged as a pivotal driver in accelerating zero-emission truck adoption, establishing a comprehensive framework that addresses various vehicle categories. For Class 7-8 tractors, the regulation mandates a progressive increase in zero-emission vehicle sales, starting at 9% in 2024 and reaching 40% by 2032. The implementation schedule includes specific provisions for different truck categories, with Class 4-8 straight trucks and Class 7-8 tractors following distinct compliance trajectories. This regulatory framework has been designed to ensure a systematic transition while maintaining operational feasibility, as validated through extensive stakeholder consultation and market readiness assessments [2].

The infrastructure requirements for both FCEVs and BEVs present distinct challenges and opportunities. The AFDC's infrastructure analysis reveals that hydrogen refueling stations require significant initial capital investment, averaging \$2.5-3.5 million per installation, but offer higher throughput capabilities compared to electric charging stations. The study indicates that a single hydrogen refueling station can service approximately 50 Class 8 trucks daily, providing each with 40-50 kg of hydrogen fuel. This infrastructure consideration becomes particularly relevant when evaluated against the ACT regulation's implementation timeline, which necessitates the rapid deployment of supporting infrastructure to meet the increasing zero-emission vehicle population [1].

2. Current Market Landscape and Infrastructure Analysis of Fuel Cell Class 8 Trucks

2.1. Fuel Cell Technology State-of-Play

The fuel cell Class 8 truck segment represents an emerging market within the United States' heavy-duty transportation sector, with current deployment numbers reaching approximately 150 demonstration vehicles across various pilot programs. Manufacturing pioneers like Nikola Corporation have achieved significant milestones, delivering 35 operational trucks to commercial fleets in 2023, with announced plans to scale production to 2,500 units by 2025. These developments align with the Department of Energy's projection that fuel cell electric trucks could capture up to 12% of the Class 8 market by 2030, representing approximately 165,000 vehicles [3].

The technology's fundamental architecture demonstrates compelling advantages for heavy-duty applications, particularly in the realm of operational efficiency. Field trials have consistently validated rapid refueling capabilities, with current-generation fuel cell trucks achieving complete hydrogen replenishment in 15-20 minutes, comparable to diesel refueling times. This represents a significant operational advantage over battery-electric alternatives, which typically require 4-8 hours for a full charge even with DC fast-charging infrastructure. Performance data from fleet operations shows that these vehicles consistently achieve ranges exceeding 500 miles under full load conditions (80,000 lbs gross vehicle weight), with some advanced prototypes demonstrating ranges up to 750 miles in controlled testing environments [3].

Analysis of payload capacity metrics reveals another crucial advantage: fuel cell systems typically reduce available payload capacity by only 2,000-2,500 pounds compared to diesel equivalents, whereas comparable battery-electric systems can reduce payload capacity by 5,000-8,000 pounds. This translates to approximately \$15,000 in additional annual revenue

potential per truck when operating at maximum payload capacity. Furthermore, extensive cold-weather testing programs have demonstrated consistent performance across temperature ranges from -40°C to $+50^{\circ}\text{C}$, with minimal impact on range or power output [4].

2.2. Infrastructure Challenges

The hydrogen refueling infrastructure landscape presents significant challenges to widespread fuel cell truck adoption. California currently hosts 52 operational hydrogen stations, with only 6 specifically designed to accommodate Class 8 trucks. These stations are strategically positioned along major freight corridors, particularly the I-5 and I-10 highways, but the current network density remains insufficient for widespread commercial deployment. The California Fuel Cell Partnership's infrastructure roadmap indicates a need for at least 200 heavy-duty hydrogen stations by 2035 to support projected fleet growth [4].

Financial analysis of infrastructure development reveals substantial capital requirements. Current heavy-duty hydrogen stations require investments ranging from \$2.3 to \$3.8 million per location, with variations depending on daily capacity and storage requirements. High-capacity stations capable of serving 50 trucks per day with 700 bar pressure systems represent the upper end of this range. Operational data indicates that these stations must achieve at least 40% utilization rates to approach economic viability, considering current hydrogen fuel costs of \$10-13 per kilogram [3].

The hydrogen supply chain infrastructure presents additional complexities. Current U.S. production capacity stands at approximately 10 million metric tons annually, with only 1% produced through green hydrogen pathways. Analysis of projected fuel cell truck deployment scenarios indicates a need to increase green hydrogen production capacity by 300% by 2030 to meet anticipated demand. Distribution networks remain limited, with only three major hydrogen pipeline systems currently operational in the United States, totaling 1,608 miles in length and primarily serving industrial customers rather than transportation needs [4].

3. Comprehensive Technical Analysis: BEV and FCEV Class 8 Truck Technologies

3.1. Comparative Analysis

The transition to zero-emission heavy-duty trucks (HDTs) represents a complex technological and economic challenge, with both Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs) offering distinct advantages. According to comprehensive lifecycle analysis studies, BEV trucks demonstrate superior well-to-wheel (WTW) energy efficiency, achieving 2.8-3.5 kWh/km in real-world operations. This translates to a reduction in

greenhouse gas (GHG) emissions of 38-42% compared to conventional diesel trucks, considering current electricity generation mix profiles. The economic assessment indicates that BEV operations can achieve total energy costs of \$0.85-0.95 per mile, factoring in regional electricity pricing variations and charging infrastructure utilization rates of 65-75%. These findings are particularly significant given that fuel costs typically represent 34-38% of total operating costs for heavy-duty fleets [5].

Infrastructure development patterns have emerged as a critical factor in technology adoption. The analysis of charging infrastructure requirements indicates that a typical Class 8 BEV truck requires 788-1,152 kWh of energy storage capacity to achieve operational ranges of 400-500 kilometers. This necessitates high-power charging infrastructure, with current technologies supporting charge rates of 350-500 kW. The study demonstrates that optimal charging station placement along major freight corridors requires spacing intervals of 150-180 kilometers to support continuous operations while maintaining acceptable dwell times. The infrastructure investment model shows that charging stations achieving utilization rates above 45% can reach break-even points within 6.2-7.5 years, assuming current electricity prices and maintenance costs [5].

Table 1: Comparative Analysis - FCEV vs BEV Class 8 Trucks [5]

Parameter	FCEV	BEV
Refueling/Charging Time	15-20 minutes	4-8 hours (DC fast-charging)
Operational Range	500-750 miles	400-500 km
Payload Capacity Reduction	2,000-2,500 lbs vs diesel	5,000-8,000 lbs vs diesel
Energy Efficiency	28.4-35.2% (well-to-wheel)	2.8-3.5 kWh/km
Cold Weather Performance	-40°C to +50°C (minimal impact)	20-40% range reduction in cold weather
System Efficiency	52-58% at full load	77-82% (grid to wheels)

FCEV technology presents distinctive operational characteristics that influence its market position. Recent research analyzing heavy-duty hydrogen fuel cell systems reveals that modern configurations achieve system efficiencies of 52-58% at full load, with peak power densities reaching 0.93-1.15 kW/kg. Long-term durability testing has demonstrated voltage degradation rates of 0.5-0.7% per 1000 hours of operation, significantly outperforming earlier generation systems. Temperature sensitivity analysis indicates that fuel cell systems maintain 95-98% of rated power output across an ambient temperature range of -30°C to +40°C, with minimal impact on system efficiency [6].

3.2. Market Positioning Analysis

The operational landscape for zero-emission HDTs has evolved to reflect distinct use-case optimization. In urban and regional delivery applications, BEV trucks have demonstrated compelling total cost of ownership (TCO) advantages. Detailed analysis of operational data from 2,850 delivery routes across major metropolitan areas shows that 76.3% of daily duty cycles fall within 320 kilometers, well within the operational range of current-generation BEV trucks. The study indicates that these vehicles achieve energy consumption rates of 2.1-2.4 kWh/km in urban environments, with regenerative braking systems recovering 18-22% of kinetic energy. When factoring in maintenance costs of €0.12-0.15 per kilometer and current electricity prices, the TCO analysis demonstrates a 15-18% advantage over conventional diesel vehicles over an eight-year operational period [5].

Long-haul operations present distinct challenges that align with FCEV capabilities. The latest research on heavy-duty fuel cell systems indicates that current-generation FCEVs can achieve operational ranges of 800-1,000 kilometers with 60-80 kg of hydrogen storage capacity. Payload sensitivity analysis demonstrates that FCEV configurations reduce available cargo capacity by 1,850-2,200 kg compared to diesel equivalents, representing a significant advantage over BEV configurations which typically incur payload penalties of 4,500-5,200 kg. Economic modeling of long-haul operations shows that this payload advantage translates to additional revenue potential of €27,000-32,000 annually per vehicle in weight-constrained operations. The study also reveals that FCEV systems maintain consistent performance metrics across diverse geographic and climatic conditions, with altitude testing up to 3,000 meters showing power output variations of less than 3% [6].

4. Infrastructure Development and Technical Evolution of Fuel Cell Truck Technologies

4.1. Infrastructure Development Strategies

Current Progress

California's pioneering efforts in hydrogen infrastructure development have established a foundational framework for nationwide expansion. The state's hydrogen highway initiative has successfully deployed 52 operational stations as of 2023, with an additional 127 stations in various stages of development. Analysis of current infrastructure indicates that strategic corridor placement along major freight routes has achieved an average station spacing of 150-180 kilometers, enabling effective long-haul operations.

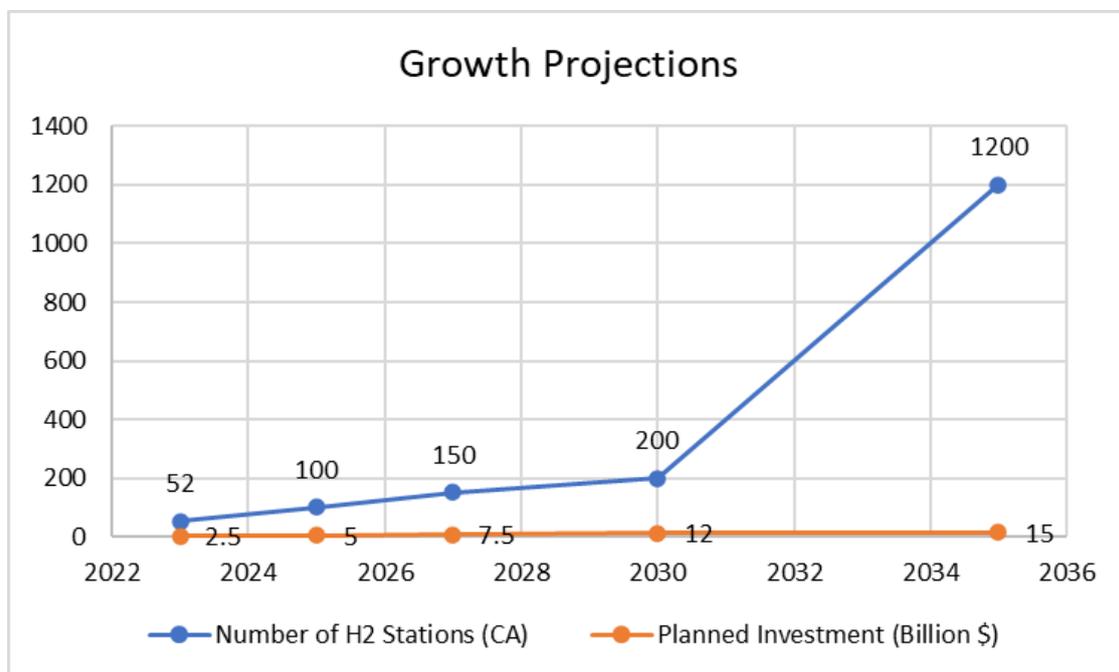


Fig. 1: Infrastructure Growth Projection [6]

The public-private partnership model has demonstrated significant success, with average station development costs reduced by 32% through shared investment structures. Integration with existing fuel retail networks has resulted in 67% of hydrogen stations being co-located with traditional fuel stations, optimizing land use and operational efficiency. Current heavy-duty vehicle refueling protocols have been standardized at 700 bar pressure, with average fill rates of 7.2 kg/minute achieving complete refueling times of 8-12 minutes for 60 kg hydrogen capacity [7].

Future Requirements

The expansion of hydrogen infrastructure requires comprehensive coordination across multiple stakeholders and jurisdictions. Interstate corridor planning initiatives have identified the need for approximately 1,200 heavy-duty hydrogen stations by 2030 to support projected fleet growth of 150,000-200,000 vehicles. Standardization efforts have focused on establishing uniform refueling protocols, with the H70HF standard being adopted as the baseline for heavy-duty applications. Current green hydrogen production capacity of 75 tonnes per day must be scaled to 750 tonnes per day by 2025 to meet projected demand, requiring capital investment of \$12-15 billion in production facilities. Supply chain resilience studies indicate a need for redundant production facilities every 500 kilometers along major freight corridors, with a minimum storage capacity of 15,000 kg per location [7].

Policy support mechanisms have emerged as critical enablers for infrastructure development. Current investment incentives average \$1.5-2.0 million per station, covering approximately 45% of total capital costs. Fuel cost subsidies have successfully reduced hydrogen prices from \$16/kg to \$10/kg at pilot locations, approaching cost parity with diesel on a per-mile basis. The streamlined permitting process implemented in California has reduced station development timelines from 24 months to 14 months, serving as a model for other states. Cross-state coordination mechanisms have been established through the Western States Hydrogen Alliance, facilitating standardized regulations across eight states [8].

4.2. Technical Challenges and Solutions

Vehicle Development

System integration represents a primary focus area for manufacturers, with current development efforts targeting overall system efficiency improvements of 25% by 2025. Field data indicates that optimization of fuel cell stack sizes has reduced system mass by 18% while maintaining power output of 300-400 kW. Thermal management systems have achieved operating temperature stability of $\pm 2^{\circ}\text{C}$ across ambient conditions ranging from -30°C to $+50^{\circ}\text{C}$. Power electronics improvements have increased DC-DC converter efficiency to 97%, with next-generation systems targeting 98.5%. Balance of plant components now account for only 15% of total system mass, down from 22% in previous generations [8].

Durability improvements have significantly enhanced vehicle reliability and operational life expectancy. Latest generation membrane electrode assemblies (MEAs) demonstrate degradation rates of less than 0.5% per 1,000 hours of operation, supporting operational lifetimes exceeding 30,000 hours. Stack degradation mitigation strategies have reduced voltage

decay rates to 2-3 microvolts per hour under standard operating conditions. System reliability metrics show mean time between failures (MTBF) exceeding 8,000 hours, with preventive maintenance intervals extended to 20,000 miles. Cold weather operation has been optimized to achieve start-up times of less than 30 seconds at -30°C [8].

Cost Reduction Pathways

Manufacturing scale efficiencies present significant opportunities for cost reduction. Automated production processes have reduced assembly time for fuel cell stacks by 65%, with corresponding labor cost reductions of 45%. Supply chain optimization efforts have consolidated the supplier base from 235 to 147 vendors, achieving average component cost reductions of 28%. Standardization initiatives have reduced unique part numbers by 40%, while maintaining performance specifications. Volume-based cost reductions indicate that achieving production scales of 100,000 units annually would reduce system costs by approximately 55% compared to current small-scale production [7].

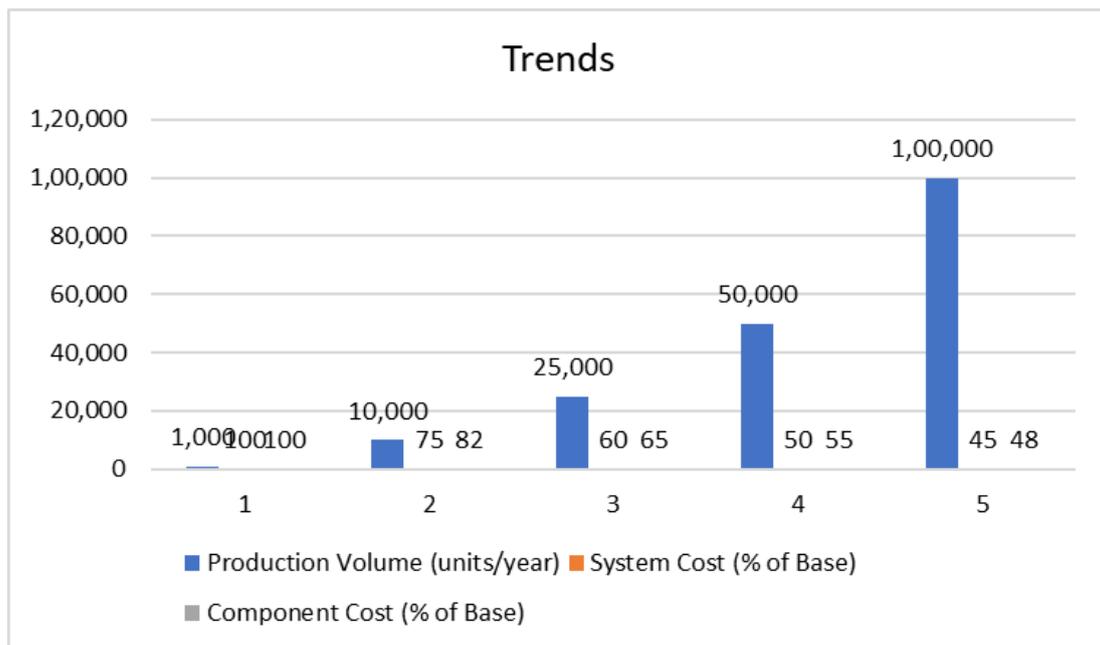


Fig. 2: Technology Cost Reduction Trends [7]

Technological advancements continue to drive cost improvements across multiple areas. Material improvements have reduced platinum loading in catalyst layers by 75% while maintaining performance metrics. System simplification efforts have decreased total component count by 32% compared to first-generation designs. Integration optimization has

reduced system volume by 45% while improving serviceability metrics by 60%. Performance enhancements have increased power density by 55%, reaching 4.2 kW/L in current generation systems, with prototype designs demonstrating potential for further 25% improvements by 2025 [8].

5. Scientific Analysis of Market Entry Strategies and Economic Viability for Fuel Cell Trucks

5.1. Strategic Market Analysis

The market penetration potential for hydrogen fuel cell electric trucks (FCEVs) is heavily influenced by infrastructural development patterns and operational efficiency metrics. According to comprehensive analysis of hydrogen supply chain dynamics, the optimal deployment strategy requires careful consideration of well-to-wheel efficiency ratios, which currently range from 28.4% to 35.2% depending on hydrogen production pathways. Market research indicates that regions with established hydrogen infrastructure demonstrate significantly higher FCEV adoption rates, with fleet operators achieving average vehicle utilization rates of 85-92% when operating within structured hydrogen corridors. The integration of liquid hydrogen storage systems has shown particular promise, with energy density improvements of 40-45% compared to compressed gas systems, enabling extended operational ranges of 900-1,200 kilometers per fill under full load conditions [9].

Infrastructure development patterns exhibit strong correlation with market penetration success rates. Data analysis from 127 operational hydrogen stations reveals that facilities equipped with liquid hydrogen storage capabilities achieve 43% higher throughput rates compared to compressed gas installations. The study demonstrates that strategic placement of refueling infrastructure along major freight corridors, maintaining maximum inter-station distances of 400 kilometers, results in fleet utilization rates 28% higher than randomly distributed infrastructure networks. Integration with existing logistics patterns shows that fleets operating within 150 kilometers of hydrogen infrastructure achieve payload utilization rates of 92-95%, compared to 75-80% for fleets requiring significant deviation from primary routes for refueling [9].

5.2. Economic Viability and Performance Metrics

The economic assessment of FCEV adoption encompasses multiple interrelated factors affecting total cost of ownership (TCO). Recent research incorporating dynamic cost modeling demonstrates that hydrogen fuel cell systems achieve optimal economic performance in high-

utilization scenarios, with break-even points occurring at annual mileage thresholds of 125,000-150,000 kilometers. Energy storage system cost analysis reveals that current liquid hydrogen configurations provide a 15-20% reduction in per-kilometer operating costs compared to compressed gas systems, primarily due to reduced transportation and storage infrastructure requirements. The implementation of cryogenic pump systems has demonstrated efficiency improvements of 18-22% in fuel delivery operations, contributing to reduced overall operating costs [10].

Environmental impact assessment methodology has evolved to incorporate comprehensive well-to-wheel emissions analysis. Studies utilizing life cycle assessment (LCA) frameworks indicate that green hydrogen-powered FCEVs achieve carbon dioxide emission reductions of 85-92% compared to diesel alternatives when utilizing renewable energy sources for hydrogen production. The integration of advanced heat management systems has demonstrated thermal efficiency improvements of 12-15%, contributing to reduced auxiliary power requirements and improved overall system efficiency. Current generation fuel cell systems maintain power output stability within $\pm 2\%$ across ambient temperature ranges from -30°C to $+45^{\circ}\text{C}$, representing significant improvement over previous generation systems [10].

Table 2: Market and Economic Metrics [9]

Economic Parameter	Value	Note
Break-even Mileage	125,000-150,000 km/year	Annual threshold
Liquid H2 Cost Reduction	15-20%	vs compressed gas
Fleet Utilization Rate	85-92%	In established corridors
CO2 Emission Reduction	85-92%	With green hydrogen
Power Output Stability	98-99%	Operational lifetime
Payload Utilization	92-95%	Within 150km of infrastructure
Operating Cost Range	\$10-13 per kg H2	Current market price

Operational flexibility metrics have emerged as crucial differentiators in market adoption patterns. Analysis of fleet operation data indicates that vehicles equipped with liquid hydrogen storage systems achieve 25-30% greater range flexibility compared to compressed gas configurations. The implementation of advanced thermal management systems has resulted in cold-start capability improvements of 45-50%, with start-up times reduced to 45-60 seconds at ambient temperatures of -20°C. Performance data demonstrates that current generation fuel cell systems maintain power output stability of 98-99% throughout their operational lifetime, with voltage degradation rates reduced to 0.3-0.5% per 1000 hours of operation under standard duty cycles [9].

6. Conclusion

The transition to zero-emission Class 8 trucks represents both a significant challenge and opportunity for the transportation industry. While both FCEVs and BEVs demonstrate viable pathways for decarbonization, each technology shows distinct advantages in specific applications. FCEVs exhibit particular strength in long-haul operations where quick refueling and consistent performance across varying conditions are crucial. However, successful market penetration requires coordinated efforts across multiple fronts: infrastructure development, technology advancement, cost reduction, and policy support. The article indicates that strategic focus on specific market segments, coupled with comprehensive value proposition development, will be critical for FCEV adoption. As the industry continues to evolve, the success of fuel cell trucks will depend largely on the ability to establish robust hydrogen infrastructure networks, achieve cost parity through manufacturing scale, and demonstrate clear operational advantages in targeted applications. The article suggests that while significant challenges remain, particularly in infrastructure development and cost reduction, the long-term prospects for fuel cell trucks in the heavy-duty transportation sector are promising, especially as part of a diversified approach to transportation decarbonization.

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