Title

Comparative Assessment of Zero-Emission Technologies for Heavy-Duty Freight: Battery Fast Charging, Battery Swapping, Catenary Electric Road, Inductive Electric Road, Hydrogen Fuel Cell and Internal Combustion, and On-Board CO_2 Capture

Authors

Zhao, Jingyuan
Fulton, Lewis

Publication Date

2026-06-01

Comparative Assessment of Zero-Emission Technologies for Heavy-Duty Freight:

Battery Fast Charging, Battery Swapping, Catenary Electric Road, Inductive Electric Road, Hydrogen Fuel Cell and Internal Combustion, and On-Board CO_2 Capture

May 2026

Jingyuan Zhao, Lewis M. Fulton

Institute of Transportation Studies

University of California, Davis

jyzhao@ucdavis.edu; lmfulton@ucdavis.edu

ITS UCDAVIS Institute of Transportation Studies

Sustainable Freight UCDAVIS Institute of Transportation Studies

Abstract

This report presents a comparative assessment of seven zero-emission vehicle and near-zero-emission pathways for heavy-duty freight applications: battery fast charging, battery swapping, catenary electric road systems, inductive electric road systems, hydrogen fuel cell electric vehicles (FCEVs), hydrogen internal combustion engine vehicles (H_2ICEVs), and diesel internal combustion engine vehicles equipped with carbon capture and storage (ICEV-CCS). To enable a consistent system-level comparison, we develop a unified techno-economic modeling framework, SHIFT (Systemic Heavy-duty Infrastructure Framework for Transition), which quantifies and contrasts these pathways across multiple key performance indicators, including fuel cost, energy efficiency, levelized system cost, and levelized cost of transport, using a stochastic Monte Carlo simulation framework with bounded techno-economic parameter sampling. The simulations incorporate variations in fleet size, electricity pricing, infrastructure costs, and system efficiencies, generating 10,080 stochastic realizations across technologies, duty cycles, and energy supply configurations. The analysis covers three representative freight applications: short-haul, regional-haul, and long-haul trucking, capturing duty-cycle-specific infrastructure and operational trade-offs.

The results suggest that in the early deployment years (e.g., 2030), battery swapping and fast charging show greater potential to achieve lower levelized system costs under small-scale deployment conditions, primarily due to lower capital intensity and better scalability at low fleet utilization. In contrast, electric road systems require substantial initial infrastructure investment but demonstrate strong scalability in high-throughput freight corridors. Among these systems, catenary electric road systems become increasingly favorable for densely trafficked long-haul corridors by 2040, particularly when infrastructure is shared across large aggregated fleets. FCEVs remain economically challenging during early deployment phases, particularly at small scale, due to both vehicle and infrastructure costs. Their competitiveness improves primarily under conditions of rapid scale-up of hydrogen production and refueling infrastructure, higher station utilization, and access to low-cost renewable hydrogen enabled by favorable supply-chain configurations. H_2ICEVs provide a transitional alternative by leveraging shared hydrogen refueling infrastructure while requiring lower vehicle capital costs, although their overall efficiency remains lower than that of fuel cell powertrains. More broadly, the long-term viability of hydrogen-based trucking depends critically on the evolution of the hydrogen supply system, with economics improving as low-cost hydrogen from off-grid renewable resources and high-utilization pipeline delivery networks become available. ICEVs equipped with CCS, operating on diesel fuel, represent a conditional decarbonization pathway toward near-zero-emission performance by reducing tailpipe CO_2 emissions through on-board carbon capture. However, residual combustion emissions and incomplete capture prevent full zero-emission performance.

Overall, these findings aim to offer strategic insights for transportation agencies, utilities, and industry stakeholders, supporting cost-effective infrastructure deployment, resilient energy planning, and targeted policy interventions to accelerate the transition to sustainable freight systems.

Keywords: zero-emission vehicles; heavy-duty; fast charging; swapping; catenary; inductive; hydrogen; electric road; levelized system cost; energy efficiency; well-to-wheel; infrastructure; policy; trucks.

Abbreviations

Abbreviation	Term
BESS	**Battery energy storage system**
BEV	**Battery electric vehicle**
Caltrans	**California department of transportation**
CAPEX	**Capital expenditure**
CARB	**California air resources board**
CCS	**Carbon capture and storage**
CEC	**California energy commission**
CO_2	**Carbon dioxide**
CRF	**Capital recovery factor**
DCFC	**Direct-current fast charging**
DOE	**U.S. department of energy**
ERS	**Electric road system**
FCEV	**Fuel cell electric vehicle**
GTW	**Grid-to-wheel**
H_2	**Hydrogen**
HDV	**Heavy-duty vehicle**
H_2ICEV	**Hydrogen internal combustion engine vehicle**
HVIP	**Hybrid and zero-emission truck and bus voucher incentive project**
ICEV	**Internal combustion engine vehicle**
ICEV-CCS	**Internal combustion engine vehicle with carbon capture and storage**
IMPACT	**Integrated market penetration and cost technologies model**
LCFS	**Low carbon fuel standard**
LCOE	**Levelized cost of electricity**
LCOT	**Levelized cost of transport**
LSC	**Levelized system cost**
OEM	**Original equipment manufacturer**
OPEX	**Operating expenditure**
SHIFT	**Systemic heavy-duty infrastructure framework for transition**
SOC	**State of charge**
TOU	**Time-of-use**
TTW	**Tank-to-wheel**
VMT	**Vehicle miles traveled**
WTW	**Well-to-wheel**
ZEV	**Zero-emission vehicle**

Table of Contents

Executive Summary

This report presents a systematic evaluation of seven pathways for heavy-duty freight decarbonization, including battery fast charging, battery swapping, catenary electric road systems, inductive in-motion charging, hydrogen fuel cell electric vehicles, hydrogen internal combustion engine vehicles, and diesel vehicles equipped with on-board CO_2 capture. Using a harmonized techno-economic simulation platform, the analysis quantifies the performance of each pathway across four core dimensions: delivered electricity cost, fuel cost, levelized system cost (excluding vehicle costs), and levelized cost of transport (including vehicle costs), evaluated under deployment scenarios spanning 2030 to 2040.

Delivered electricity cost ($/kWh)

The delivered cost of electricity (Figure ES1) exhibits substantial variation across energy supply architectures and vehicle technologies. From the electricity-source perspective, conventional grid electricity generally results in the highest delivered costs, driven by demand charges, limited load flexibility, and elevated marginal costs during peak periods. In contrast, grid-connected renewables typically offer the lowest costs, benefiting from declining capital expenditures, favorable policy incentives, and minimal operational expenses. Off-grid renewable systems, while capital-intensive, can achieve relatively low effective energy costs in applications that support high and stable utilization, particularly in hydrogen production systems with pipeline delivery in solar-rich regions by 2040. Hybrid configurations, integrating renewables, grid, and battery energy storage, strike a balance between cost, reliability, and dispatchability, supporting resilience in more variable operating conditions. Collectively, these upstream electricity architectures critically influence downstream vehicle economics and should guide infrastructure investment and policy prioritization.

Across the 2030–2040 horizon, changes in delivered energy costs reflect a combination of technology learning, system-scale expansion, and energy supply maturation. The relative improvement of hydrogen pathways between 2030 and 2040 is driven by shifts in energy sourcing logistics and infrastructure configuration. By 2040, lower off-grid renewable electricity costs, higher effective utilization of hydrogen production and delivery systems, and the amortization of regional pipeline infrastructure collectively compress effective markups. These conditions indicate a transition toward a supply architecture in which throughput, logistics optimization, and capital recovery increasingly dominate delivered energy costs. (i) The largest cost reductions occur in capital-intensive systems that benefit from high utilization and scale effects, including electric road systems and hydrogen production and delivery infrastructure. (ii) Modular technologies (e.g., fast charging and battery swapping) exhibit more moderate cost-reduction potential, as they already operate near efficient scales at lower deployment volumes. (iii) Energy architectures decoupled from the conventional grid, particularly off-grid renewables for hydrogen, exhibit increasingly favorable cost performance by 2040 due to avoided demand charges, improved capacity factors, and mature supply chains.

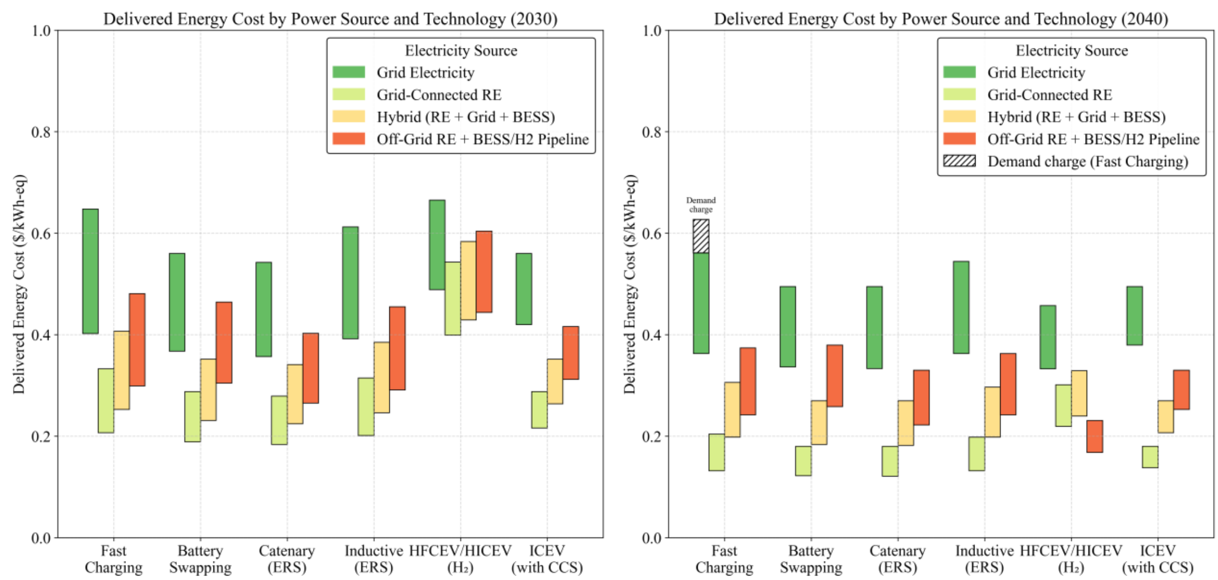


Figure ES1. Delivered Electricity Cost (2030 and 2040). The "Off-Grid RE + BESS / H_2 Pipeline" category denotes parallel logistics configurations: off-grid renewable electricity for battery-electric technologies and off-grid renewable hydrogen production with pipeline delivery for fuel-cell pathways. Hydrogen values are expressed in electricity-equivalent units (kWh-eq) based on the lower heating value of hydrogen (33.3 kWh/kg) and represent hydrogen used as a vehicle fuel for FCEV and H_2ICEV.

Fuel cost ($/mile)

A comparative evaluation of fuel costs across seven ZEV/near-ZEV pathways (Figure ES2) highlights substantial variation in operational economics, driven by differences in drivetrain efficiency, energy sourcing strategies, and infrastructure maturity. The fuel cost results are reported as conditional outcomes across alternative electricity and fuel supply architectures. In 2030, catenary configurations exhibit relatively favorable fuel cost profiles, reflecting their high electricity-to-wheel efficiency and access to stable grid electricity supply. Battery swapping follows, supported by centralized charging, efficient energy management, and the ability to utilize low-cost, off-peak renewable electricity. Fast charging, while similarly efficient at the vehicle level, faces higher energy costs at the site level due to demand charges and localized grid dependency. Similarly, wireless inductive solutions provide comparable operational flexibility but incur higher system-level energy costs due to power-transfer inefficiencies and additional infrastructure requirements. FCEVs and H2ICEVs tend to exhibit higher costs than other pathways, reflecting the relatively early stage of hydrogen production and delivery systems as well as their lower tank-to-wheel efficiency. By 2040, all pathways exhibit substantial potential for cost reduction, driven by declining renewable electricity costs, improvements in wireless power transfer efficiency, and more flexible energy provisioning strategies. Notably, scenarios that combine low-cost, off-grid renewable electricity with high-utilization hydrogen production and pipeline delivery show the greatest potential for reducing hydrogen fuel costs, thereby narrowing the operational cost gap between fuel cell electric vehicles and battery-electric drivetrains. In this more mature ecosystem, relative fuel cost advantages are not only shaped by drivetrain type, but also increasingly determined by the extent to which each technology aligns with evolving energy infrastructure and supply-chain conditions. These findings indicate that fuel cost outcomes are strongly influenced by the interaction between energy supply characteristics and infrastructure utilization conditions.

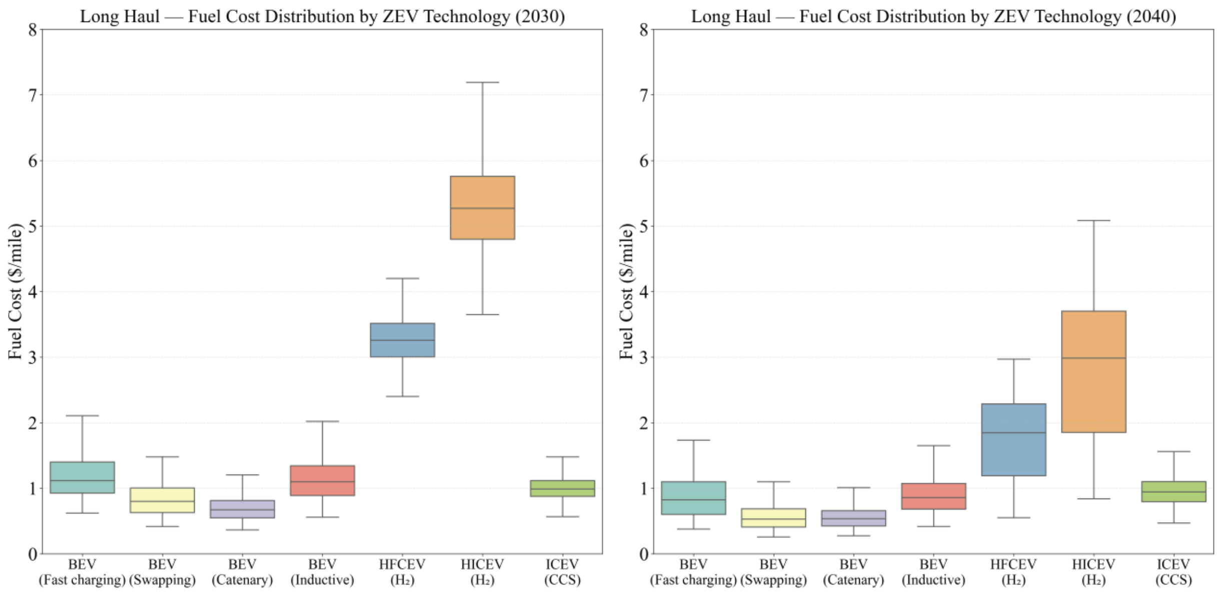


Figure ES2. Fuel Cost by Different ZEV Pathways for Long-haul Vehicles (2030 and 2040).

Levelized system cost ($/vehicle·year)

Figure ES3 compares the levelized system costs of the seven pathways for long-haul trucking (on the order of hundreds of thousands of dollars per vehicle per year). These system costs include the construction and operating costs of the charging or refueling systems needed to support the vehicles, but not the costs associated with vehicles themselves, or the energy costs shown above. In 2030, fast charging and battery swapping exhibit the lowest levelized system costs, with relatively narrow variability across scenarios. This variation reflects differences in modeled deployment conditions, including fleet size and utilization, energy price assumptions, infrastructure costs, and other key techno-economic parameters sampled within the scenario framework.

The scale effects of infrastructure give an advantage in early years to charging and battery swapping systems. These have better scalability, over other systems that require major construction efforts even for a small-scale system. In this regard, electric road systems display substantially higher and more variable costs, driven by low near-term utilization, their capital-intensive nature, and reliance on corridor-scale throughput. FCEVs fall within an intermediate cost range, with moderate variability contingent on achieving hydrogen delivery costs of $10/kg through production scale-up. By 2040, the cost hierarchy shifts markedly. The results indicate that increased corridor utilization (e.g., exceeding 2,000 vehicles per day along major freight routes) enables catenary systems to amortize infrastructure investments more effectively, reducing costs below those of depot-based alternatives. Inductive electric road systems, while benefiting from higher utilization, remain relatively high-cost due to lower charging efficiency and higher roadway infrastructure costs ($/mile·kW). Concurrent improvements in hydrogen logistics and supply costs ($6/kg), expanded integration of renewable electricity, and advances in power electronics further reduce cost dispersion across all technologies.

Overall, the results indicate that no single factor dominates. Instead, three mechanisms jointly drive the decline in levelized system cost: (i) increased infrastructure utilization, particularly for capital-intensive systems such as electric road infrastructure, which significantly reduces per-vehicle cost through scale; this effect is especially pronounced for electric road systems, which transition from low-utilization conditions in 2030 to high-utilization, corridor-scale deployment in 2040, leading to the largest relative cost reductions among all pathways; (ii) reductions in effective energy cost ranges and hydrogen supply costs within the modeled scenarios, lowering operational expenditures across both battery and hydrogen pathways; and (iii) capital cost improvements and more favorable capital recovery conditions, which reduce the annualized burden of infrastructure investment. These effects are embedded in the scenario assumptions and act simultaneously, leading to substantial cost compression across all technologies. However, the magnitude of cost reduction differs across technologies. In particular, compared to catenary systems, inductive electric road systems exhibit a smaller decline due to their higher baseline infrastructure costs, lower power capacity, and lower power transfer efficiency, which limit the extent to which utilization gains translate into cost reductions. Over the long term, as deployment scales and infrastructure utilization improves, levelized system costs across pathways converge toward comparable ranges. This convergence reflects increasing technological maturity and the dominant role of utilization in determining cost competitiveness, provided that infrastructure is appropriately sited and matched to operational demand.

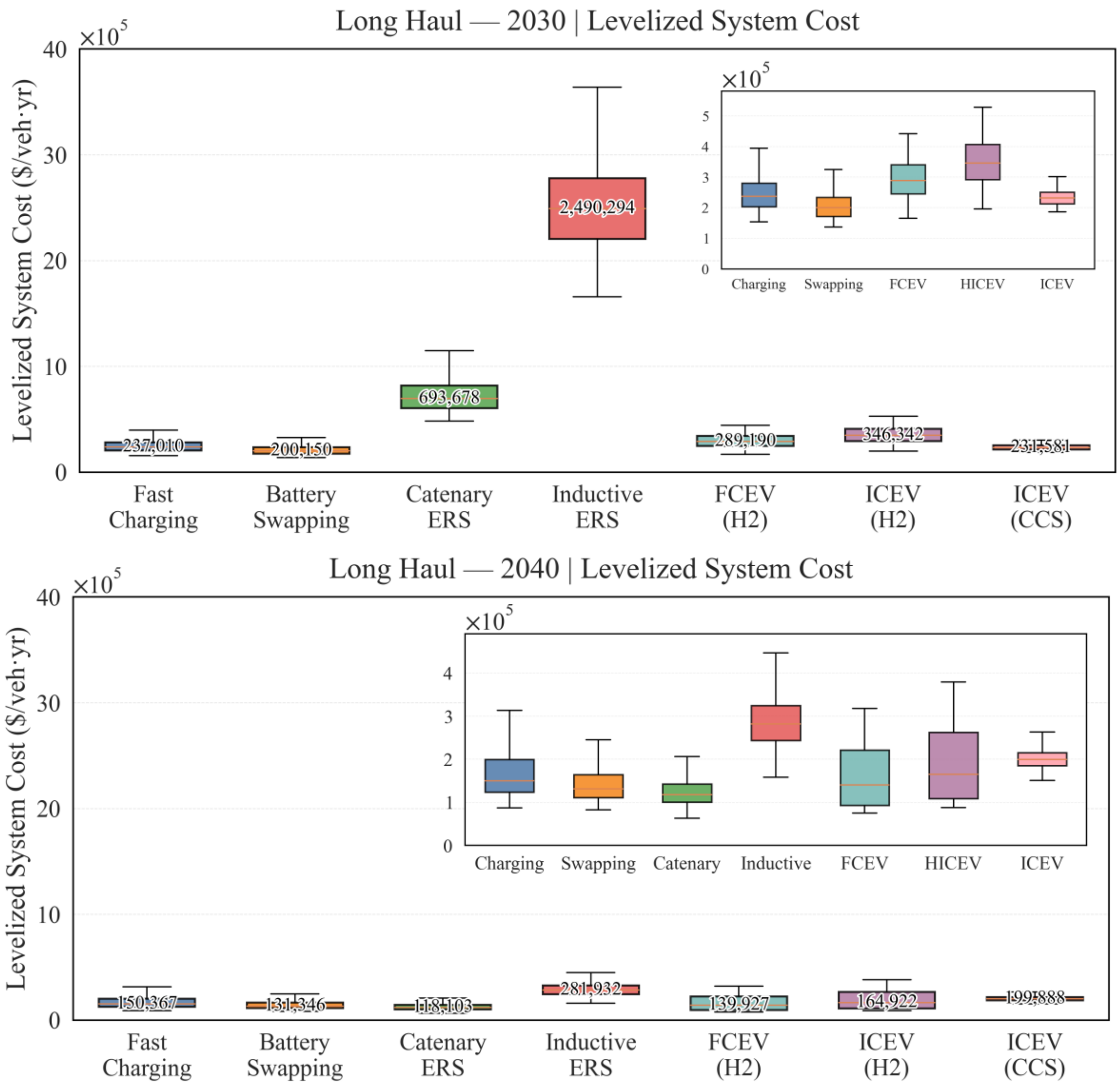


Figure ES3. Levelized System Cost Distributions for Long-haul Vehicles (2030 and 2040).

Levelized cost of transport ($/vehicle·year)

Taking into account these three key inputs (electricity cost, energy cost, and system cost), we can add in the cost of vehicles and combine everything to estimate total levelized cost of transport. Comparisons for long-haul trucking are shown in Figure ES4. This metric represents the average annual cost of providing transportation service per vehicle over its economic lifetime. It integrates the first three aspects above, including vehicle capital costs, infrastructure investments, energy/fuel expenditures (based on energy costs and vehicle efficiency), and maintenance costs. The results show that the overall levelized cost of transport follows a similar trend to the levelized system cost across the seven pathways, with relatively small differences arising from variations in initial vehicle costs among the pathways.

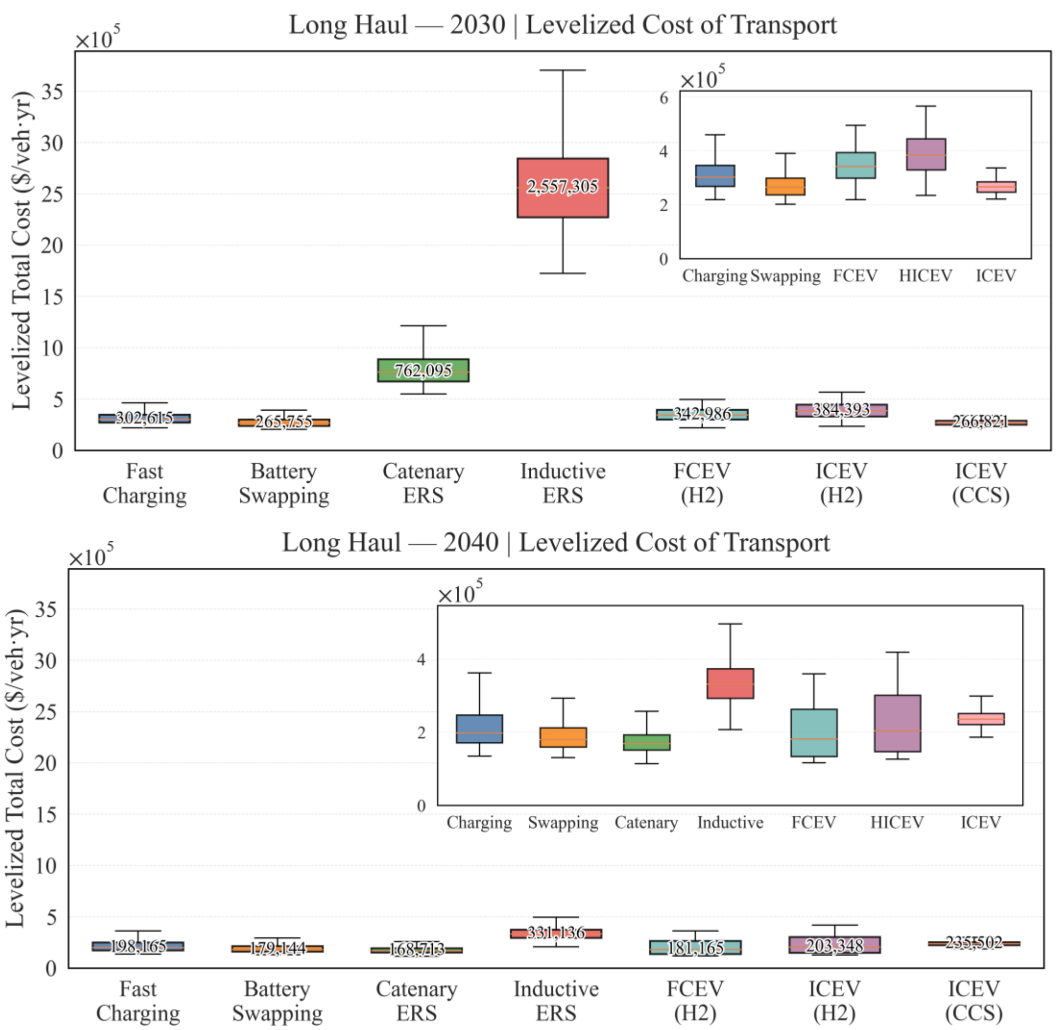


Figure ES4. Levelized Cost of Transport for Long-haul Vehicles (2030 and 2040).

Results for 2030 and 2040 show a substantial reduction in overall costs across all technologies over the decade. By 2040, cost variation across technologies narrows, although notable differences remain. The range of outcomes (as indicated by the “whiskers” in the results) reflects simulated cost variation across fleet sizes, system utilization levels, energy price assumptions, infrastructure costs, and other key techno-economic parameters sampled within the scenario-based modeling framework. These results indicate that no single zero-emission vehicle technology offers clear, universal advantages, and the cost ranges overlap considerably. Deployment outcomes remain highly contingent on specific use cases, fleet scale, and the maturity of supporting energy infrastructure. While the comparative results are robust within the modeled techno-economic space, certain pathways, particularly electric road systems, may exhibit additional cost reduction potential under spatially optimized deployment. Quantifying such effects would require geographically explicit modeling and the outcomes are expected to be highly context dependent.

Furthermore, we find that depot-based solutions, such as battery swapping and fast charging, are better suited to small- and medium-scale fleet applications, for example fleets of 30 to 70 vehicles, whereas electric road systems become cost-effective under high-throughput conditions in freight corridors, potentially at the scale of thousands of vehicles, when supported by coordinated infrastructure planning. This is likely to take many years to achieve. Similarly, hydrogen fuel cell electric vehicles exhibit low minimum and median cost outcomes in the long term, in several modeled scenarios, alongside a comparatively wide cost dispersion across assumptions, indicating substantial sensitivity to hydrogen costs and infrastructure utilization conditions.

Across all technologies, key cost determinants include system scale, infrastructure utilization, electricity pricing mechanisms (such as transmission and distribution charges and demand tariffs), and capital recovery periods. Future research should integrate real-world fleet telematics, regional grid constraints, energy storage requirements, and lifecycle emissions. Pilot projects, interoperable standards (for example, for battery modules or electric road system interfaces), and transparent performance data from these demonstrations are critical for reducing uncertainty and informing equitable infrastructure investment. By aligning techno-economic modeling with deployment realities, this study aims to inform the development of zero-emission freight systems that are both cost-effective and scalable across diverse contexts. Given these uncertainties, commitments to technologies such as electric road systems require a long term planning approach and may not deliver significant cost advantages over more incremental approaches, such as battery depot charging, public fast charging, and battery swapping systems.

1 Introduction

The freight transportation sector plays a pivotal role in the global economy, enabling the movement of goods across regional, national, and international supply chains [1]. However, it is also a major contributor to greenhouse gas emissions, air pollution, and petroleum dependence, especially in the heavy-duty vehicle segment [2]. In California, for example, heavy-duty vehicles account for a disproportionate share of transportation-related emissions, despite comprising a small fraction of total vehicle stock. These impacts are particularly acute in disadvantaged communities located near ports, warehouses, and freight corridors. As states and nations commit to aggressive climate goals, decarbonizing the freight sector has emerged as a major policy priority, not only for climate mitigation but also for advancing environmental justice and public health.

While ZEVs offer a promising pathway to decarbonize freight transport, no single technology has demonstrated universal applicability across all freight operational contexts to date. Battery electric vehicles (BEVs) [3], fuel cell electric vehicles (FCEVs) [4], hydrogen internal combustion engine vehicles (H_2ICEVs) [5], and electric road systems (ERS), including catenary [6] and inductive charging [7], each present distinct trade-offs in terms of energy efficiency, infrastructure complexity, cost structure, range capability, and scalability. Battery swapping [18] expands the BEV solution space, offering a high-throughput alternative to battery fast charging [8], particularly for time-sensitive trucking applications. However, many existing comparative analyses focus on light-duty passenger vehicles or are limited to a narrow set of comparisons, such as BEVs versus FCEVs. As a result, a gap remains in rigorous, technology-neutral evaluations tailored to heavy-duty freight operations across a broad range of zero-emission and near-zero-emission pathways. Policymakers and industry leaders increasingly require integrated, scenario-based assessments that systematically quantify the performance and cost-effectiveness of multiple technologies under diverse deployment conditions.

This study aims to address this gap by developing a unified techno-economic framework, SHIFT, the Systemic Heavy-duty Infrastructure Framework for Transition. The framework builds on results from the IMPACT model [9]-[13], Integrated Market Penetration and Cost Technologies, which was specifically designed for freight decarbonization analysis. IMPACT integrates three core sub-models, namely a vehicle cost model, a vehicle energy and operational dynamics model, and an infrastructure deployment model. Together, these components provide critical inputs and reference benchmarks for constructing the SHIFT framework, which is used to compare seven pathways for heavy-duty freight applications: battery fast charging, battery swapping, catenary electric roads, inductive electric roads, fuel cell electric trucks, hydrogen internal combustion engine trucks, and diesel trucks equipped with onboard carbon dioxide capture. Using a unified simulation platform and scenario-based analysis, the framework evaluates each technology across key performance indicators, including fuel cost, energy efficiency, levelized system cost, levelized cost of transport, and feasibility across different deployment scales. By systematically quantifying these metrics, the study provides analytical insights to inform infrastructure planning, investment prioritization, and policy formulation, thereby contributing to the analysis of cost-effective and equitable transition toward zero-emission freight transportation.

Table 1. Overview of the Seven Zero- and Near-Zero-Emission Freight Pathways.

Technology	Characterization	Core Strength	Key Limitation
Fast Charging	Flexible, decentralized electrification	Mature ecosystem, broad OEM compatibility	Grid impact at peak loads; moderate charging downtime
Battery Swapping	Centralized high-throughput logistics	Ultra-fast energy replenishment with decoupled battery ownership	Requires fleet standardization and station co-location
Catenary Electric Roads	Corridor-based continuous electrification	Eliminates charging downtime; minimal onboard energy storage	High infrastructure and civil engineering demands
Inductive Charging	Embedded charging for dynamic or static use cases	Enables seamless, in-motion or curbside charging	Efficiency loss, cost, and technological immaturity
Fuel Cell Electric Vehicles	Energy-dense alternative for long-range and remote freight	Fast refueling and high range with minimal grid reliance	Hydrogen supply chain cost and refueling infrastructure gaps
H_2ICEVs	Transitional hydrogen utilization pathway	Leverages existing ICE platforms; lower capital cost than FCEVs	Lower efficiency; higher hydrogen consumption than fuel cells
ICEVs with CO_2 Capture	Compliance-oriented retrofit of diesel systems	Uses existing diesel supply chains; enables CO_2 emissions mitigation at scale	Dependent on capture efficiency, diesel costs, and costly CO_2 transport/storage

2 Background: Zero-Emission Technologies for Heavy-Duty Freight

The decarbonization of heavy-duty freight transport has emerged as a major policy priority for achieving national climate goals and enhancing energy resilience. A diverse portfolio of zero-emission vehicle technologies is currently under active development and deployment to address the distinct operational demands of long-haul trucks, drayage fleets, and regional delivery vehicles. As illustrated in Figure 1, this report examines representative zero-emission technology pathways alongside their associated infrastructure configurations. To provide a holistic assessment, this chapter contextualizes these technologies across four key analytical dimensions: (i) technological readiness and application fit, (ii) lifecycle performance metrics, including energy efficiency, (iii) infrastructure feasibility and capital risk, and (iv) policy frameworks that shape investment, planning, and supply chain integration.

Figure 1. Framework for Evaluating Zero-Emission Technologies in Heavy-Duty Freight.

2.1 Battery Fast Charging

Battery fast charging represents a critical technological pathway for accelerating the adoption of BEVs in the heavy-duty freight sector. By delivering electricity at high power levels, typically ranging from 250 kW to 1000 kW for truck applications [14],[15], this approach significantly reduces charging time compared to conventional Level 2 chargers or early-generation DC fast chargers. For regional trucking applications, where vehicle downtime directly translates into economic loss, the ability to restore 80% state of charge within 30–90 minutes is a key enabler of operational feasibility. High-power charging stations are generally deployed at freight depots, logistics hubs, highway rest areas, and public charging corridors. The plug-in interface represents one of the most mature and widely adopted charging configurations and continues to benefit from ongoing standardization efforts. These stations can be co-located with energy storage systems or renewable energy sources to mitigate peak load impacts on the grid, although such integrations introduce additional system complexity and capital cost.

One study evaluates the technical and economic feasibility of high-capacity static chargers (600 kW and 1 MW) for electric heavy goods vehicles across different logistics scenarios in the UK and South Africa [16]. High-capacity chargers are especially effective for long-haul routes with short dwell times, enabling battery downsizing without disrupting operations. Economic break-even analysis suggests that with moderate electricity profit margins (£0.06–£0.08/kWh), these chargers can be financially viable if used for approximately 6–7 hours per day, equivalent to about twenty charging events of 20 minutes each. However, for short-range, multi-stop operations, fast charging offers limited benefit over slower alternatives. The study concludes that while high-capacity static charging is promising for specific freight use cases, full electrification of long-distance trucking depends on integration with dynamic on-road charging and context-specific infrastructure planning. Nonetheless, despite these apparent advantages, the large-scale deployment of battery fast charging remains technically and economically challenging. Energy demand is highly concentrated, which can impose substantial stress on local grids, requiring costly upgrades to substations and distribution infrastructure. Moreover, high C-rate charging accelerates battery degradation and poses thermal management constraints, limiting practical charge speeds. From a cost perspective, fast charging stations face volatility due to fluctuating electricity tariffs, demand charges, and variable utilization, all of which complicate investment recovery. Compared to battery swapping or hydrogen refueling, fast charging typically benefits from lower upfront capital costs but suffers from higher operational uncertainty, especially in deregulated electricity markets.

2.2 Battery Swapping

Battery swapping is an emerging zero-emission refueling strategy designed to address one of the key limitations of BEVs: extended charging time. The core concept involves the rapid replacement of a depleted battery pack with a fully charged one at a designated swap station, thereby minimizing vehicle downtime and decoupling energy replenishment from grid-constrained fast charging [17]. This technology has gained renewed attention for its potential application in heavy-duty freight, where long daily driving ranges, tight delivery schedules, and high vehicle utilization rates pose serious challenges for conventional plug-in charging. The battery swapping approach offers several operational advantages. First, it enables near-instantaneous energy replenishment, typically within 5 to 10 minutes, comparable to diesel refueling, which is critical for commercial fleets operating under time-sensitive logistics. Second, it allows for centralized energy storage and load balancing, supporting more efficient use of renewable electricity and off-peak grid power. Third, it reduces the onboard battery capacity required for each vehicle, potentially lowering vehicle purchase costs and alleviating range anxiety for drivers.

From a system and market perspective, battery swapping has demonstrated strong economic viability under real-world deployment, especially in China. Studies show that battery swapping can achieve cost savings up to 0.79 CNY/km when high utilization rates, mid-sized battery capacities (350 kWh), and long daily mileage (400 km) are achieved [18]. These savings stem from decoupling battery ownership, optimizing energy throughput, and leveraging station-integrated energy storage systems. At the same time, system-level feasibility depends critically on battery standardization and modularity. Modular energy blocks allow diverse vehicle classes to use the same infrastructure, simplifying logistics and maintenance. Nonetheless, key challenges remain: high capital expenditures for stations, complex battery lifecycle and safety management, and the need for cross-OEM interoperability. The success of battery swapping, therefore, hinges not only on cost and efficiency metrics, but also on coordinated policy frameworks, platform compatibility, and operational scale.

2.3 Catenary Charging (overhead wire, pantograph)

Catenary charging, also referred to as overhead ERS, enables in-motion electrification by delivering continuous power to heavy-duty vehicles via overhead wires and pantograph connectors. Adapted from conventional electric rail and trolleybus systems, this approach allows electric trucks to operate without stopping for recharging or carrying oversized battery packs, thereby reducing two major barriers to BEV deployment in freight transport: downtime and vehicle weight penalties. In a catenary system, electric power is transmitted through overhead lines installed along designated highway corridors. Vehicles equipped with roof-mounted pantographs automatically engage the lines while driving, drawing electricity directly into the drivetrain or to onboard batteries for hybrid operation when off-corridor. This "dynamic charging" model enables high-power energy transfer during motion, reducing reliance on fixed-location chargers and optimizing vehicle energy efficiency across long-distance routes.

In recent years, a series of analyses and investigations has focused on the UK as a case study, providing valuable information and engineering insights into the deployment of ERS. For example, one study concentrated on developing the technical specifications for a UK-based ERS demonstrator along a 50 lane-kilometer stretch of the M180 corridor, marking an early but concrete step toward real-world implementation of catenary infrastructure [19]. The proposed system is designed to deliver 300 kW of continuous power per vehicle and accommodate three vehicle configurations: a 150 kWh ERS-BEV, a 500 kWh ERS-BEV, and a 300 kWh hybrid ERS vehicle equipped with a diesel or biogas range extender. To maintain operational flexibility beyond the electrified segment, the study also recommended supplemental static charging infrastructure at logistics hubs, warehouses, and rest stops. Fast charging at 1.2C rates would enable a near-full recharge during a 45-minute rest stop or a partial (50%) recharge during a 20-minute drop-off. While initially scoped as a demonstrator, the study proposed scaling toward national-level simulation based on real-world freight routes to assess system-wide economic and environmental impacts. Building on this, subsequent research extended the analysis to national-scale deployment across the UK Strategic Road Network [20]. By modeling phased electrification of over 15,000 lane-km, the study suggests that ERS can provide a cost-effective pathway for long-haul freight electrification under high-utilization conditions, particularly when infrastructure financing mechanisms and energy taxation structures are considered. However, these economic outcomes remain contingent on sustained corridor utilization and coordinated infrastructure deployment, rather than intrinsic cost advantages of the technology alone.

To complement technoeconomic comparisons and nationwide rollout scenarios, a simulation-based study was conducted to explore how different ERS and static charging configurations impact vehicle design and operational requirements at the route level [21]. Using a detailed vehicle and logistics model, the study assessed eight representative freight journeys, including warehouse-to-warehouse, multi-drop, and tramping operations, under four ERS topography scenarios (none, light, medium, and heavy) and three static charging configurations (none, drop-off, and rest stop). The simulation results showed that, in the absence of any ERS or on-route charging, battery capacities as large as 1500 kWh would be required to complete some journeys, significantly increasing vehicle cost and embodied emissions. In contrast, even partial ERS coverage was found to substantially reduce battery requirements, by 41% to 75% depending on infrastructure extent, resulting in potential per-vehicle cost savings of $25,000–

112,000 and carbon savings up to 127 tCO_2. These results highlight a fundamental system-level trade-off: reductions in onboard battery capacity are achieved at the expense of increased reliance on in-motion energy delivery, requiring sufficient ERS coverage length and power transfer capacity to maintain operational energy balance, particularly for long-haul applications. Furthermore, a follow-up study conducted a cross-country cost–benefit analysis of ERS deployment across four distinct national contexts: England, France, India, and South Africa [22]. By formulating a breakeven model based on traffic density and annual freight flow per road segment, the study identified the extent to which ERS infrastructure could be economically justified across major freight corridors. The analysis found that up to 9,700 lane-km in England, 11,500 in France, 14,000 in India, and 5,600 in South Africa could be electrified with a payback period under 20 years, supporting 30–70% of road freight depending on national conditions. However, achieving smaller battery sizes and lower ERS infrastructure costs depends on the availability of complementary off-corridor charging infrastructure. Without such support, vehicles would either require larger onboard batteries or necessitate more extensive and higher-capacity ERS deployment to maintain energy balance over complete duty cycles, particularly in long-haul applications.

These studies indicate that catenary ERS has the potential not only to reduce onboard battery size, but also to enable a system-level redistribution of energy storage from the vehicle to the infrastructure [21]-[23]. This can improve payload capacity, reduce vehicle cost, and enhance operational efficiency under suitable conditions. Moreover, continuous power delivery enables near-zero charging downtime, which is particularly valuable for long-haul freight operations. Despite these advantages, the deployment of catenary systems entails substantial infrastructure and coordination challenges. Evidence from electrified railway systems highlights the exposure of catenary infrastructure to environmental conditions and the system-level consequences of component failures, underscoring the capital intensity, engineering complexity, and multi-jurisdictional coordination required for corridor-scale electrification [24]. The technology also necessitates standardization across vehicle platforms and pantograph interfaces, as well as robust control systems for safe and stable engagement at highway speeds. Overall, catenary charging represents a technically mature and operationally efficient electrification pathway, but its performance and economic viability are fundamentally conditioned on corridor utilization, infrastructure continuity, and integration with complementary charging systems, rather than on standalone deployment.

2.4 Inductive Charging (embedded coils)

Inductive charging, also known as wireless power transfer, delivers electrical energy to electric vehicles without physical connectors by generating an electromagnetic field between road-embedded coils and onboard receivers. This approach can operate in either static mode (e.g., at terminal stops or loading docks) or dynamic mode (e.g., while vehicles are in motion along electrified road segments). For heavy-duty freight applications, dynamic inductive charging offers the potential to extend range, reduce battery size, and maintain operational continuity, similar in principle to catenary systems, but with less visible infrastructure. The embedded-coil system typically consists of segmented primary coils installed beneath the road surface and activated only when a compatible vehicle is present overhead. The secondary coil on the vehicle receives energy through magnetic induction, which is then converted and used to power the drivetrain or recharge the onboard battery. Operating frequencies are engineered to balance energy efficiency with electromagnetic safety, while modular design enables flexible installation and targeted deployment.

An early study systematically compares overhead catenary systems and inductive power transfer-based electric road systems as two principal “charge-on-the-move” (CoM) technologies for decarbonizing long-haul freight [25]. Their simulation results show that both systems can feasibly deliver the required mean effective charging rate of 9.3 kJ/m, equivalent to approximately 140 kW of continuous power, to sustain heavy-duty electric freight vehicles on trunk roads. Catenary systems, such as Siemens’ eHighway, benefit from technological maturity and established high-power performance, but are limited by infrastructure complexity, safety concerns, and incompatibility with smaller vehicles. In contrast, inductive power transfer systems offer cleaner integration, multi-vehicle applicability, and reduced roadside visual and safety impacts, though current commercial devices fall short of the required power levels and would demand extensive road modification and multiple pick-up coils per vehicle. The study concludes that while both systems are viable, trade-offs in scalability, cost, maintenance, and grid integration should be carefully evaluated. A national CoM backbone, complemented by battery-electric urban logistics and stationary charging at depots, is proposed as a technically and economically feasible pathway for full-spectrum freight electrification, with potential to reduce CO_2 emissions by over 70% by 2030 and over 90% by 2040, contingent on electricity grid decarbonization. Among the two primary CoM approaches, inductive (wireless) dynamic charging is distinguished by its distinctive infrastructure and operational characteristics. Inductive charging provides several system-level advantages. First, it preserves the structural and aesthetic integrity of roadways and urban landscapes by eliminating the need for overhead hardware. Second, it supports flexible vehicle routing and route electrification in dense urban or terminal areas where catenary or fast-charging infrastructure is often impractical. Third, it can enable nearly continuous operation with minimal driver intervention, which is advantageous in logistics settings where turnaround time is tightly constrained. However, wireless charging for heavy-duty vehicles remains at a relatively early stage of commercialization. Key technical challenges include energy transfer efficiency, alignment tolerance, vehicle speed sensitivity, and durability of embedded infrastructure under high-axle loads. Efficiency losses, typically 10–20% compared to wired systems, compound energy demand and increase electricity-related operational costs [26]. Additionally, the high cost of road retrofitting and limited standardization across vehicle platforms remain substantial barriers to deployment. Economic viability depends on utilization density, deployment scale, and the ability to co-optimize with broader infrastructure investments such as smart road networks. Inductive charging presents a promising but complex solution for zero-emission freight applications, offering unique benefits in environments where wired systems are infeasible. Its long-term role in the freight electrification ecosystem will depend on the maturation of its efficiency, cost, and standardization profile, as well as strategic deployment aligned with freight flows and urban design constraints.

2.5 Hydrogen FCEV

Hydrogen refueling offers a technically viable zero-emission option for heavy-duty vehicle applications that demand high energy throughput, rapid turnaround, and extended driving ranges. FCEVs generate electricity onboard by converting compressed hydrogen into electrical energy through an electrochemical process, with water vapor as the only direct emission. This architecture enables rapid refueling, typically under 10 minutes for short-haul and up to 15 minutes for long-haul heavy-duty trucks, and supports operational profiles comparable to those of conventional diesel fleets.

For long-haul freight, hydrogen refueling offers three primary advantages. First, it decouples energy storage from battery limitations, allowing for extended driving ranges without the weight and volume penalties associated with large battery packs. Second, it minimizes refueling downtime, which is crucial for logistics efficiency and vehicle asset utilization. Third, hydrogen can be produced from diverse energy sources, including electrolytic, biomass-derived, or fossil-based pathways with carbon capture, offering flexibility in fuel sourcing and carbon intensity management. Despite these operational merits, hydrogen refueling infrastructure is capital-intensive and logistically complex. Establishing high-throughput stations requires advanced compression, storage, and dispensing systems, often costing several million dollars per site for truck-scale facilities. In addition, the volumetric energy density of gaseous hydrogen (even at 700 bar) is low, necessitating larger storage and delivery systems compared to liquid fuels or electricity. Liquefied hydrogen offers improved density but introduces further challenges related to boil-off losses, cryogenic handling, and energy-intensive liquefaction.

Policy and regulatory support are critical to accelerating hydrogen infrastructure deployment [27],[28]. California's Low Carbon Fuel Standard (LCFS) [29], federal tax credits [30], and DOE H_2Hubs [31] exemplify mechanisms to stimulate production, reduce delivered costs, and de-risk early investments. Standardization in refueling protocols, nozzle design, and safety systems is also advancing, guided by organizations such as SAE, ISO, and the Hydrogen Council. Hydrogen refueling provides a zero-emission pathway suited to freight segments characterized by long range, high utilization, and fast refueling requirements. While still maturing in terms of infrastructure scale and cost competitiveness, it remains a system-relevant option, especially for long-haul applications and corridor-based logistics where battery-based electrification is constrained by range, charging time, or infrastructure requirements.

2.6 H_2ICEV

H_2ICEVs represent an evolutionary pathway that leverages the mature internal combustion engine platform while substituting hydrogen for conventional fossil fuels. In principle, H_2ICEVs retain the architecture of diesel or gasoline engines, including pistons, crankshafts, and drivetrains, and require targeted modifications to fuel injection, ignition timing, materials, and thermal management to accommodate the high diffusivity, wide flammability limits, and low ignition energy of hydrogen. The key technical advantage lies in the relative simplicity and robustness of the engine system, which enables lower vehicle manufacturing costs and faster industrial deployment compared to FCEVs. However, H_2ICEVs typically exhibit lower tank-to-wheel efficiency (32–40%) than FCEVs (45–55%), translating into substantially higher hydrogen consumption per mile. Moreover, while H_2ICEVs achieve zero carbon dioxide emissions at the tailpipe, they still generate nitrogen oxides (NO_X) due to high-temperature combustion, necessitating additional aftertreatment technologies for stringent air-quality compliance. Despite these challenges, recent demonstrations by major OEMs, such as Volvo's announced hydrogen trucks [32], are based on hydrogen internal combustion engines, retaining a conventional engine architecture with high-pressure direct-injection hydrogen combustion and positioned as a complementary long-haul decarbonization pathway.

From a systems perspective, H_2ICEVs rely on the same hydrogen refueling infrastructure as FCEVs, including high-pressure storage and dispensing facilities. In this study, H_2ICEVs are evaluated under the same hydrogen specification and shared production, distribution, and refueling infrastructure framework as FCEVs. This common infrastructure basis enables coordinated station planning within a unified hydrogen network. Under this unified infrastructure assumption, differences between H_2ICEV and FCEV pathways arise primarily from vehicle-side performance and fuel consumption characteristics.

2.7 ICEV with CCS

Internal combustion engine vehicles equipped with on-board CO_2 capture represent an emerging and still early-stage engineering concept aimed at reducing net CO_2 emissions from conventional engine platforms. The principle involves integrating a capture device, typically an adsorption or absorption unit, into the vehicle exhaust system, enabling partial removal of CO_2 emissions before release to the atmosphere. Captured CO_2 is temporarily stored in high-pressure or cryogenic tanks on the vehicle and subsequently unloaded at designated depots or refueling stations. Off-board infrastructure, consisting of regeneration units and compression or liquefaction facilities, then conditions the CO_2 for transport and permanent geological storage. Pilot-scale demonstrations of on-board capture systems have been reported in the United States [33], although large-scale deployment pathways and regulatory frameworks remain under development.

Technically, ICEV with carbon capture builds upon existing internal combustion engine architectures that are robust, widely deployed, and cost-effective, while integrating additional subsystems for CO_2 capture, storage, and regeneration. However, this approach introduces additional system-level considerations, including increased fuel consumption, potential increases in vehicle mass and volume associated with onboard storage, and added operational complexity related to CO_2 handling, unloading, and logistics. Early prototypes have demonstrated capture rates in the range of 50–90%, though practical performance remains highly context-dependent. Furthermore, the requirement for a parallel CO_2 transport and storage infrastructure introduces additional system dependencies beyond the conventional fuel supply chain.

From a systemic perspective, ICEV with carbon capture does not eliminate fossil fuel dependence but provides a conditional and transitional pathway in regions where ICE manufacturing capacity, fueling infrastructure, and supply chains are deeply entrenched. Compared with direct electrification pathways, this approach involves lower overall system efficiency and greater infrastructure complexity, particularly in high-throughput freight applications. The approach can mitigate near-term CO_2 emissions while leveraging existing refueling networks, although its long-term role depends on the evolution of energy penalties, infrastructure requirements, and lifecycle system costs over time.

2.8 Operational Principles and Comparison

A flagship study by the International Transport Forum provides a comprehensive and uncertainty-aware assessment of zero-emission heavy-duty vehicle technologies in the European context [34]. By simulating over 1,000 cost scenarios across nine truck size segments, the study compares the total cost of ownership trajectories of battery electric vehicles, electric road system vehicles, and hydrogen fuel cell electric vehicles against diesel internal combustion engine vehicles. The report stands out for its robust treatment of technoeconomic uncertainty, accounting for variability in energy costs, vehicle costs, infrastructure deployment timelines, and energy efficiency improvements, and offers a transparent view of how these factors affect cost parity timelines. Importantly, the analysis finds that battery electric vehicles and electric road system vehicles are on track to become cost-competitive with diesel trucks by 2040 across all segments without policy support, while fuel cell electric vehicles are only competitive in limited edge cases. These findings highlight the potential feasibility of direct electrification but also inform technology-neutral policy design and infrastructure investment priorities for the decarbonization of freight transport in Europe.

Building on these insights, this study aims to provide a more granular and technology-inclusive comparison by incorporating additional charging and refueling pathways, including battery swapping and inductive electric road systems, into the assessment framework. To support an integrated evaluation of zero-emission technologies for heavy-duty freight, it is critical to establish a clear understanding of their operational principles. While all ZEV technologies aim to eliminate tailpipe emissions, they vary substantially in how energy is delivered, stored, and consumed during freight operations. These distinctions have profound implications for system design, fleet logistics, infrastructure planning, and overall cost-effectiveness.

(a) Battery Fast Charging delivers high-power electricity to a vehicle's battery at stationary charging stations, often at power levels ranging from 150 kW to 1000 kW. This approach leverages existing plug-in interfaces and can be deployed incrementally with relatively low infrastructure complexity, but can create substantial grid load and induces battery degradation under repeated high-C-rate usage.

(b) Battery Swapping involves replacing depleted battery packs with fully charged ones at dedicated stations. This decouples energy replenishment from grid capacity and minimizes vehicle downtime, but it requires standardized battery platforms, high initial capital investment, and sophisticated inventory management for spare packs.

(c) Catenary Charging delivers continuous electric power to vehicles through overhead wires and pantograph systems while they are in motion. It allows for smaller onboard batteries and virtually eliminates charging downtime. However, it is corridor-dependent, capital-intensive, and requires full system interoperability.

(d) Inductive Charging transfers power wirelessly from road-embedded coils to vehicle receivers, either while stationary or in motion. It offers seamless integration with urban environments and reduces driver intervention, but suffers from lower efficiency and high retrofitting costs.

(e) Hydrogen Refueling enables onboard electricity generation via fuel cells using compressed or liquefied hydrogen. It supports long-range, fast-refueling operation and is well suited for high-duty-cycle trucks, but depends on complex, high-cost refueling infrastructure and hydrogen production logistics.

(f) H_2ICEVs combust hydrogen directly in modified internal combustion engines. This pathway builds on the robustness and established manufacturing base of conventional engine platforms, enabling faster industrial deployment at lower incremental vehicle cost. While H2ICEVs emit no CO_2, they exhibit lower tank-to-wheel efficiency than fuel cell systems and generate nitrogen oxides under combustion conditions, necessitating aftertreatment. They rely on the same hydrogen refueling infrastructure as fuel cell trucks.

(g) ICEVs with On-board CO_2 Capture integrate capture units into conventional internal combustion vehicles to trap a substantial share of exhaust CO_2. Captured gas is temporarily stored onboard and unloaded at depots for regeneration and permanent storage. This approach reduces net CO_2 emissions without departing from existing ICE architectures, but it imposes fuel penalties, storage and maintenance burdens, and requires supporting CO_2 regeneration and transport infrastructure.

To synthesize these differences,

Table 2 provides a side-by-side comparison of the seven ZEV technologies across key technical and operational attributes:

Table 2. System-Level Characteristics of Zero-Emission and Low-Carbon Trucking Technologies.

Technology	Energy Delivery	Infrastructure Complexity	Charging/Refueling Time	Vehicle Modification (Platform-Specific)	Technical Maturity	Use Cases
Fast Charging	Direct plug-in (DCFC, 150–1000 kW)	Moderate to High (grid or EES interconnection, site upgrades)	Medium (20–90 min to 100% SOC; 20-60 min to 80% SOC*)	No	High	Flexible long-haul and corridor-based freight
Battery Swapping	Battery exchange at stations	High (standardization, logistics, storage)	Very Fast (≤5 minutes)	Yes (battery interface)	Medium (commercial pilots)	High-frequency regional routes with centralized depots
Catenary Electric Roads	Overhead wires + pantograph	Very High (road electrification, continuous power lines)	Real-time while driving	Yes (pantograph)	Medium (pilots in EU/China)	Dense highway corridors with predictable freight flows
Inductive Charging	Wireless charging (static/dynamic)	Very High (embedded coils, road retrofitting)	Real-time (dynamic) or slow (static)	Yes (receiver coil)	Low to Medium (mostly pilots)	Urban freight with frequent stops and constrained depot space
FCEV	Hydrogen refueling	High (storage, compression, dispensing)	Fast (10–15 minutes)	No	Medium to High	Long-haul and remote-area trucking with limited grid access
H_2ICEV	Combustion of hydrogen in ICE	High (similar to FCEV, simpler vehicle-side integration)	Fast (10–15 minutes)	No	Medium (prototypes, OEM pilots)	Near-term heavy-duty applications leveraging existing ICE platforms
ICEV with CO_2 Capture	Diesel combustion	High to very high (CO_2 unloading facilities, regeneration, transport to storage)	Fast (fueling as ICEV) + additional time for CO_2 unloading	Yes (capture module, tanks)	Low (early-stage R&D, limited pilots)	Transitional decarbonization in regions with entrenched ICE fleets and CCS infrastructure

3 Analytical Framework and Methodology

To conduct a comparative evaluation of zero-emission technologies for heavy-duty freight, this study adopts the IMPACT model, a modular simulation platform developed at the UC Davis Institute of Transportation Studies. The IMPACT model enables integrated assessment of vehicle performance, infrastructure investments, and economic viability under representative deployment conditions. A tailored framework used for the investigation and comparative analysis of the ZEV technologies is shown in Figure 2. The framework adopts a stochastic techno-economic modeling approach in which key system parameters are sampled using Monte Carlo methods to represent uncertainty in infrastructure costs, energy prices, utilization levels, and system efficiencies.

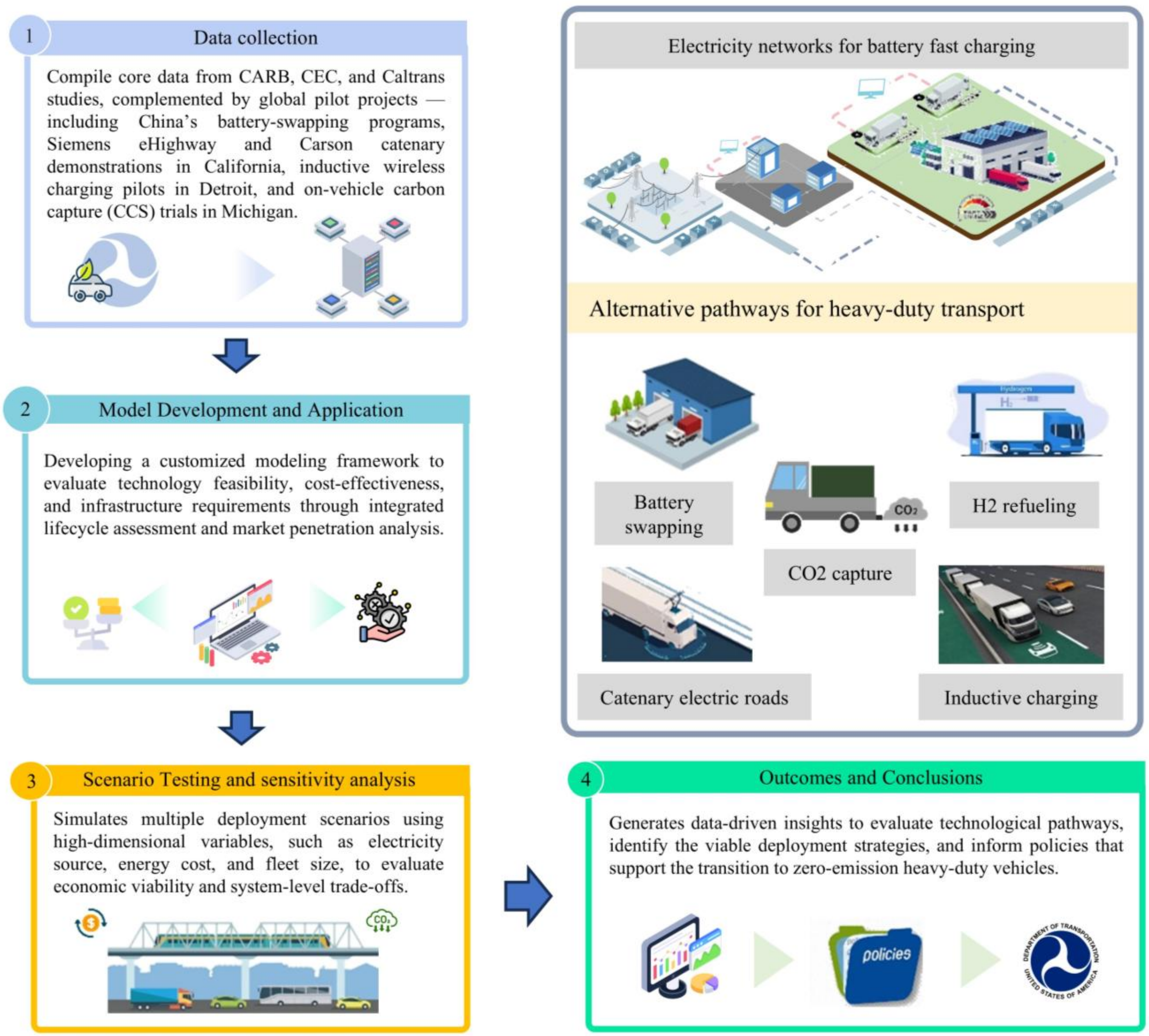


Figure 2. Integrated Modeling Workflow for Evaluating Zero-Emission Freight Technologies.

The analytical framework consists of four sequential components:

(a) Data Collection

The model is grounded in empirical datasets from California and international case studies, drawing on data provided by state agencies including the California Energy Commission (CEC), the California Air Resources Board (CARB), and California Department of Transportation (Caltrans). These sources encompass vehicle performance characteristics [35], truck road network attributes [36], energy pricing and tariff structures [37], infrastructure configurations [38], and relevant regulatory constraints [39],[40]. In addition, the framework incorporates field evidence from pilot demonstrations and early commercial deployments in the heavy-duty trucking sector. These reference cases include fast-charging hubs developed by Terawatt Infrastructure [41], Prologis [42], and WattEV [43]; battery-swapping deployments in China [44]; Siemens' conductive overhead eHighway system [45]; Electreon's dynamic wireless electric road technology [46]; hydrogen refueling infrastructure provided by First Element Fuel [47]; and carbon capture systems developed by Remora [33].

(b) Model Development

The modeling framework integrates vehicle energy demand, infrastructure capacity requirements, and energy supply costs within a unified techno-economic representation of zero-emission freight systems. The core structure links vehicle characteristics, such as battery capacity, fuel cell system size, and drivetrain efficiency, with infrastructure specifications including charging power levels, hydrogen refueling throughput, and electric road coverage. Through this coupling, the framework evaluates whether specific infrastructure configurations can satisfy fleet energy demand while maintaining economic feasibility. For each technology pathway and freight duty cycle, the model estimates vehicle-level energy consumption and scales it to the fleet level based on operational intensity and fleet size. The resulting energy demand determines the required infrastructure capacity, including charging power, refueling throughput, or electric road power delivery. Infrastructure sizing is therefore determined endogenously by matching fleet energy demand with the operational capability of the corresponding energy supply system. The framework further incorporates technology-specific parameters such as charging efficiency, hydrogen conversion efficiency, and infrastructure operating hours, enabling consistent comparison across battery-electric, hydrogen-based, and electric road system pathways.

(c) Scenario Testing and Sensitivity Analysis

To capture uncertainty in techno-economic inputs while accounting for differences in infrastructure deployment regimes across technologies, the framework adopts a scenario-based Monte Carlo simulation approach. The outer modeling space is defined as a deterministic configuration space, constructed from combinations of projection year t, technology pathway k, freight duty cycle h, and energy supply architecture s. In the present analysis, these dimensions span two projection years (2030 and 2040), seven technology pathways, four energy supply architectures, and three freight duty cycles, yielding 168 deterministic system configurations.

Within each deterministic configuration, technology-specific deployment parameters are varied to represent system scale and infrastructure design conditions. These parameters differ across technology pathways (e.g., fleet size for depot-based charging systems, station throughput for hydrogen refueling infrastructure, and corridor traffic throughput for electric road systems), reflecting the fundamentally different operational regimes of the respective infrastructure types. Uncertainty in techno-economic parameters is represented through Monte Carlo sampling. For a generic uncertain parameter x, stochastic realizations are generated within bounded ranges according to:

$$x_i = x_{\min} + U_i (x_{\max} - x_{\min}) \tag{1}$$

where x_i denotes the sampled realization of parameter x, $x_{\min}$ and $x_{\max}$ represent the lower and upper bounds of the parameter range, and U_i is a random variable drawn from a uniform distribution on [0,1]. The resulting parameter vector for realization *i* is:

$$x_i = (x_{1,i}, x_{2,i}, \cdots, x_{n,i}) \tag{2}$$

where *n* denotes the number of uncertain techno-economic parameters considered in the simulation. For each stochastic realization, the techno-economic system model evaluates the corresponding outcome:

$$y_i = f(x_i) \tag{3}$$

where $f(\cdot)$ represents the deterministic system model and y_i denotes the resulting model output for realization *i*.

Multiple Monte Carlo realizations are generated for each deterministic configuration to propagate uncertainty in key variables, including energy prices, infrastructure utilization levels, demand-charge structures, and system efficiency parameters. Across the full configuration space, this procedure yields 10,080 stochastic realizations of system outcomes. The resulting ensemble of stochastic realizations enables the framework to quantify variability in system outcomes and to identify sensitivity of technology performance to uncertain future energy-system conditions.

(d) Outcome

Model outputs include levelized system cost, fuel cost per mile, energy efficiency (well-to-wheel), infrastructure utilization, and carbon mitigation potential. These indicators are tracked across key milestone years (2030, and 2040), facilitating cross-temporal comparisons. Results are interpreted with respect to national freight resilience goals, capital risk exposure, and alignment with policy instruments (e.g., LCFS, HVIP, IRA incentives). By implementing this structured, multi-layered methodology, the IMPACT model provides a framework for evaluating the feasibility, cost dynamics, and system impacts of alternative zero-emission strategies. Its hybrid architecture, combining engineering-level constraints with economic scenario modeling, can inform deployment strategies that are not only cost-effective but also operationally feasible and policy-aligned.

4 Case Study and Model Inputs

The simulation framework relies on a harmonized set of assumptions to enable consistent and transparent techno-economic evaluation across zero-emission vehicle technologies. These inputs reflect both current industry conditions and forward-looking projections tailored to commercial deployment in the United States between 2030 and 2040. In this framework, the later-year scenarios represent a multi-dimensional transition, capturing (i) technology learning and performance improvements, (ii) shifts in system scale and utilization, particularly for corridor- and hub-based infrastructures, and (iii) maturation of energy supply and delivery architectures, rather than cost reductions alone. Vehicle operations are therefore represented using duty-cycle-specific characterizations that distinguish short-haul (Class 7 trucks, GVWR 26,000–33,000 lb), regional-haul (Class 8 day-cab tractor-trailers), and long-haul (Class 8 sleeper tractor-trailers, GVWR 80,000 lb) freight applications. These categories differ in daily utilization intensity and cumulative energy demand and therefore shape infrastructure sizing and utilization.

Short-haul trucking represents an early and widely discussed application domain for zero-emission freight technologies. These operations are characterized by relatively fixed routes, centralized fleet management, and predictable daily usage, as commonly observed in urban logistics, port drayage, and regional delivery services. Such conditions allow multiple energy delivery strategies to be deployed with limited operational disruption. Accordingly, the seven decarbonization pathways are modeled in ways that reflect their suitability for depot-centric operations, in-motion energy supplementation, or rapid refueling. This application emphasizes operational flexibility, infrastructure compatibility, and ease of integration with existing logistics practices, providing a consistent baseline for cross-technology comparison.

(a) Regional-haul trucking serves as an intermediate application between urban short-haul and corridor-dominated long-haul operations. These fleets typically operate over moderate distances with partial route predictability, fewer opportunities for mid-day energy replenishment, and higher cumulative energy demand per vehicle. As a result, regional-haul applications highlight trade-offs between onboard energy capacity, infrastructure density, and system utilization. Within this context, both depot-based and corridor-based energy delivery strategies remain viable, but their relative performance becomes more sensitive to infrastructure placement, utilization levels, and operational coordination. This use case captures a critical transition regime in which scalability, flexibility, and logistics integration jointly shape technology feasibility.

(b) Long-haul trucking represents one of the most demanding application scenarios for zero-emission freight systems, characterized by extended driving distances, sustained highway operation, and strong reliance on corridor-scale infrastructure. These operations prioritize continuous energy availability, high-throughput refueling or charging, and wide-area network coverage over depot centralization or turnaround speed. Consequently, technologies are evaluated in terms of their ability to support long-range operation through high-power energy delivery, in-motion charging, or large-scale fueling networks. This use case functions as a stress test for system scalability and infrastructure intensity, highlighting the importance of corridor utilization, network effects, and supply-chain coordination in enabling cost-effective long-distance freight decarbonization.

For battery electric trucks, energy consumption is treated as a duty-cycle-dependent parameter that reflects aggregated vehicle characteristics and operating conditions. For hydrogen-based vehicles, fuel consumption is allowed to evolve over time to reflect expected improvements associated with technology maturation. Together, these operational representations provide a common basis for estimating daily energy demand and for evaluating charging, swapping, refueling, and in-motion energy delivery requirements across pathways. Electricity and hydrogen energy costs are modeled to capture both supply-side diversity and delivery-architecture effects. Electricity supply is represented through a limited set of stylized configurations, including grid-based, renewable, hybrid, and off-grid systems. Delivered electricity cost is expressed as an effective metric that incorporates generation cost together with system-level adjustments associated with energy delivery, capacity provision, and operational constraints. Hydrogen fuel cost is similarly represented as an aggregate of production and delivery components, allowing the model to reflect how upstream supply structures and utilization conditions influence downstream operating costs. Infrastructure capital costs are parameterized using technology-specific cost representations that account for differences in scale, power level, and deployment form. Charging, swapping, electric road systems, and hydrogen refueling infrastructure are each modeled using specialized cost structures appropriate to their respective functional roles. Across all pathways, infrastructure investments are annualized using a uniform cost-recovery framework, ensuring that cost comparisons are not biased by inconsistent financial assumptions.

Table 3 summarizes the harmonized input assumptions across technologies and duty cycles, providing a consistent foundation for scenario analysis and cross-technology comparison. Simulations are conducted for two representative deployment years to capture the effects of technological learning, infrastructure maturation, and evolving energy supply conditions over time. Across all technologies and duty cycles, sensitivity analyses are performed by varying infrastructure investment levels, energy costs, fleet sizes, energy transfer efficiencies, and utilization factors. Outlier filtering (e.g., interquartile range methods) is applied to ensure the robustness of simulated cost distributions. The resulting datasets enable a detailed and policy-relevant assessment of how technology-specific constraints and economic drivers shape the levelized system cost landscape under evolving market conditions. By capturing both common system structures and duty-cycle-specific dynamics, this modeling framework supports analytical insights into infrastructure planning, technology selection, and the strategic deployment of zero-emission freight systems.

Table 3. Comparative Parameters of Zero-Emission Technologies.

Parameter	Fast Charging	Battery Swapping	Catenary Charging	Inductive Charging	Fuel Cell (Hydrogen)	Hydrogen ICEV	ICEV with CO_2 Capture
Years	2030, 2040	2030, 2040	2030, 2040	2030, 2040	2030, 2040	2030, 2040	2030, 2040
Duty Cycles	Short-haul / regional-haul / long-haul	Short-haul / regional-haul / long-haul	Short-haul / regional-haul / long-haul	Short-haul / regional-haul / long-haul	Short-haul / regional-haul / long-haul	Short-haul / regional-haul / long-haul	Short-haul / regional-haul / long-haul
Fleet Size[a]	2030: 10–70 2040: 10–70	2030: 10–70 2040: 10–70	2030: 320–440 2040: 2800–4,600	2030: 320–440 2040: 2800–4,600	2030: 10–70 2040: 10–70	2030: 10–70 2040: 10–70	2030: 10–70 2040: 10–70
Daily VMT (mi)	150 / 250 / 500	150 / 250 / 500	150 / 250 / 500	150 / 250 / 500	150 / 250 / 500	150 / 250 / 500	150 / 250 / 500
Energy consumption (2025)[b]	1.8 / 2.1 / 2.4 kWh/mi	1.8 / 2.1 / 2.4 kWh/mi	1.8 / 2.1 / 2.4 kWh/mi	1.8 / 2.1 / 2.4 kWh/mi	0.10 / 0.12 / 0.14 kgH2/mi	0.12 / 0.15 / 0.17 kgH2/mi	5.5 / 6.3 / 7.5 mpgD
Charging / Fueling Power (kW, equivalent)[c]	150, 350, 800, 1000	50, 150, 350, 1000	250, 350, 450	150, 200	7,000–14,000	7,000–14,000	20,000–30,000
Infrastructure Type[d]	Depot chargers	Depot + remote chargers + buffer	Overhead lines on corridor	Embedded coils on corridor	Refueling stations	Refueling stations (shared with FCEV)	Diesel stations + CO_2 transport & storage
Infrastructure Cost	Station + chargers	Station + chargers + battery buffer	$/mile × corridor length	$/mile × corridor length	Station cost (throughput-based)	Station cost (throughput-based)	Station + capture unit + CO_2 handling
Maintenance rate (annual, % of infrastructure CAPEX)	3.5 / 3.0 / 2.5 %	4.0 / 3.5 / 3.0 %	5.0 / 4.5 / 4.0 %	6.0 / 5.0 / 4.0%	6.0 / 5.0 / 4.0 %	6.0 / 5.0 / 4.0 %	3.0 / 2.8 / 2.5 %
Capital Recovery	10% / 9% / 8% DR, 15 yr	10% / 9% / 8% DR, 15 yr	10% / 9% / 8% DR, 15 yr	10% / 9% / 8% DR, 15 yr	10% / 9% / 8% DR, 15 yr	10% / 9% / 8% DR, 15 yr	10% / 9% / 8% DR, 15 yr
Features	Charger sharing; demand charge sensitivity	Offsite logistics; buffer pool	In-motion charging; corridor dependency	Wireless charging; efficiency loss	Fast refueling; nonlinear CAPEX	Engine retrofit; high H_2 use	On-board CO_2 capture; off-board transport & storage

[a] Corridor-based technologies (catenary and inductive charging) are modeled at the infrastructure-segment level, where capital costs are allocated across aggregate vehicle flow rather than discrete fleet size per station. This reflects their continuous power-delivery architecture, which differs structurally from node-based charging or refueling systems. All technologies are evaluated under internally consistent scale formulations aligned with their respective infrastructure topology.

[b] Energy consumption is assumed to improve by 2% annually from the 2025 baseline.

[c] Equivalent fueling power for hydrogen and diesel is estimated from delivered fuel energy (based on modeled fuel consumption and lower heating value) and representative 10–15 minute refueling durations.

[d] This study focuses on infrastructure configurations capable of supporting high-utilization freight operations, including corridor-based and high-throughput deployment models. Static or low-utilization variants are not explicitly modeled. For conductive and inductive applications, electricity balance is assumed to be achieved solely through the electric road infrastructure without reliance on external depot charging; therefore, battery sizing is assumed to be identical to that of BEVs.

5 Results and Comparative Evaluation

A central element of the analytical framework is the adoption of standardized cost metrics to ensure consistent comparison across diverse ZEV technologies. This section describes the formulation and application of four primary economic indicators: delivered electricity cost, fuel cost, levelized system cost, and levelized cost of transport.

5.1 Delivered Electricity Cost ($/kwh)

A fundamental component in the cost modeling of ZEV infrastructure is the delivered electricity cost, the effective unit cost of electricity available at the point of use, prior to accounting for vehicle-side conversion efficiencies. The core of this estimation is the levelized cost of electricity (LCOE), which represents the average lifetime cost per kilowatt-hour of electricity produced, and is calculated as:

$$\mathrm{LCOE} = \frac{\mathrm{CAPEX} \times \mathrm{CRF} + \mathrm{OPEX}}{E_{\mathrm{annual}}} \tag{4}$$

$$E_{\mathrm{annual}} = P_{\mathrm{rated}} \cdot CF \cdot H_{\mathrm{annual}} \tag{5}$$

where, *CAPEX* represents the upfront capital investment, *OPEX* denotes the annual operating and maintenance costs, and *CRF* is the capital recovery factor accounting for the time value of money over the system's lifetime. The annual energy production E_{annual} is computed as the product of the installed capacity P_{rated}, the capacity factor *CF*, and the annual number of operating hours H_{annual}.

The capital recovery factor accounts for the financing cost over the system lifetime, defined as:

$$\mathrm{CRF} = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{6}$$

where *r* is the discount rate and *n* is the asset lifetime in years. Herein, CRF is calculated using discount rates of 10%, 9%, and 8% for the years 2025, 2030, and 2040, respectively. Asset lifetimes are assumed to be 15 years.

To capture the range of electricity provisioning strategies relevant to zero-emission freight, this study considers four representative supply configurations: (i) conventional grid electricity, (ii) on-site renewable generation (grid-connected), (iii) hybrid systems integrating grid, renewables, and battery storage, and (iv) fully off-grid renewable systems coupled with battery energy storage systems. Electricity cost assumptions are informed by forward-looking projections of levelized costs for new generation resources from the U.S. Energy Information Administration [48] and Lazard [49].

The delivered electricity cost represents a pre-efficiency, upstream electricity price; all energy conversion losses from the primary energy carrier to wheel-level energy are captured separately through the well-to-wheels efficiency term (η_{system}). The pre-efficiency delivered electricity cost can be represented as:

$$\text{Delivered Electricity Cost}_{\text{pre-efficiency}} = \text{LCOE} \times \text{Markup} \tag{7}$$

$$\text{where Markup} = (1 + \lambda_{\text{loc}}) + \frac{C_{\text{demand}} + C_{\text{storage}} + C_{\text{trans}} + C_{\text{dist}}}{\text{LCOE}} \tag{8}$$

where λ_{loc} denotes the locality/interconnection factor (dimensionless) capturing regional tariff multipliers and proportional surcharges. C_{demand} represents demand charges typically associated with high-power consumption patterns, for example, fast-charging events that trigger peak-load pricing. $C_{storage}$ accounts for cost premiums related to the deployment and integration of energy storage systems, particularly when co-optimized with intermittent renewable resources. The terms C_{trans} and C_{dist} correspond to standardized charges levied for transmission and distribution services, respectively. These components elevate the base LCOE into a technology- and context-specific delivered electricity cost that reflects real-world operational and infrastructural constraints. This formulation incorporates both technical losses (e.g., line losses, electrolyzer efficiency) and financial adders (e.g., infrastructure markup, demand charges, pipeline amortization), offering a consistent cost basis across technologies with disparate energy sourcing strategies. For battery-electric pathways, the delivered electricity cost therefore includes upstream electricity price, transmission and distribution losses, charging or ERS infrastructure amortization, and where applicable, demand charges associated with high-power charging. For hydrogen pathways, delivered hydrogen costs are converted to electricity-equivalent costs using the lower heating value of hydrogen (33.3 kWh/kg-H_2), while upstream electricity requirements are accounted for through the well-to-tank efficiency component of the overall well-to-wheels efficiency. The hydrogen supply chain representation further includes electrolysis, compression or liquefaction, storage, transportation and refueling station infrastructure costs. In the 2040 off-grid hydrogen scenario, alternative delivery logistics are represented, including pipeline-based hydrogen supply as the baseline case and truck-based delivery (liquid hydrogen tanker or high-pressure tube trailer) as an additional cost envelope.

As shown in Figure 3, the delivered electricity cost varies significantly depending on the synergy, or mismatch, between the energy carriers, infrastructure form, and deployment context.

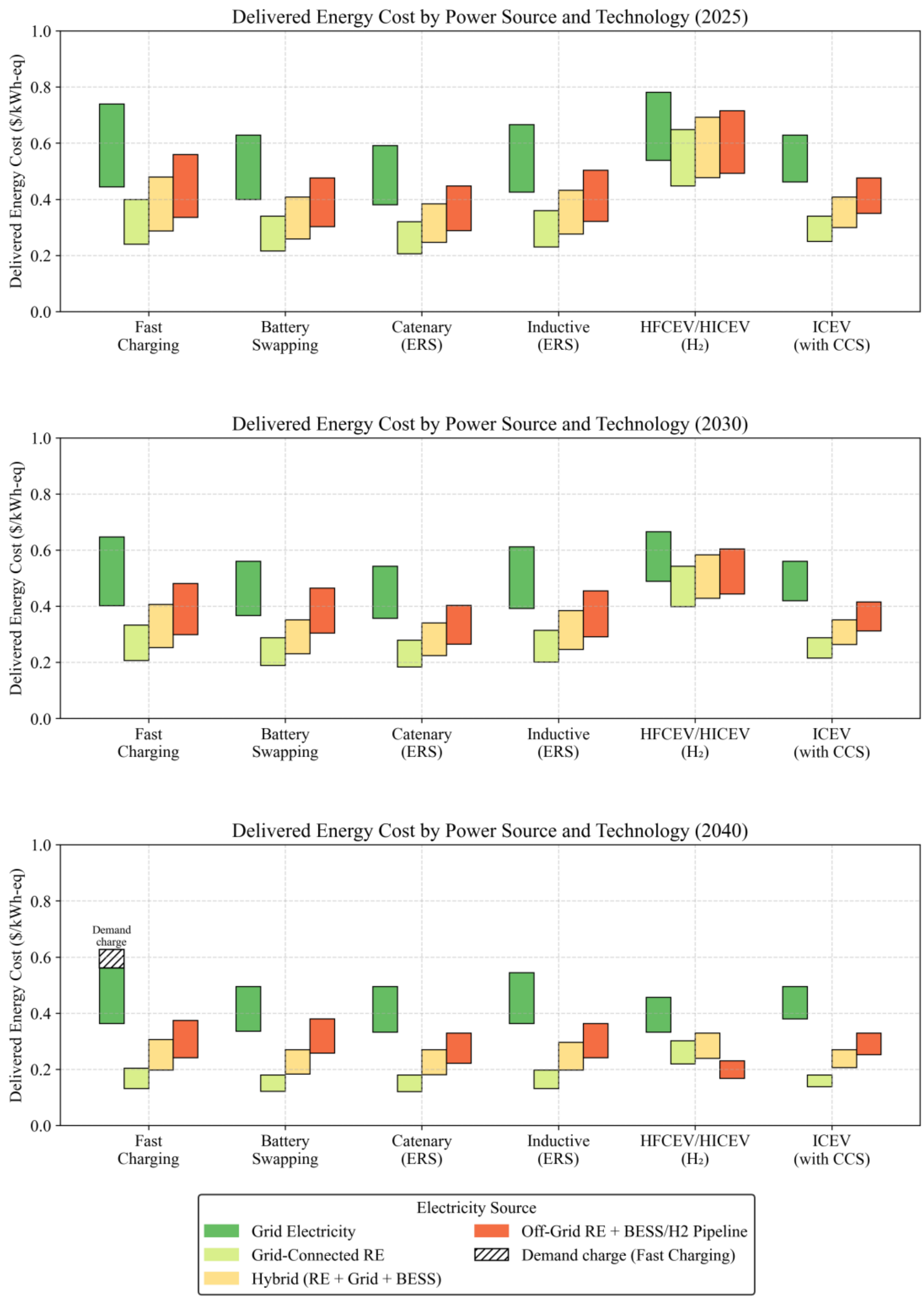


Figure 3. Delivered Electricity Cost by Power Source and Technology (2025, 2030 and 2040). Demand charges are incorporated as an additional uplift to the markup range for Fast Charging under Grid Electricity in 2040. The hatched overlay visualizes the incremental effect relative to the baseline markup (solid bars). Other technologies do not include explicit demand-charge adjustments in this figure.

In 2030, electricity supply for many ZEV technologies is expected to rely primarily on grid-dependent configurations, particularly in the case of fast charging, which exhibits the highest delivered electricity cost range (up to $0.65/kWh) due to high instantaneous power demand and localized demand charges. In contrast, battery swapping and road electrification (catenary/inductive) benefit from more distributed energy demands and infrastructure amortization, resulting in more moderate markups. For FCEVs, the delivered electricity cost in 2030 remains high (~$0.68/kWh equivalent), reflecting reliance on relatively expensive hydrogen production using grid electricity or semi-isolated renewables, combined with costly refueling infrastructure. However, by 2040, substantial changes in energy sourcing and delivery assumptions begin to influence cost outcomes. One scenario explores a forward-looking, high-utilization configuration in which hydrogen production uses low-cost off-grid renewable electricity in high solar-resource regions, where generation-side electricity costs can reach $0.03/kWh or even lower. After accounting for potential pipeline-related losses and delivery adders (e.g., compression and seasonal storage), the effective electricity cost entering electrolysis in this scenario is on the order of $0.04–0.10/kWh. The use of high-volume hydrogen pipelines, if deployed and operated at sufficiently high utilization, amortized across regional demand, could significantly lower the effective markup. This results in a delivered energy cost that could approach $0.40/kWh-eq at the low end for hydrogen, making it cost-competitive with electric alternatives under specific high-throughput and system-optimized conditions. This scenario is explicitly included in the 2040 fuel cell pathway to represent a conditional, long-term configuration involving regional hydrogen hubs. Other technologies also evolve by 2040: battery swapping begins to incorporate off-site renewable recharging closer to vehicle depots, reducing energy cost volatility. Inductive and catenary systems, while still grid-tied, avoid high demand charges due to their distributed and smoothed power demand profile, yielding relatively stable delivered electricity cost trajectories. By contrast, fast charging tends to exhibit relatively higher delivered electricity costs because of its inflexible power profile and reliance on peak-time urban grid electricity. As infrastructure systems diversify and supply chains become more optimized, scenario-based analysis of delivered electricity cost trajectories will become increasingly important for policy design and fleet transition planning.

To further explore these interactions,

Table 4 summarizes how zero emission technologies, battery swapping, catenary systems, fast charging, inductive charging, and hydrogen fuel cells, respond to four different energy supply architectures: conventional grid electricity, grid connected renewable electricity, hybrid renewable energy and grid systems with storage, and fully off grid renewable energy systems. The table provides a scenario-specific, qualitative assessment of cost drivers and operational trade-offs that influence the delivered cost of electricity across these configurations.

Table 4. Structural Drivers of Delivered Electricity Cost by Technology and Supply Architecture.

Technology	Conventional Grid	Grid-Connected Renewables	Hybrid (RE + Grid + BESS)	Off-Grid Renewables + Storage
Fast Charging	High instantaneous charging power; exposure to demand charges; limited on-site buffering	Inverter/converter losses; limited firming; intermittency exposure	BESS-based firming; additional reliability-driven capacity sizing	Autonomous supply; large BESS sizing required for peak coverage
Battery Swapping	Distributed charging load; reduced peak volatility; centralized storage	Renewable electricity use; buffering required to align charging cycles	Battery buffer enables temporal decoupling of supply and demand	Full autonomy requires oversized battery inventory and storage system
Catenary	Continuous traction load; direct grid coupling; stable power draw	Requires stable renewable integration and grid synchronization	Continuous delivery reduces peak demand variability	Requires continuous off-grid supply and large-scale storage
Inductive Charging	Embedded infrastructure; distributed load along corridor	Renewable supply losses; dynamic control and buffering required	Hybrid firming mitigates variability but increases infrastructure complexity	Dynamic load requires continuous storage-backed supply
FCEV (H_2 electrolysis)*	Electricity-driven electrolysis; compression and dispensing; demand-charge exposure	Electrolyzer losses; renewable intermittency; backup power requirements	Hybrid balancing stabilizes hydrogen production profile	Remote renewable electrolysis; pipeline delivery reduces local grid exposure
H_2ICEV (H_2 electrolysis)*	Electricity-driven electrolysis; compression; hydrogen throughput-driven cost	Electrolyzer losses; renewable variability managed via flexible production	Hybrid balancing stabilizes hydrogen production profile	Remote renewable production; pipeline delivery; higher hydrogen intensity increases fuel cost sensitivity
ICEV (with CCS)	Continuous capture load; auxiliary compression power requirement	Steady electricity demand for capture; limited buffering need	Hybrid supply hedges electricity cost volatility	Continuous capture operation requires storage-backed supply

* Hydrogen production is modeled via electrolysis within the electricity-centered system boundary adopted in this study to isolate infrastructure cost dynamics.

To better interpret the trends across use cases, the influences can be distilled into five major determinants that systematically govern delivered electricity cost across technologies and deployment scenarios: (a) time-of-use sensitivity, as reflected in the technology-specific markup structure, since electricity rates vary by time of day and technologies such as fast charging, typically operating during peak periods, incur higher costs due to tariff structures, whereas battery swapping systems can shift charging to off-peak hours to minimize exposure; (b) power intensity and demand charges, as high instantaneous loads increase grid infrastructure requirements and utility-imposed demand charges, with fast charging stations being particularly sensitive under low utilization conditions; (c) system efficiency losses, because pathways with substantial conversion inefficiencies, such as inductive charging or hydrogen production via electrolysis, require more input energy to achieve the same propulsion output; (d) grid integration architecture, since off-grid or hybrid systems often demand oversized buffers, redundancy, and balancing mechanisms that raise both capital and operational expenditures relative to grid-tied solutions; and (e) contractual structures and market access, where long-term power purchase agreements can stabilize costs while retail exposure leaves operators vulnerable to volatility and uncertainty. Collectively, these determinants constitute a generalized framework for evaluating variation in delivered electricity costs across zero-emission freight infrastructure systems, and their interactions are critical for techno-economic modeling as well as for infrastructure planning, tariff design, and policy development aimed at cost-effective electrification of medium- and heavy-duty transport.

5.2 Fuel Cost ($/mile)

The fuel cost per mile is a fundamental operational metric for ZEV technologies, capturing the monetary expenditure required to propel a vehicle over a unit distance. This cost metric arises from the interplay between two core factors: the effective electricity rate, which reflects the adjusted cost of delivered energy accounting for upstream losses, and the energy consumption at the wheels, which is intrinsic to the vehicle's design and performance characteristics. Their relationship is defined as:

$$\text{Fuel Cost}_{\text{per mile}} = \text{Effective Electricity Rate} \times E_{\text{wheels}} \tag{9}$$

$$\text{Effective Electricity Rate} = \frac{\text{Delivered Electricity Cost}}{\eta_{\text{system}}} \tag{10}$$

$$\eta_{\text{system}} = \eta_{\text{WTW}} = \eta_{\text{well-to-tank}} \times \eta_{\text{tank-to-wheel}} \tag{11}$$

where *Fuel Cost*$_{\text{per mile}}$ represents the monetary expenditure required to move a vehicle one mile; *Effective Electricity Rate* is the adjusted cost of electricity accounting for system-level energy conversion losses; *Delivered Electricity Cost* reflects the cost of electricity after incorporating upstream markups such as transmission and distribution fees, storage premiums, demand charges, and time-of-use pricing; η_{system}, or well-to-wheels efficiency, represents the overall energy efficiency of the powertrain system and is defined as the product of well-to-tank efficiency (capturing upstream generation, delivery, and conversion losses) and tank-to-wheel efficiency (reflecting drivetrain and auxiliary system performance);

E_{wheels} denotes the energy consumed per mile at the wheels, typically measured in kWh/mile and determined by vehicle characteristics and drive cycle conditions.

Table 5 summarizes the energy conversion pathways and corresponding well-to-wheel efficiency ranges across the analyzed propulsion architectures. All pathways are evaluated under a consistent well-to-wheel system boundary. Fuel cost per mile is calculated as the product of energy consumption per mile and the corresponding unit energy cost (electricity or hydrogen), with system-level efficiency losses explicitly incorporated into the energy conversion chain to ensure comparability across technologies.

The results reveal that system-level efficiency varies substantially across propulsion pathways, reflecting the cumulative effect of multi-stage energy conversions. Among combustion-based pathways, conventional diesel systems achieve well-to-wheel efficiencies of approximately 28–36%, constrained primarily by upstream refining losses and the thermodynamic limits of internal combustion engines. The addition of onboard carbon capture introduces further energy penalties, reducing overall efficiency to approximately 21–31%. Hydrogen-based pathways also exhibit a wider efficiency range and stronger dependence on upstream energy conversion conditions, due to the inclusion of electrolysis, conditioning, and delivery stages. Hydrogen combustion pathways fall toward the lower end of the efficiency range (approximately 17–27%), as they combine upstream hydrogen production losses with the inherent inefficiency of combustion engines. Fuel cell systems achieve higher efficiency relative to hydrogen combustion, with overall well-to-wheel efficiency ranging from approximately 20–39%. This range partially overlaps with combustion-based pathways, particularly at the upper bound, but remains sensitive to assumptions on hydrogen production, compression, and transport. The multi-stage conversion chain, including electrolysis, compression, transport, and electrochemical conversion, results in substantial cumulative energy losses prior to traction.

By contrast, direct electrification pathways demonstrate significantly higher system-level efficiencies due to their shorter conversion chains. Catenary electric road systems achieve the highest efficiency (approximately 82–89%), enabled by direct grid-to-vehicle power transfer with minimal intermediate conversion. Battery-based pathways exhibit slightly lower efficiencies due to charging and storage losses. Battery swapping achieves approximately 72–82% efficiency, reflecting additional storage and handling stages, while fast charging systems range from approximately 68–80%, with losses dominated by high-power conversion and battery cycling. Inductive electric road systems exhibit comparatively lower efficiency (approximately 62–76%), primarily due to wireless transfer losses and alignment sensitivity.

Table 5. Technology Pathways and Ener gy Efficiency.

Technology	Primary energy pathway	Step efficiencies	WTW efficiency (%)	Key determinants
Catenary ERS (conductive)	Renewable electricity → grid → overhead line → motor	Grid delivery: 94–97%; catenary/pantograph transfer: 95–97%; motor/drivetrain: 92–95%	82–89	Direct electrification with minimal conversion and no onboard storage losses
Battery swapping (managed charging)	Renewable electricity → station storage → battery → motor	Grid delivery: 94–97%; managed charging: 92–95%; battery storage/discharge: 91–94%; motor/drivetrain: 92–95%	72–82	Centralized charging enables load optimization, but adds battery inventory, storage, and handling losses
Battery electric (fast charging)	Renewable electricity → grid → battery → motor	Grid delivery: 94–97%; fast charger conversion: 90–94%; battery charge/discharge: 88–92%; motor/drivetrain: 92–95%	68–80	Few conversion steps; losses dominated by high-power charging, battery cycling, and drivetrain conversion
Inductive ERS (wireless)	Renewable electricity → grid → inductive transfer → motor	Grid delivery: 94–97%; power electronics: 90–94%; wireless transfer/alignment: 80–87%; motor/drivetrain: 92–95%	62–76	Wireless coupling losses and alignment inefficiencies reduce grid-to-wheel efficiency
Hydrogen fuel cell (green H_2)	Renewable electricity → electrolysis → H_2 delivery (CGH_2 or LH_2) → fuel cell → motor	Electrolysis: 62–70%; delivery (CGH_2/LH_2): 60–90%; fuel cell: 55–65%; motor/drivetrain: 92–95%	20–39	Multi-stage conversion losses across electrolysis, hydrogen delivery, and fuel-cell conversion
Conventional diesel	Crude oil → refining → diesel → ICE	Extraction/refining/distribution: 84–90%; engine/drivetrain TTW: 33–40%	28–36	Governed by upstream extraction, refining, and distribution losses, with TTW performance fundamentally limited by combustion thermodynamics
Diesel + onboard CO_2 capture	Crude oil → refining → diesel → ICE + capture/compression	Extraction/refining/distribution: 84–90%; engine/drivetrain TTW: 33–40%; onboard CO_2 capture/compression penalty: 75–85%	21–31	CO_2 capture, compression, added mass, and auxiliary loads reduce effective diesel pathway efficiency
Hydrogen combustion (green H_2)	Renewable electricity → electrolysis → H_2 → conditioning/transport → ICE	Electrolysis: 65–75%; conditioning/storage/transport: 80–90%; H_2 ICE/drivetrain TTW: 32–40%	17–27	Combustion losses combined with upstream hydrogen production and delivery losses

Figure 4 summarizes the modeled fuel cost per mile across seven technologies under three representative freight duty cycles: short-haul (150 mi/day), regional-haul (250 mi/day), and long-haul (500 mi/day). From a ZEV pathway perspective, the results show that hydrogen-based pathways generally exhibit higher per-mile fuel costs than direct electrification options, reflecting upstream energy conversion losses and fuel provisioning costs. Between the two hydrogen pathways, H_2ICEVs consistently incur higher fuel costs than FCEVs at a given hydrogen price, primarily due to lower tank-to-wheel efficiency and higher hydrogen consumption per mile. This difference arises from a combination of thermodynamic limitations of combustion-based systems, efficiency degradation under part-load operation, and additional auxiliary and thermal management losses.

By contrast, catenary electric road systems deliver the lowest operational fuel costs, enabled by continuous on-route power delivery that eliminates the need for large onboard battery capacities and achieves the highest drivetrain efficiency among electric pathways, although corridor-level infrastructure capital requirements are evaluated separately at the system-cost level. Battery swapping ranks second in cost-effectiveness, leveraging centralized depot-based infrastructure to reduce peak demand charges and enable rapid energy replenishment. Across scenarios, battery-swapping systems maintain fuel costs close to those of catenary systems due to comparable drivetrain efficiency and operational flexibility. Fast charging and inductive charging systems also exhibit relatively low fuel cost profiles in 2030. However, their costs tend to be moderately higher than those of catenary and battery-swapping systems due to either grid-integration constraints or lower system efficiency. Fast charging is constrained by localized grid congestion and demand-charge exposure, while inductive charging is penalized by lower energy-transfer efficiency and the added complexity of embedded infrastructure. Among combustion-based pathways, internal combustion engine vehicles with carbon capture and storage generally fall toward the lower end of the cost spectrum in the near term, although their fuel costs remain higher than those of many battery-electric pathways because of lower drivetrain efficiency and additional energy requirements associated with carbon capture and storage.

Looking toward the long term (e.g., 2040), technological learning, improved system integration, and maturing supply chains significantly narrow cost differentials across pathways. Battery-electric technologies converge in fuel cost as improvements in charging infrastructure utilization and vehicle efficiency reduce operational differences among fast charging, battery swapping, and catenary systems. Hydrogen-based pathways experience comparable cost reductions. In particular, FCEV per-mile fuel costs decline by more than 50% relative to 2025, driven by improvements in hydrogen production, distribution, and station utilization. Despite these improvements, hydrogen-based pathways (FCEV and H_2ICEV) generally remain more expensive than battery-electric options due to intrinsic efficiency penalties in hydrogen conversion and use. Combustion-based configurations such as ICE vehicles equipped with carbon capture and storage also improve but remain constrained by fuel conversion inefficiencies and residual carbon capture and transport costs. Across truck applications, similar cost ranking trends are observed across duty cycles, with differences in absolute cost levels primarily driven by daily mileage and total energy demand.

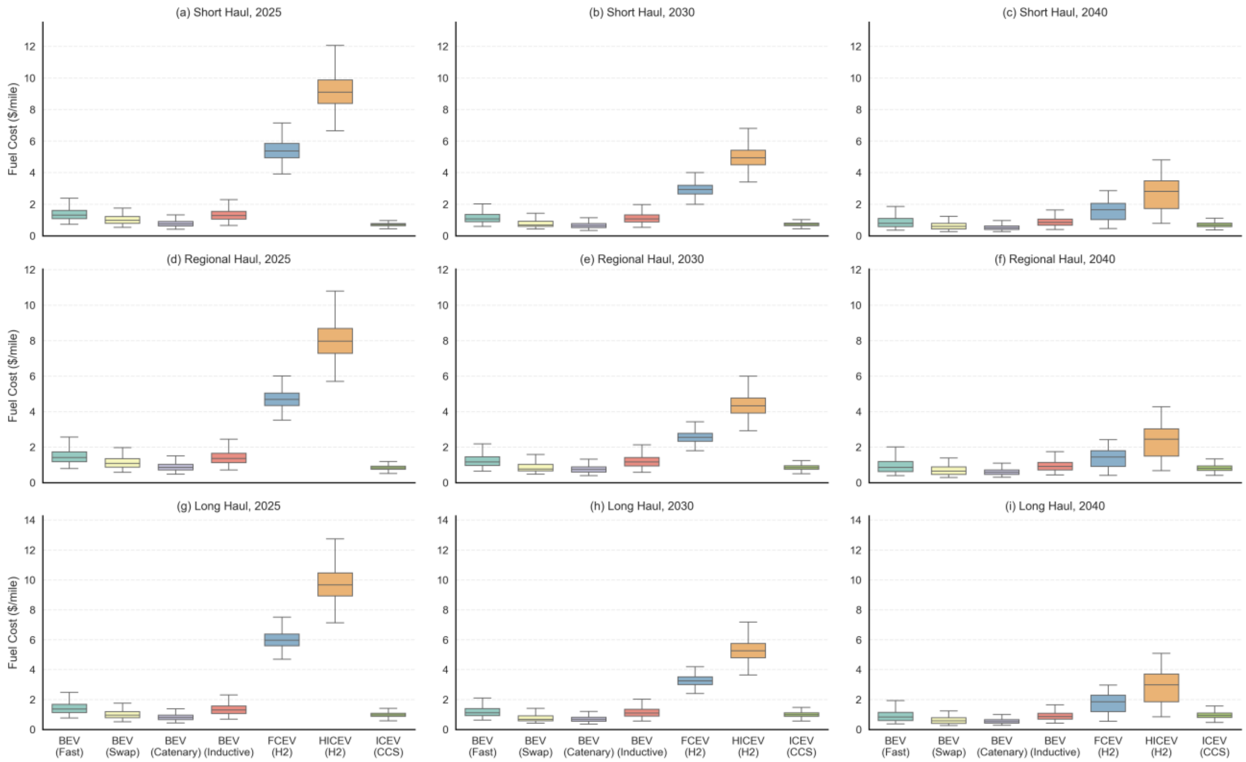


Figure 4. Fuel Costs by Energy Source for ZEV Technologies in Short-, Regional-, and Long-Haul Trucks.

5.3 Levelized System Cost ($/vehicle·year)

The levelized system cost provides a comprehensive metric to assess the annualized infrastructure and operational expenditure per vehicle associated with each ZEV technology pathway (Table 6). The generalized formula is given by:

$$\mathrm{LSC} = \frac{CAPEX_{\mathrm{Infra}} \cdot CRF + C_{\mathrm{maint}}}{N_{\mathrm{fleet}}} + C_{\mathrm{energy}} + C_{\mathrm{other}} \tag{12}$$

where $CAPEX_{infra}$ is the total capital expenditure on infrastructure such as charging stations, refueling depots, or electric road systems; CRF is the capital recovery factor that annualizes capital investments over the assumed infrastructure lifetime and discount rate; C_{maint} denotes the annual maintenance cost of the infrastructure; N_{fleet} is the effective number of vehicles utilizing the infrastructure on a daily or annual basis; C_{energy} represents the annual energy cost per vehicle, accounting for fuel or electricity consumption; and C_{other} includes all other recurring annual costs such as labor, insurance, and administrative overheads.

To operationalize the levelized system cost framework in real-world contexts, we apply a unified four-stage evaluation procedure across all seven propulsion pathways considered in this study. The methodology encompasses feasibility validation, cost annualization, energy cost estimation, and total system cost synthesis. This consistent analytical structure enables comparison of how infrastructure characteristics, energy conversion efficiency, and utilization assumptions influence economic competitiveness across technology classes. Table 6 summarizes representative values for each cost component across ZEV technologies, illustrating how differences in infrastructure complexity, maintenance intensity, and energy delivery mechanisms shape overall system costs under different provisioning pathways.

Table 6. Levelized System Cost of Different ZEV Technologies.

ZEV	CAPEX	O&M Cost	Annual Energy Cost
Battery Fast Charging	Site-host infrastructure including fixed station assets, DC fast chargers (power- and count-based), on-site electrical equipment and installation	Power electronics, cooling systems, grid interface maintenance	Daily vehicle energy × 365 × TOU-weighted delivered electricity cost
Battery Swapping	Swap station civil works, robotic handling system, on-site chargers, battery buffer inventory (capitalized and annualized), station base and marginal scaling	Robotic handling, charging system maintenance	Daily vehicle energy × 365 × delivered electricity cost
Catenary ERS	Corridor electrification infrastructure (per-mile CAPEX), wayside substations, power electronics (annualized)	Overhead lines, substations, grid interface upkeep	Total propulsion energy × 365 × electricity cost
Inductive ERS	Embedded roadway coils, power electronics, roadside substations (per-mile CAPEX)	Embedded coils, power electronics, roadway integration maintenance	Total propulsion energy × 365 × electricity cost
FCEV	Hydrogen refueling station base CAPEX, compressors, storage vessels, dispensers (base + marginal scaling with economies of scale)	Station compression and cooling O&M	Annual H_2 consumption × effective H_2 cost
H_2ICEV	Hydrogen station infrastructure (same structural formulation as FCEV)	Station compression and cooling O&M	Annual H_2 consumption × electricity-derived H_2 cost
ICEV (with CCS)	CCS-equipped fueling station base and dispensers (annualized with scale effect)	Station maintenance, carbon capture and handling systems	Annual diesel use × diesel cost

5.3.1 Battery Fast Charging

Fast charging is an important enabling infrastructure for battery-electric freight transportation, particularly for time-sensitive operations and high-utilization fleet configurations. To rigorously assess the viability of fast charging under real-world conditions, we adopt a structured four-stage framework:

5.3.1.1 Stage 1: Siting Feasibility and Power Adequacy

The technical feasibility of a fast-charging depot hinges on its ability to satisfy the full daily energy demand of the fleet under realistic operational constraints. For a given fleet size *N*, the minimum number of chargers required is preliminarily estimated using:

$$N_{\text{charger}}^{(0)} = \left\lceil \frac{N \cdot E_{\text{daily}}}{P \cdot \text{H}_{\text{year}} \cdot \eta_{\text{charge}}} \right\rceil \tag{13}$$

where E_{daily} is the per-vehicle daily energy demand (kWh), *P* is the rated charger power (kW), and η_{charge} is the charging efficiency. The available charging hours are year-dependent $\text{H}_{\text{year}} \in \{18,20,24\}$ for 2025/2030/2040.

A feasibility check is conducted to ensure that the total energy delivery capacity of the chargers exceeds the total fleet demand, accounting for charging efficiency η_{charge}:

$$N_{\text{charger}} \cdot P \cdot t_{\text{avail}} \cdot \eta_{\text{charge}} \geq N \cdot E_{\text{daily}} \tag{14}$$

If the inequality is not satisfied, additional chargers are incrementally added until the system is technically viable. This iterative validation is embedded directly within the simulation logic, guaranteeing that all reported configurations reflect realizable energy sufficiency under baseline assumptions.

5.3.1.2 Stage 2: Infrastructure Cost Annualization

Capital costs include both charger (Figure 5) and site-specific station infrastructure, including land acquisition. Total capital expenditure is computed as:

$$C_{\text{capex}} = C_{\text{station}} + N_{\text{ch}} \cdot C_P \tag{15}$$

where C_P is the cost of a single charger at power level *P* and C_{station} is the fixed depot cost. These are annualized using a capital recovery factor and maintenance rate r_{maint}:

$$C_{\text{infra}}^{\text{annual}} = C_{\text{capex}} \cdot (CRF + r_{\text{maint}}) \tag{16}$$

where *CRF* reflects the annuitized financing cost based on discount rate and asset lifetime, and r_{maint} is the annualized infrastructure maintenance rate.

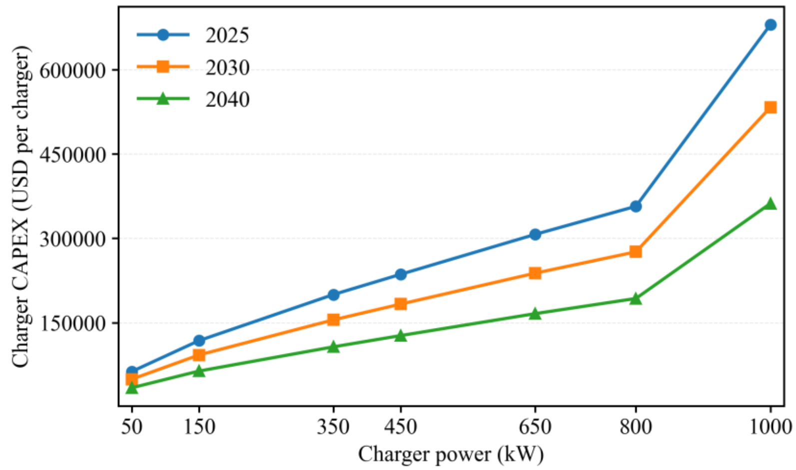


Figure 5. Charger Capital Cost as a Function of Power Rating

5.3.1.3 Stage 3: Energy Cost Estimation and Demand Charges

The annual energy cost per vehicle C_{energy} depends on the electricity cost and daily energy needs:

$$C_{\text{energy}} = p_{\text{eff}} \cdot E_{\text{daily}} \cdot 365 \tag{17}$$

where p_{eff} is directly sampled from year- and source-specific ranges of delivered electricity cost.

Demand charges are also incorporated into the analysis and are calculated as follows:

$$C_{\text{demand}} = N_{\text{charger}} \cdot P \cdot C_{\text{peak}} \tag{18}$$

where C_{peak} is the demand charge per unit of power (in $/kW), and $N_{charger}$ is the number of chargers installed, and P is the rated power of each charger (in kW).

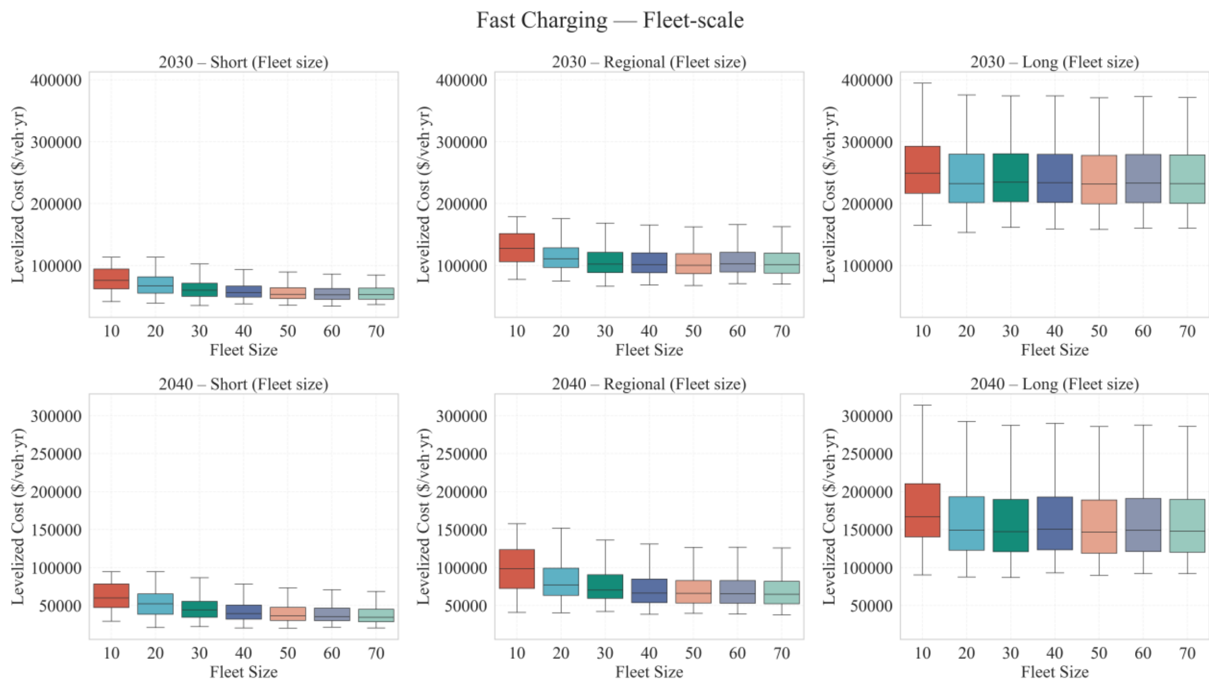
5.3.1.4 Stage 4: Levelized System Cost

The overall levelized system cost aggregates annualized infrastructure burden and energy expenses:

$$C_{\text{LSC, fast charge}} = C_{\text{infra, veh}} + C_{\text{energy, veh}} + C_{\text{demand, veh}} \tag{19}$$

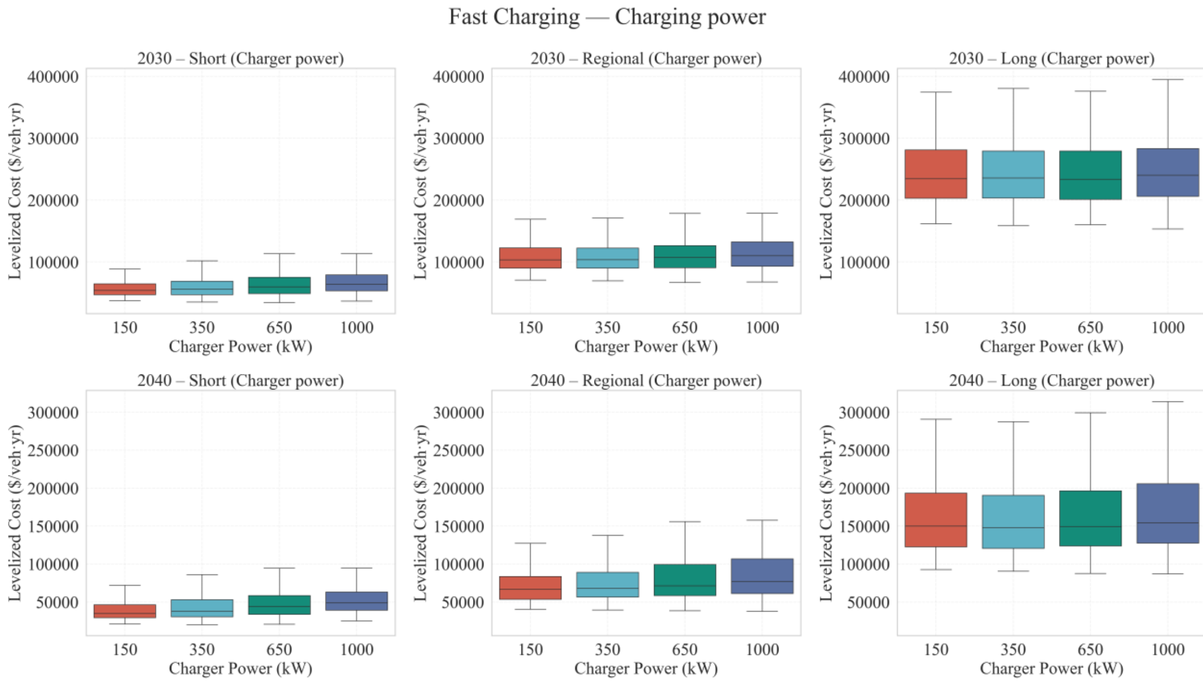
The results are summarized in Figure 6, which decomposes system-cost outcomes into four complementary perspectives: fleet-scale sensitivity, charging-power sensitivity, energy-supply sensitivity, and overall system-cost distributions.

System costs decline systematically as fleet deployment increases (Figure 6a), indicating the role of infrastructure utilization in fast-charging economics. Larger fleets allow charging infrastructure to be shared across more vehicles, thereby reducing the per-vehicle allocation of capital and fixed station costs. This scale effect is observed across all duty cycles and becomes less pronounced when infrastructure utilization approaches steady operational conditions. These results indicate that early-stage deployments with small fleets face higher per-vehicle system costs, whereas coordinated fleet expansion can improve economic performance.



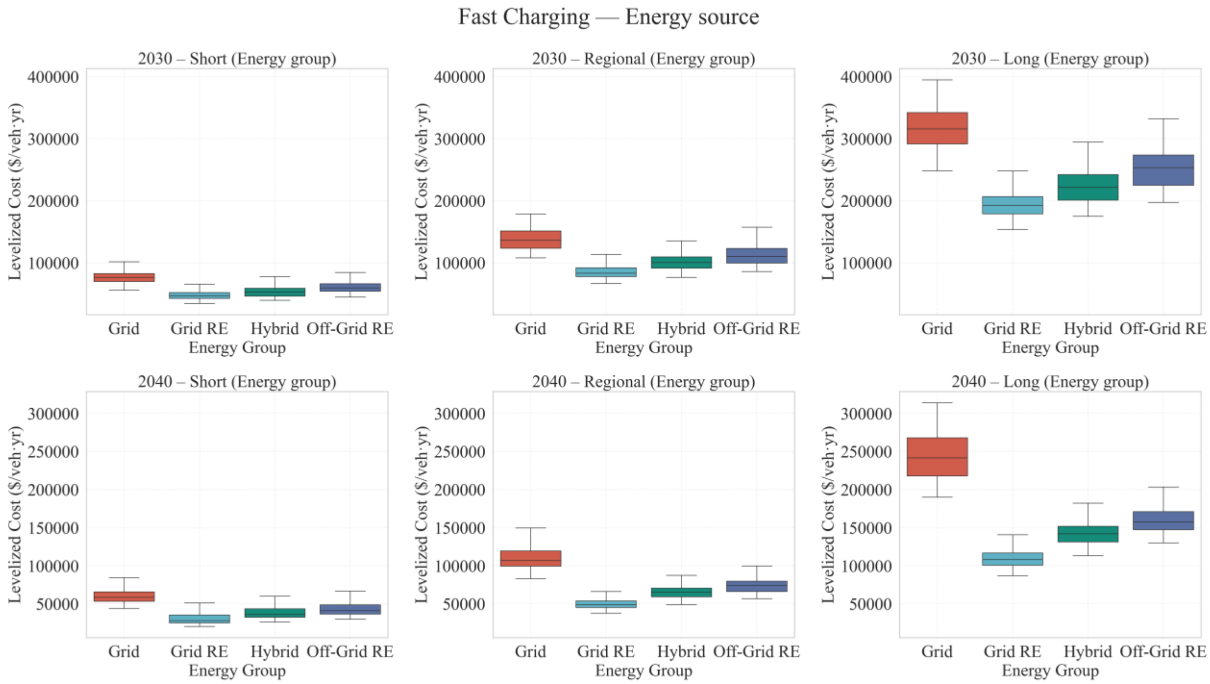
6(a) Fleet-size sensitivity

Charging power selection introduces an important trade off between infrastructure requirements and station level capital intensity (Figure 6b). Higher-power charging systems reduce the number of chargers required to meet fleet energy demand but increase the capital cost and peak-demand exposure associated with each unit. Conversely, lower-power chargers require a larger number of installations to provide equivalent energy throughput, yet the lower equipment costs and reduced exposure to grid demand charges can lead to lower overall system costs under high-utilization conditions. As a result, charging power choices influence overall system costs through their effects on infrastructure utilization, capital allocation, and grid interaction. The optimal charging power level therefore depends on fleet size, charging dwell time, and station utilization conditions.



6(b) Charger-power sensitivity

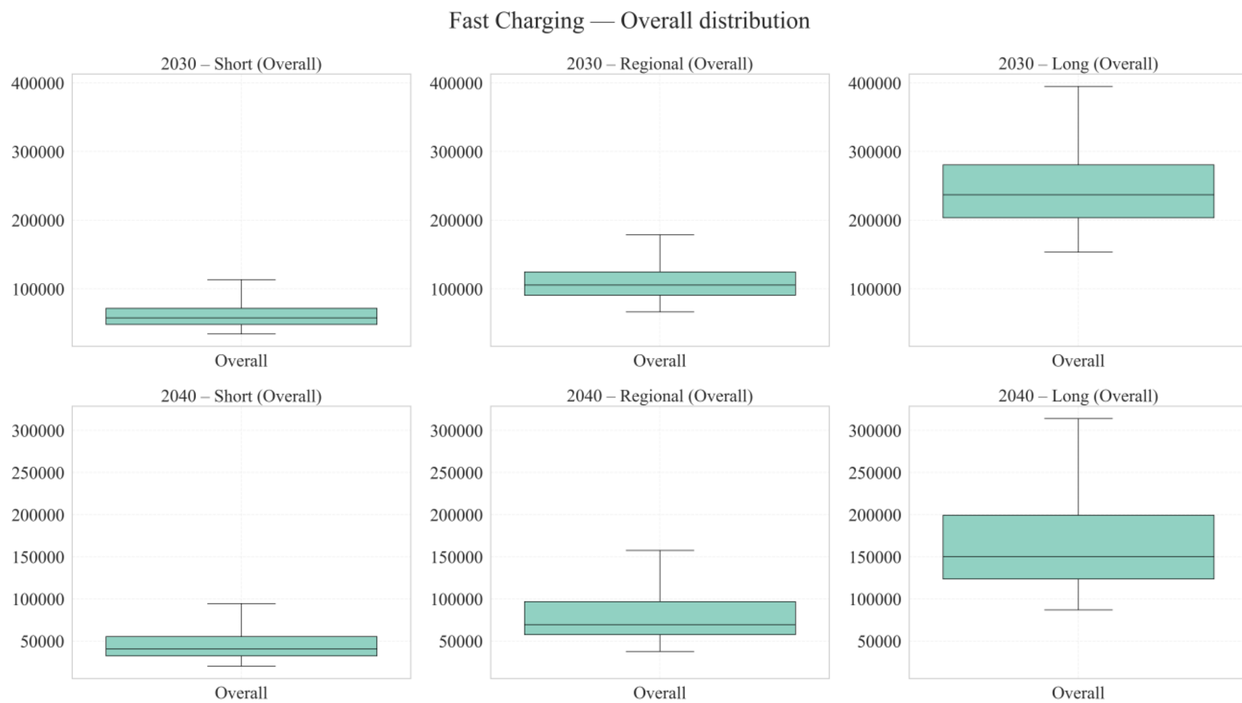
System costs are also strongly shaped by the characteristics of the underlying electricity supply (Figure 6c). Configurations associated with lower and more predictable delivered electricity costs, particularly grid connected renewable electricity, consistently yield lower system costs and narrower cost distributions. In contrast, electricity supply pathways exposed to higher energy prices, demand charges, or infrastructure constraints exhibit wider cost ranges and greater dispersion. These differences persist across duty cycles, underscoring the importance of electricity market conditions in shaping the economics of heavy duty charging infrastructure.



6(c) Energy-supply sensitivity

When these factors are considered jointly, the resulting system cost distributions reveal clear temporal and operational patterns (Figure 6d). Later year scenarios exhibit both lower central cost estimates and narrower cost ranges, reflecting the combined effects of infrastructure learning, technological maturation, and improving electricity supply conditions. Cost outcomes also vary across freight duty cycles. Short haul and regional haul applications tend to achieve relatively stable cost ranges at moderate deployment scales, whereas long haul operations display greater sensitivity to infrastructure configuration and utilization intensity.

Overall, the results indicate that the long term cost competitiveness of battery fast charging for heavy duty freight depends less on vehicle technology in isolation and more on system level alignment among fleet scale, duty cycle, and electricity supply architecture. Effective deployment therefore requires coordinated planning across vehicle adoption, charging infrastructure development, and electricity market integration.



6(d) Overall cost distribution

Figure 6. Levelized System Cost of Battery Fast Charging for Short-Haul, Regional-Haul, and Long-Haul Applications in 2030 and 2040

5.3.2 Battery Swapping

Battery swapping represents a distinct refueling architecture for electric freight, enabling rapid energy replenishment without vehicle-side charging downtime. Instead of charging the battery onboard, the depleted battery is replaced with a fully charged unit at dedicated swapping stations. This architecture supports high vehicle utilization, particularly for logistics fleets operating on fixed schedules. We adopt a four-stage analytical framework that mirrors the fast-charging section:

5.3.2.1 Stage 1: Siting Feasibility and Throughput Adequacy

To ensure technical feasibility, each battery swapping configuration is required to satisfy both vehicle-level energy demand and station-level recharging capacity. The total daily fleet energy requirement is given by:

$$E_{\text{fleet}} = N \cdot E_{\text{daily}} \tag{20}$$

where N is the number of vehicles in the fleet and E_{daily} is the daily energy consumption per vehicle. Battery packs are assumed to be rechargeable over a 24-hour daily charging window. This reflects the asynchronous architecture of battery swapping systems, in which battery exchange and battery recharging occur independently.

The charging infrastructure, whether implemented as on-site charging at the swap station or off-site charging at a dedicated facility, is required to replenish this energy within the daily charging window, which leads to the following estimate of the minimum number of chargers required:

$$N_{\text{charger}} = \left\lceil \frac{E_{\text{fleet}}}{P \cdot t_{\text{avail}}} \right\rceil \tag{21}$$

where P is the rated power of each charger (50–1000 kW), and t_{avail} is the number of operational hours per day for battery charging (24 h).

To ensure service continuity, each battery swapping station maintains a combination of shared buffer packs, charger-associated reserves, and peak-demand safeguards. In practice, the buffer and reserve scale sub-linearly with fleet size, but lower bounds are enforced to prevent under-provisioning. In addition, a peak-swap margin of roughly 10–15% of daily demand is included to handle short-term surges, while payload constraints cap the number of packs moved in each trip. This layered inventory strategy balances cost efficiency with operational resilience and ensures high service availability across fleet sizes.

5.3.2.2 Stage 2: Infrastructure Cost Annualization

The capital expenditure of a battery swapping system includes the cost of battery inventory, charging equipment (deployed either onsite at the swap station or at a dedicated offsite facility), onsite mechanical infrastructure, and associated charging depots, when required. The total investment is:

$$C_{\text{capex}} = C_{\text{battery}} + C_{\text{charger}} + C_{\text{station}} + C_{\text{offsite}} \tag{22}$$

where $C_{\text{battery}}=N_{\text{battery}}\cdot E_{\text{pack}}\cdot c_{\text{battery}}$, with E_{pack} as the battery capacity per pack, and c_{battery} is the year-specific system-level battery cost. Here, system-level battery cost refers to the fully integrated battery pack cost, which includes battery cells, module and pack assembly, thermal management components, mechanical housing, high-voltage wiring, the battery management system, safety hardware, and manufacturing overhead. A uniform 35% markup is applied relative to projected cell-level costs to account for integration, testing, and manufacturing margin, resulting in effective system-level battery pack costs of \$180/kWh (2030) and \$120/kWh (2040) [50]. C_{charger} represents the unit capital cost of a charger (Figure 5). For configurations in which charging is co-located with the swap station, the offsite charging component is zero. The cost of onsite infrastructure includes a fixed baseline investment (e.g., land acquisition, core facility construction) and a scalable component that grows linearly with fleet size to reflect additional vehicle-handling equipment, layout expansion, and utility upgrades. This is expressed as:

$$C_{\text{station}} = C_{\text{base}} + C_{\text{scale}} \cdot N \tag{23}$$

where C_{base} is the fixed capital investment, and C_{scale} represents the marginal infrastructure cost per additional vehicle served.

The annualized infrastructure cost is then computed as:

$$C_{\text{infra, annual}} = CRF \cdot C_{\text{capex}} + r_{\text{maint}} \cdot C_{\text{capex}} \quad (24)$$

where *CRF* is the capital recovery factor and r_{maint} is the annual maintenance rate.

5.3.2.3 Stage 3: Energy and Delivery Cost Estimation

Each vehicle incurs annual electricity cost based on daily energy use and source-/year-specific delivered electricity cost. Electricity cost per vehicle:

$$C_{\text{elec}} = 365 \cdot E_{\text{daily}} \cdot p_{\text{elec}} \quad (25)$$

where p_{elec} is drawn from year and source specific distributions. In addition, a fixed delivery cost, accounting for battery transport, thermal conditioning, and automated swapping logistics, is included as:

$$C_{\text{log,veh}} = 365 \cdot E_{\text{daily}} \cdot p_{\text{log}} \quad (26)$$

where $C_{\text{log,veh}}$ denotes the annual logistics cost per vehicle, and p_{log} represents the logistics cost per unit of delivered energy ($/kWh), accounting for battery transport, handling, and scale-related factors.

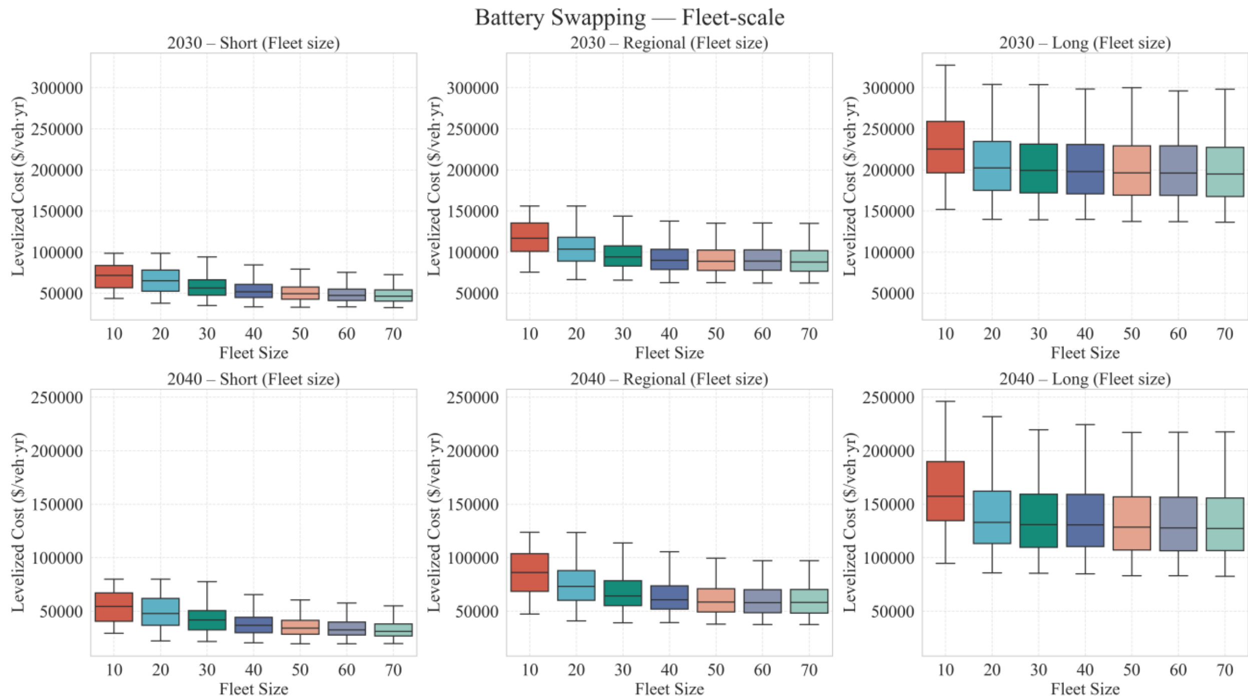
5.3.2.4 Stage 4: Levelized System Cost

The final levelized system cost per vehicle per year is the sum of infrastructure, energy, and delivery costs:

$$C_{\text{LSC, swapping}} = C_{\text{infra, veh}} + C_{\text{batt, veh}} + C_{\text{elec, veh}} + C_{\text{log, veh}} \quad (27)$$

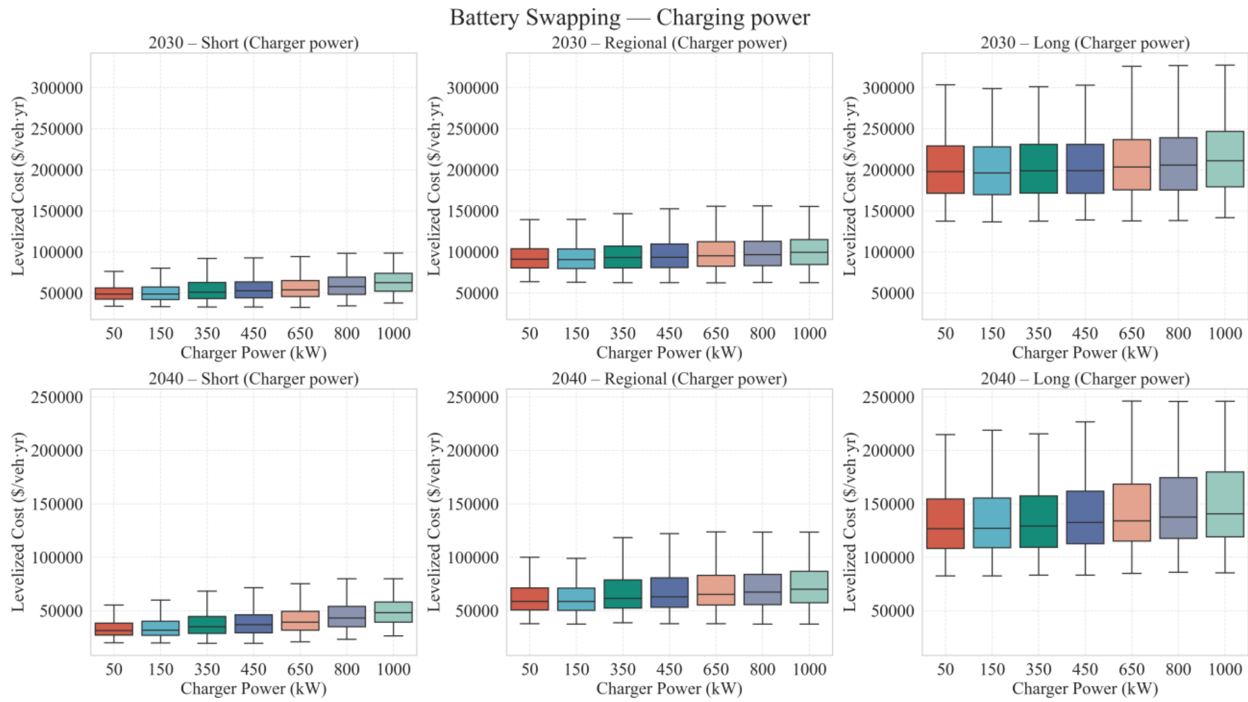
Figure 7 presents the levelized system cost of battery swapping for heavy-duty freight applications across different duty cycles, fleet deployment scales, and electricity supply configurations.

System costs decline systematically as fleet deployment increases (Figure 7a), underscoring the central role of utilization and infrastructure sharing in battery swapping economics. Larger fleets distribute fixed station and balance of plant costs across more vehicles, while higher throughput improves the effective use of swap bays and charging assets. As a result, early stage deployments with small fleets face materially higher per vehicle system costs, whereas coordinated fleet expansion yields rapid cost improvements and more stable outcomes.



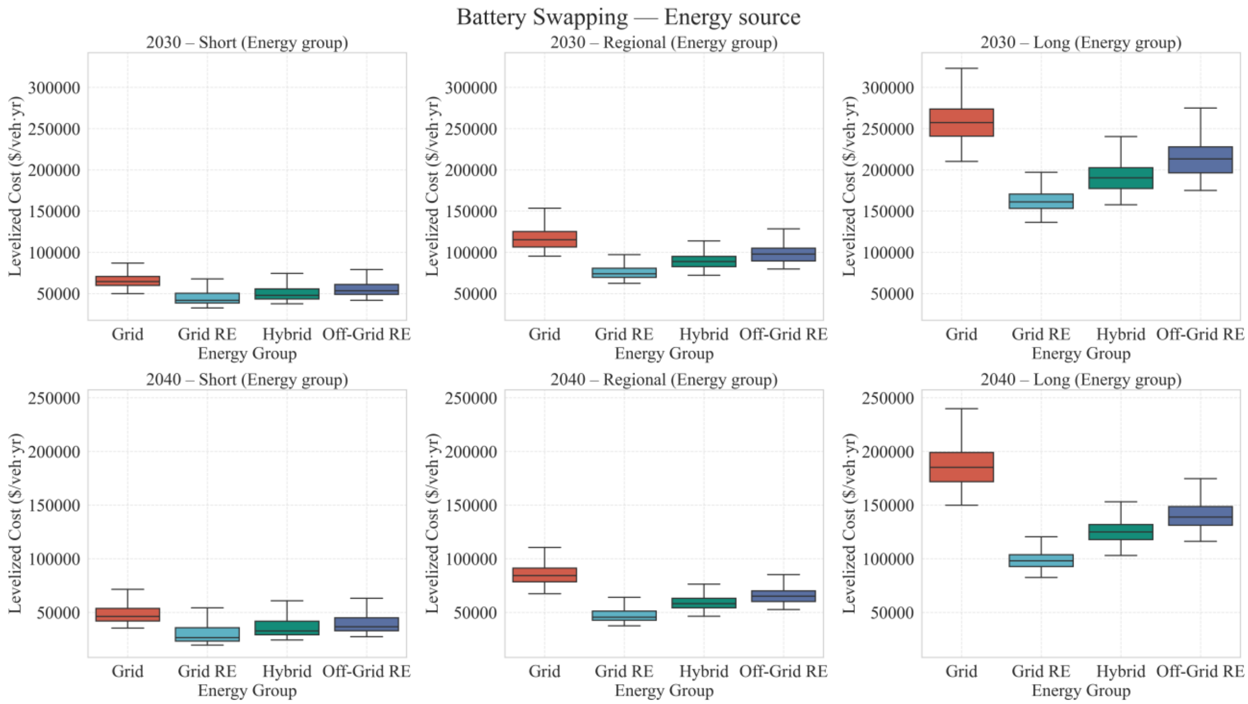
7(a) Fleet-size sensitivity

Charging power affects system costs through a utilization and capital intensity trade off (Figure 7b). Higher power charging reduces the number of chargers required to replenish the battery pool, but increases per unit capital costs and elevates site level power requirements that can amplify interconnection and demand charge exposure. Lower power charging reduces peak power needs but requires more chargers to sustain the same energy throughput. Overall, the results indicate that charging power selection shapes the cost envelope, with higher power levels occasionally associated with higher costs under certain infrastructure utilization conditions.



7(b) Charger-power sensitivity

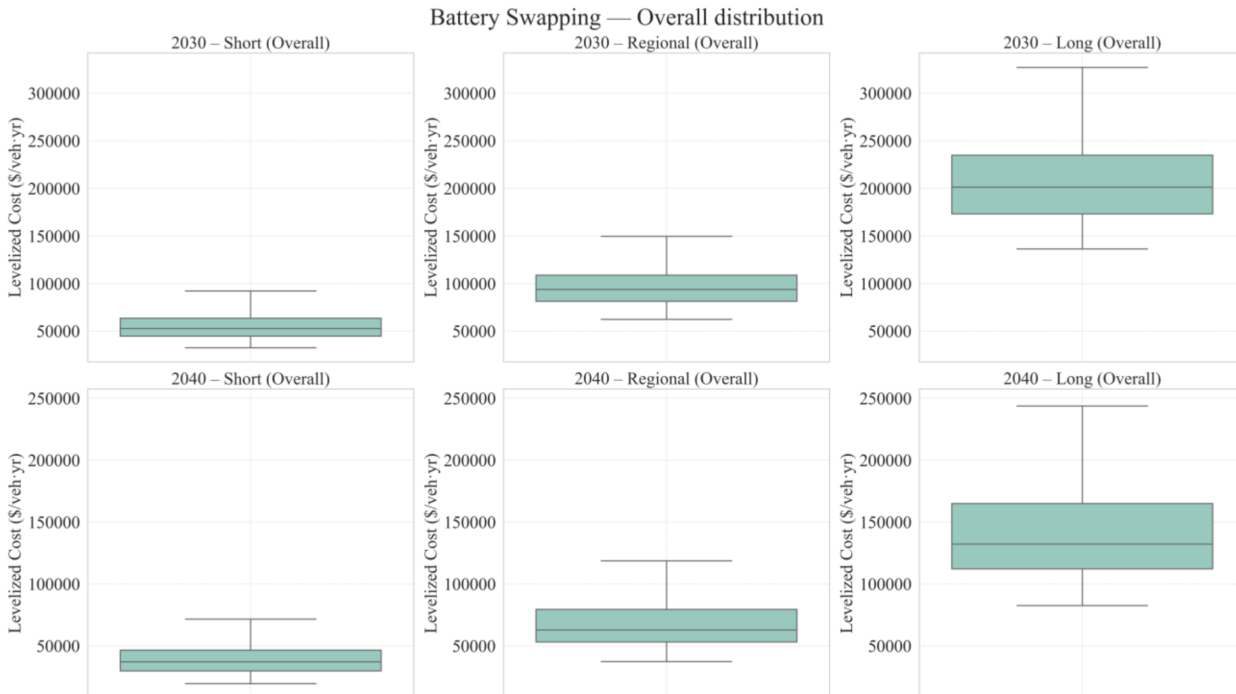
Electricity supply conditions strongly shape both average costs and dispersion (Figure 7c). Supply configurations associated with lower and more predictable delivered electricity prices consistently reduce system costs and compress variability, whereas supply pathways exposed to higher delivered prices, demand charge pressure, or infrastructure constraints exhibit wider cost ranges and greater tail risk. These patterns persist across duty cycles, emphasizing that swapping competitiveness is tightly linked to the delivered electricity price structure rather than to station design choices alone.



7(c) Energy-supply sensitivity

When all sources of scenario variation are considered jointly, the resulting system cost distributions show clear temporal and operational differentiation (Figure 7d). Later year scenarios exhibit both lower central cost estimates and narrower distributions, indicating improved cost stability as infrastructure, supply chains, and operational practices mature. Cost outcomes also differ across freight duty cycles. Short haul and regional haul applications tend to achieve more stable cost ranges at moderate deployment scales, while long haul operations remain more sensitive to configuration and utilization intensity, implying that long haul competitiveness depends more strongly on coordinated, high utilization deployment strategies.

Overall, the results suggest that battery swapping represents a structurally distinct electrification pathway whose economic performance improves disproportionately with higher levels of fleet coordination and system integration. Cost competitiveness is therefore determined less by vehicle technology in isolation and more by alignment among deployment scale, duty cycle demand, and electricity supply architecture, with direct implications for infrastructure planning and policy design in heavy duty transport decarbonization.



7(d) Overall cost distribution

Figure 7. Levelized System Cost of Battery Swapping for Short-Haul, Regional-Haul, and Long-Haul Applications in 2030 and 2040

5.3.3 Catenary Electric Road System

Catenary-based electric road systems represent a corridor-oriented infrastructure option for decarbonizing long-haul freight by enabling continuous in-motion electric power delivery. To comprehensively evaluate their techno-economic viability, we adopt a four-stage analytical framework encompassing feasibility validation, infrastructure cost estimation, annual propulsion energy cost quantification, and integrated cost synthesis through the levelized system cost metric.

5.3.3.1 Stage 1: Feasibility Assessment Based on Energy Sufficiency

The foundational requirement for deploying a catenary system is the ability to reliably deliver sufficient energy to meet vehicle operational demand, particularly on route segments that are not fully covered by overhead lines. The feasibility condition is established by comparing the daily propulsion energy requirement and the net catenary-delivered surplus energy available to charge the battery for off-wire segments:

$$E_{\text{deficit}} = (D_{\text{total}} - D_{\text{cat}}) \cdot e_{\text{mile}} \tag{28}$$

$$E_{\text{cat}} = P_{\text{charge}} \cdot \eta \cdot \left(\frac{D_{\text{cat}}}{v_{\text{avg}}} \right) \tag{29}$$

where D_{total} and D_{cat} denote total and catenary-covered daily miles respectively, e_{mile} is energy consumption per mile, P_{charge} is power transfer capacity of the pantograph system, η is system efficiency, v_{avg} is average driving speed. The configuration is feasible only if the catenary surplus can cover the off-wire energy need:

$$\max(0, P_{cat}\eta - e_{mile}v_{avg}) \cdot \frac{D_{cat}}{v_{avg}} \geq (D_{total} - D_{cat})e_{mile} \tag{30}$$

5.3.3.2 Stage 2: Infrastructure Cost Annualization

Capital expenditure is proportional to the route length electrified, while maintenance is modeled as a fixed fraction of CAPEX:

$$CAPEX_{cat} = C_{cat/mile} \cdot D_{cat} \tag{31}$$

$$C_{infra} = CAPEX_{cat} \cdot CRF \tag{32}$$

$$C_{maint} = CAPEX_{cat} \cdot r_{maint} \tag{33}$$

where $C_{cat/mile}$ denotes the unit catenary cost, set at \$4.1 million per mile in 2025 for a 300 kW reference configuration [22], scaling with installed power as $(P/300\ \text{kW})^{0.85}$, and decline at an assumed rate of 2.0% per year. *CRF* is the capital recovery factor derived from financing assumptions, r_{maint} is the maintenance rate. These annual costs are then allocated across the operating fleet, yielding a per-vehicle infrastructure cost burden:

$$C_{infra,\ veh} = \frac{C_{infra} + C_{maint}}{N_{fleet}} \tag{34}$$

where N_{fleet} is the size of the served fleet.

5.3.3.3 Stage 3: Electricity Cost Estimation

The annual propulsion electricity cost is calculated based on the total daily energy demand, multiplied by the effective electricity cost:

$$E_{annual} = E_{deficit} \cdot 365 \tag{35}$$

$$C_{energy} = p_{elec} \cdot E_{annual} \tag{36}$$

where p_{elec} denotes the effective electricity cost (e.g., source-dependent/region-specific).

5.3.3.4 Stage 4: Levelized System Cost

Sensitivity analyses are conducted by varying parameters such as catenary coverage, charging power, fleet size, and electricity pricing to evaluate system scalability and policy responsiveness. To facilitate such comparisons, the total per-vehicle cost is formulated using a levelized system cost framework that incorporates infrastructure amortization and supplemental energy expenditures. Specifically, the levelized system cost for catenary-based systems is defined as:

$$\mathrm{LSC}_{\text{catenary}} = \left(\frac{C_{\text{cat/mile}} \cdot D_{\text{cat}} \cdot (CRF + r_{\text{maint}})}{N_{\text{fleet}}} \right) + (E_{\text{deficit}} \cdot 365 \cdot P_{\text{elec}}) \tag{37}$$

$$\text{subject to } E_{\text{cat}} \geq E_{\text{deficit}} \tag{38}$$

where $C_{\text{cat/mile}}$ is the capital cost per mile of catenary infrastructure, D_{cat} is the daily catenary-covered distance, *CRF* is the capital recovery factor, r_{maint} is the annual maintenance rate, and N_{fleet} is the number of vehicles served. The supplemental energy cost is defined by the product of the annual residual energy demand and the effective electricity cost. The system is deemed technically feasible only if the catenary can deliver sufficient in-motion energy to satisfy propulsion demands over uncovered segments, defined by the constraint:

$$E_{\text{cat}} = \frac{P_{\text{charge}} \cdot \eta \cdot D_{\text{cat}}}{v_{\text{avg}}} \geq E_{\text{deficit}} = (D_{\text{total}} - D_{\text{cat}}) \cdot e_{\text{mile}} \tag{39}$$

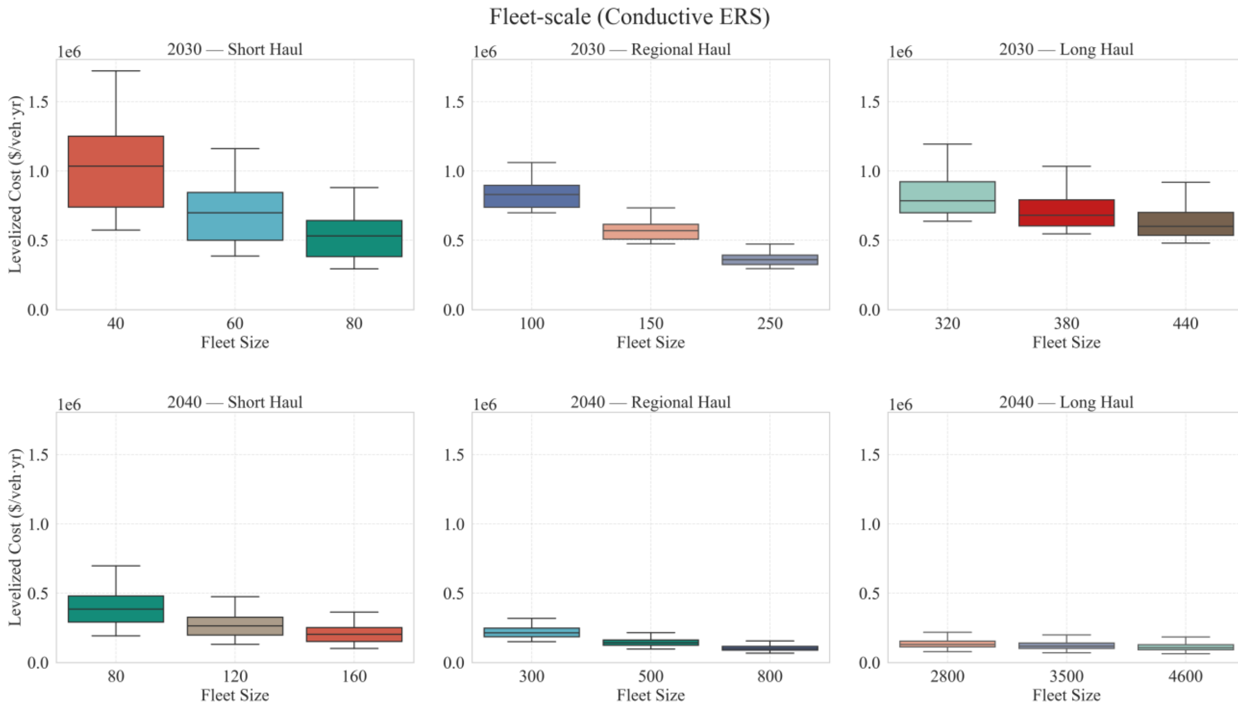
This formulation enables systematic comparisons across deployment conditions and underpins the scenario-based sensitivity analysis conducted for two temporal benchmarks: an early deployment year (2030) and a mature infrastructure horizon (2040).

In short, the levelized system cost of the catenary electric road system can be expressed as:

$$C_{\text{LSC, catenary}} = C_{\text{infra, veh}} + C_{\text{energy, veh}} \tag{40}$$

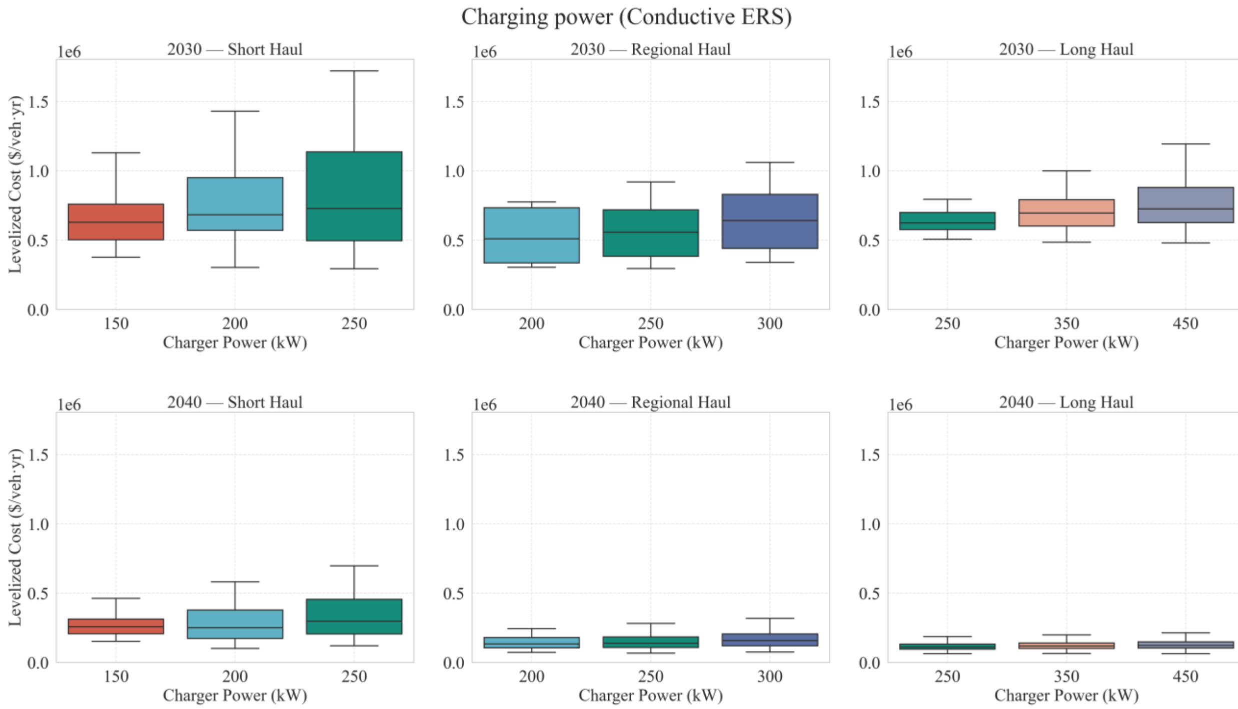
where $C_{\text{infra,veh}}$ represents the portion of infrastructure capital and maintenance costs allocated to each vehicle on an annual basis (\$/veh·yr); $C_{\text{energy,veh}}$ denotes the annual cost of electricity consumption per vehicle (\$/veh·yr).

Results across key operational and infrastructural dimensions are summarized in Figure 8a to Figure 8f, with each subfigure presented as a single page to enable direct cross time comparison between 2030 and 2040 for short haul, regional haul, and long haul applications. Across all duty cycles, the results indicate that conductive electric road systems are primarily shaped by deployment scale and corridor design in earlier years, while operational energy conditions become more influential as the system matures. System costs exhibit strong scale dependence in 2030 (Figure 8a). Small fleets face markedly higher per vehicle costs because corridor capital expenditures and associated fixed costs cannot be amortized over sufficient utilization. As fleet size increases, the levelized system cost declines sharply, reflecting economies of scale and improving corridor utilization. By 2040, the marginal benefit of additional fleet scale diminishes and cost curves flatten, indicating that once corridor assets are highly utilized, further fleet expansion yields smaller incremental reductions in per vehicle cost.



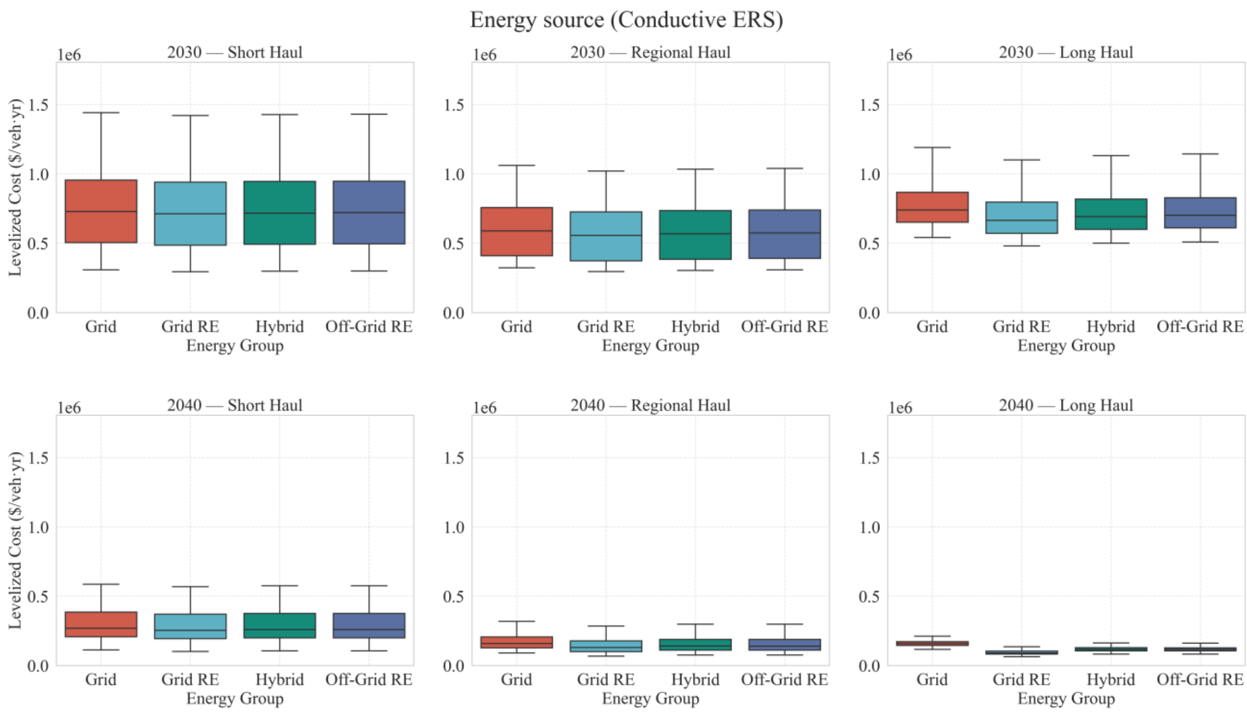
8(a) Fleet-size sensitivity

Charging power also exerts a substantial influence on cost outcomes (Figure 8b), particularly under low utilization rates (e.g., short-haul and regional-haul operations considered in this study). Higher power enables greater energy transfer per unit time during catenary operation and can reduce the electrified road length required to satisfy vehicle energy balance constraints. However, higher power levels also increase corridor costs per mile due to power-dependent infrastructure scaling. As a result, the cost envelope reflects a trade-off between power-driven corridor cost escalation and the operational benefit of sufficient in-motion energy delivery. This effect becomes more pronounced under low corridor utilization conditions, where infrastructure costs are distributed across fewer vehicles.



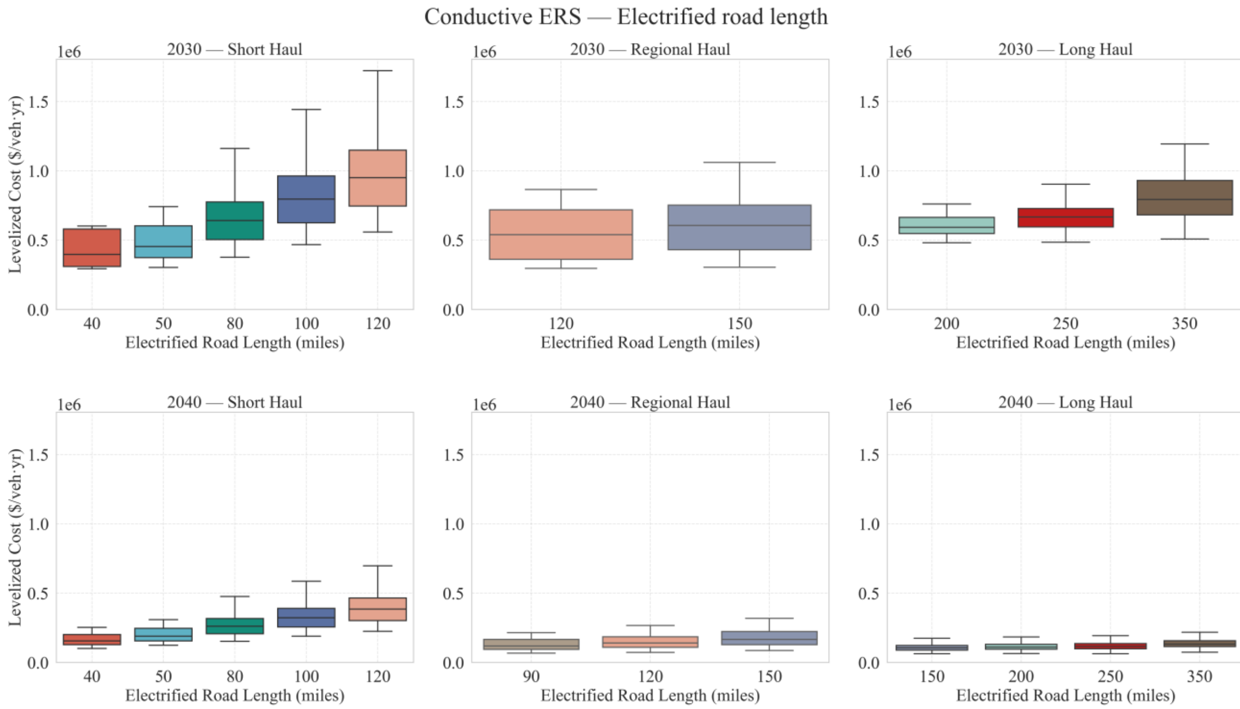
8(b) Charger-power sensitivity

Electricity supply conditions have limited leverage in 2030 (Figure 8c), when corridor capital costs dominate the levelized system cost. Under these conditions, grid electricity and renewable-based pathways yield broadly comparable outcomes because the energy cost component occupies a relatively small share of the total levelized system cost. By 2040, as fleet sizes increase, such as in long-haul truck application scenarios, electricity source becomes more consequential as delivered electricity costs decline and diversify, increasing the relative importance of operational energy pricing in the total cost composition. This temporal shift indicates that energy procurement strategies become more relevant after corridor cost reductions and utilization improvements have been realized.



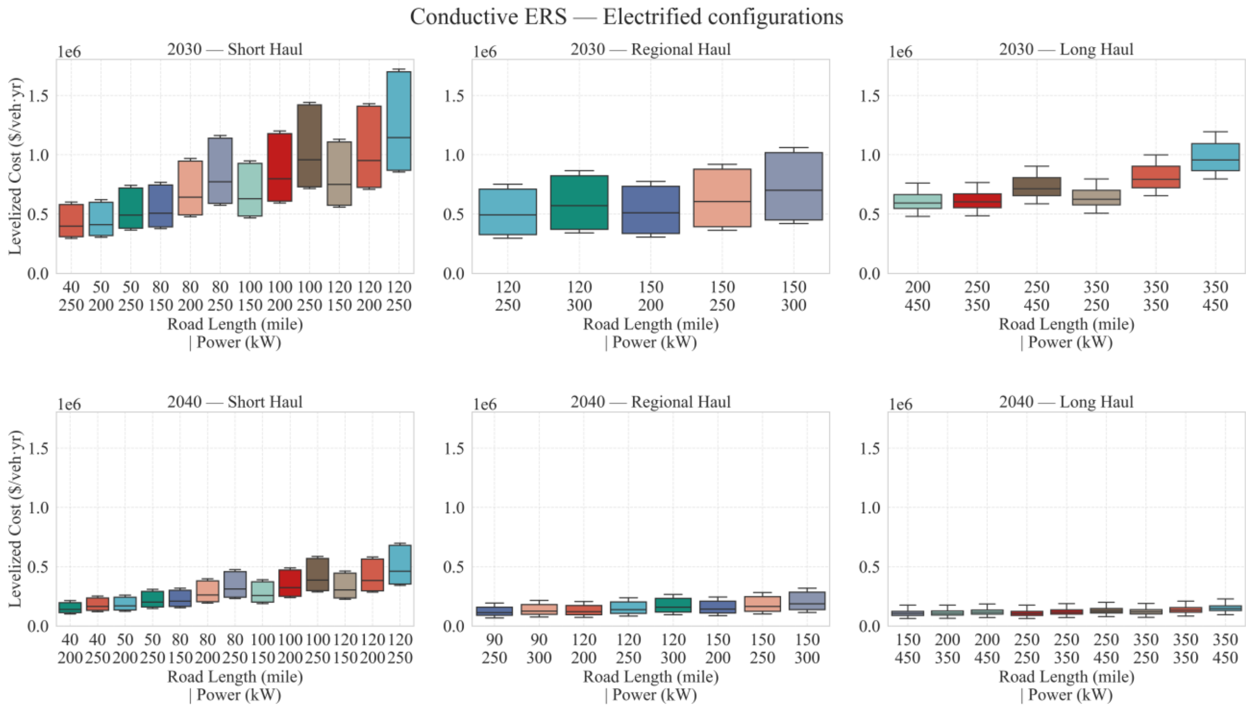
8(c) Energy-supply sensitivity

Electrified road length is one of the major driver of cost for trucks applicaitons (Figure 8d). Increasing corridor length leads to substantial increases in levelized system cost, consistent with the capital-intensive nature of extending electrified infrastructure over longer routes. The sensitivity is especially pronounced for short-haul applications under low utilization rates, where infrastructure costs are distributed across fewer vehicles and operating miles. This result suggests that corridor prioritization and targeted segment electrification are important for cost control, particularly during early deployment stages.



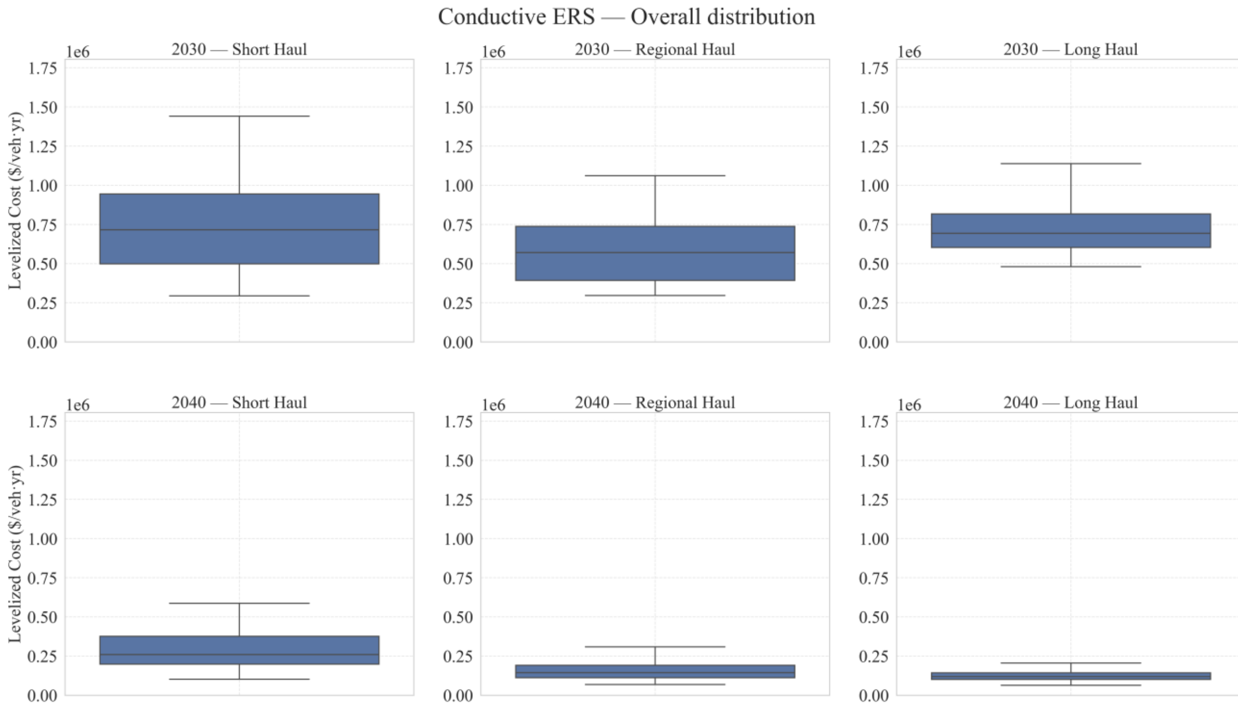
8(d) Electrified road length

Joint configuration effects reveal a consistent interaction between charging power and electrified road length (Figure 8e). Configurations that pair higher charging power with shorter electrified segments tend to reduce levelized system costs because they can satisfy energy balance constraints with less corridor build-out while avoiding the capital burden associated with longer electrified corridors. Conversely, lower-power configurations often require longer electrified segments to achieve feasibility, which can increase costs rapidly. The interaction is utilization-dependent, with long-haul cases exhibiting greater sensitivity due to higher power demand and longer daily mileage.



8(e) Electrified configurations

These sensitivities translate directly into the overall uncertainty envelope (Figure 8f). In 2030, the levelized system cost distribution is broad, reflecting the outsized influence of design choices related to fleet scale, corridor length, and feasible power length combinations under early deployment conditions. By 2040, the distribution compresses substantially across all duty cycles, indicating improved cost stability as corridor costs decline, charging efficiency improves, and high utilization becomes more attainable. Although no single globally optimal configuration emerges across the full sensitivity space, many 2040 scenarios converge toward comparably low costs, implying greater deployment flexibility provided that electrification is focused on well planned, high throughput freight corridors.



8(f) Overall cost distribution

Figure 8. Levelized System Cost of Catenary Electric Road for Short-Haul, Regional-Haul, and Long-Haul Applications in 2030 and 2040

5.3.4 Inductive Electric Road System

Inductive in-motion charging (dynamic wireless power transfer) represents a novel approach to decarbonizing heavy-duty transportation by embedding power transmitters beneath roadways, enabling continuous energy transfer to equipped vehicles. To evaluate the viability and economic competitiveness of this technology, we adopt a structured four-stage framework that integrates feasibility validation, infrastructure cost allocation, operational energy expenditure estimation, and final levelized system cost computation.

5.3.4.1 Stage 1: Feasibility Assessment Based on Energy Sufficiency

The first step examines whether inductive charging can deliver sufficient real-time power to reduce or eliminate reliance on onboard battery charging. Feasibility is determined by comparing the energy delivered via inductive segments to the vehicle's total residual propulsion energy demand:

$$E_{\text{ind}} = \frac{P_{\text{ind}} \cdot \eta \cdot D_{\text{ind}}}{v_{\text{avg}}} \quad (41)$$

$$E_{\text{deficit}} = (D_{\text{total}} - D_{\text{ind}}) \cdot e_{\text{mile}} \quad (42)$$

where D_{total} refers to the vehicle's total daily driving distance, D_{ind} is the length of inductive roadway traversed daily, v is average vehicle speed, P_{ind} is rated charging power per vehicle, and η is system transfer efficiency. The configuration is considered feasible only if the delivered energy equals or exceeds the vehicle's battery requirement over non-inductive segments. This criterion ensures system-level reliability and forms the basis for subsequent cost assessment.

5.3.4.2 Stage 2: Infrastructure Cost Annualization

Inductive systems involve substantial embedded infrastructure, including roadway modifications, coil embedding, and control electronics, which are amortized over time.

The total capital expenditure is estimated as a function of inductive miles deployed, with unit costs defined at $6.5 million per mile in 2025 (100 kW reference) [51], scaling with installed power as $(P/100\ \text{kW})^{0.80}$, while annual maintenance is modeled as a fixed proportion of CAPEX:

$$CAPEX_{\text{ind}} = C_{\text{ind/mile}} \cdot D_{\text{ind}} \tag{43}$$

$$C_{\text{infra}} = CAPEX_{\text{ind}} \cdot CRF\sqrt{a^2 + b^2} \tag{44}$$

$$C_{\text{maint}} = CAPEX_{\text{ind}} \cdot r_{\text{maint}} \tag{45}$$

These infrastructure costs are then apportioned per vehicle across the served fleet:

$$C_{\text{infra, veh}} = \frac{C_{\text{infra}} + C_{\text{maint}}}{N_{\text{fleet}}} \tag{46}$$

This per-vehicle burden reflects both the capital recovery and upkeep of the embedded inductive system.

5.3.4.3 Stage 3: Electricity Cost Estimation

Even with inductive charging, vehicles require additional onboard energy for portions of the trip not covered by inductive segments. The annual energy cost is calculated by scaling daily propulsion energy to annual mileage and applying prevailing electricity prices:

$$E_{\text{annual}} = D_{\text{total}} \cdot e_{\text{mile}} \cdot 365 \tag{47}$$

$$C_{\text{energy}} = E_{\text{annual}} \cdot P_{\text{elec}} \tag{48}$$

This captures the recurring operational cost associated with electricity consumption, which remains a key driver of total cost despite infrastructure deployment.

5.3.4.4 Stage 4: Levelized System Cost

The levelized system cost for inductive electric road configurations combines the amortized infrastructure cost and the ongoing energy expenditure per vehicle. This comprehensive formulation enables rigorous cross-technology comparisons with other electrification strategies such as catenary systems or battery swapping, supporting techno-economic evaluation across varying capital intensities, operational requirements, and deployment feasibility. Moreover, the framework can be readily adapted for scenario analysis under different assumptions of inductive coverage, power level, traffic density, or electricity pricing. The levelized system cost for inductive systems is formally expressed as:

$$\mathrm{LSC}_{\mathrm{inductive}} = \left(\frac{C_{\mathrm{ind/mile}} \cdot D_{\mathrm{ind}} \cdot (CRF + r_{\mathrm{maint}})}{N_{\mathrm{fleet}}} \right) + (E_{\mathrm{deficit}} \cdot 365 \cdot P_{\mathrm{elec}}) \tag{49}$$

$$\text{subject to } E_{\mathrm{ind}} \geq E_{\mathrm{deficit}} \tag{50}$$

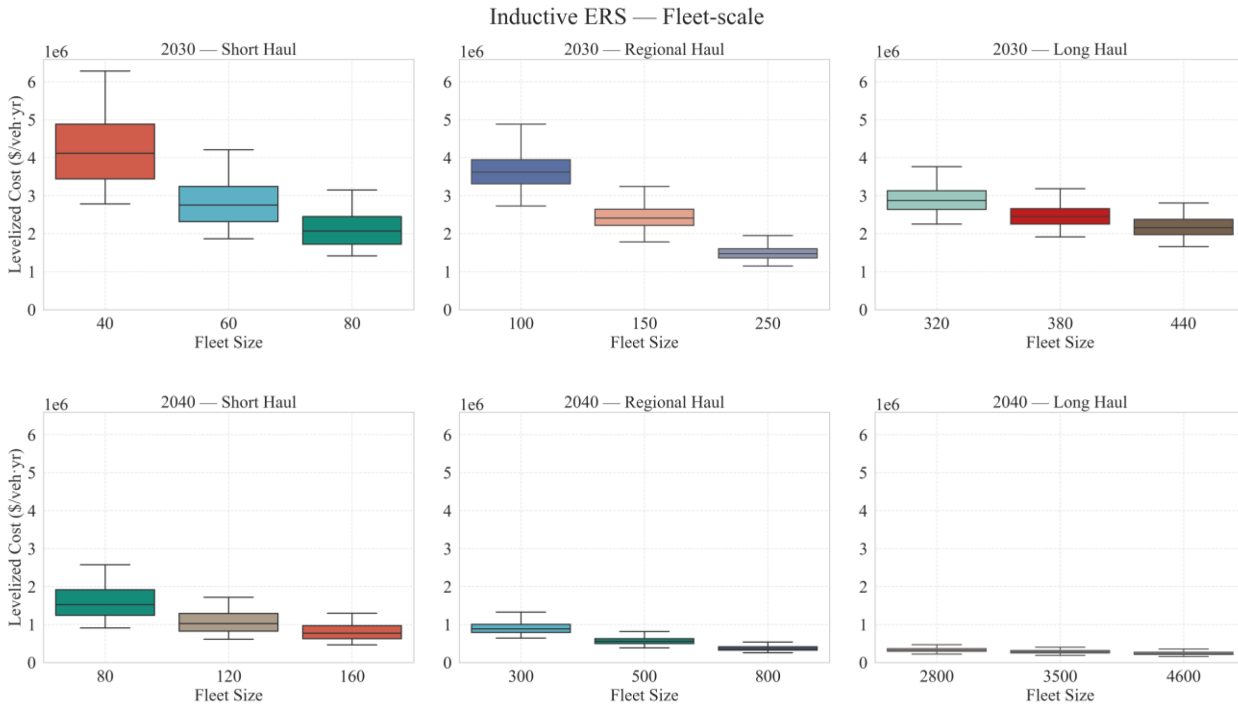
where $C_{ind/mile}$ is the unit capital cost of embedded inductive infrastructure per mile, D_{ind} is the daily inductive road distance covered by the vehicle, *CRF* is the capital recovery factor, and r_{maint} denotes the annual maintenance rate. N_{flee}t is the effective number of vehicles utilizing the infrastructure. The term E_{supp} represents the residual annual energy demand not covered by inductive charging, and p_{elec} is the applicable electricity cost for supplementary energy provisioning. The feasibility of an inductive configuration is ensured by satisfying the condition.

In short, the levelized system cost of the inductive electric road system can be expressed as:

$$C_{\mathrm{LSC,\ inductive}} = C_{\mathrm{infra,\ veh}} + C_{\mathrm{energy,\ veh}} \tag{51}$$

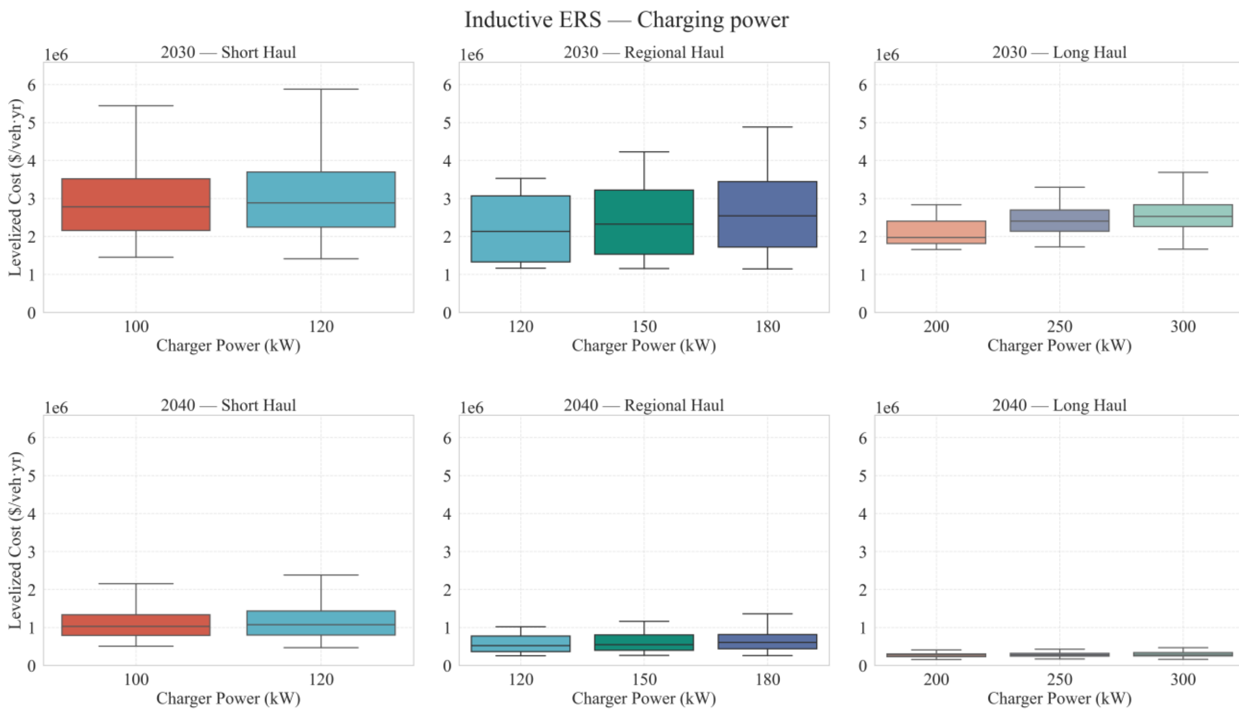
where $C_{infra,veh}$ represents the annualized infrastructure cost allocated per vehicle (\$/veh·yr); $C_{energy,veh}$ denotes the annual energy cost per vehicle (\$/veh·yr).

Figure 9 presents a comparative sensitivity analysis of the levelized system cost of inductive electric road systems under intermediate deployment conditions in 2030 and more mature system configurations in 2040. System costs exhibit strong scale dependence across both years (Figure 9a). In 2030, small fleets face substantially higher per vehicle costs because the capital expenditures associated with embedded inductive infrastructure must be distributed across a limited number of vehicles. As fleet size increases, per vehicle costs decline rapidly as infrastructure utilization improves. By 2040, the marginal cost benefit of additional fleet expansion becomes less pronounced, indicating that once corridor infrastructure is sufficiently utilized, further increases in fleet size yield diminishing reductions in system cost.



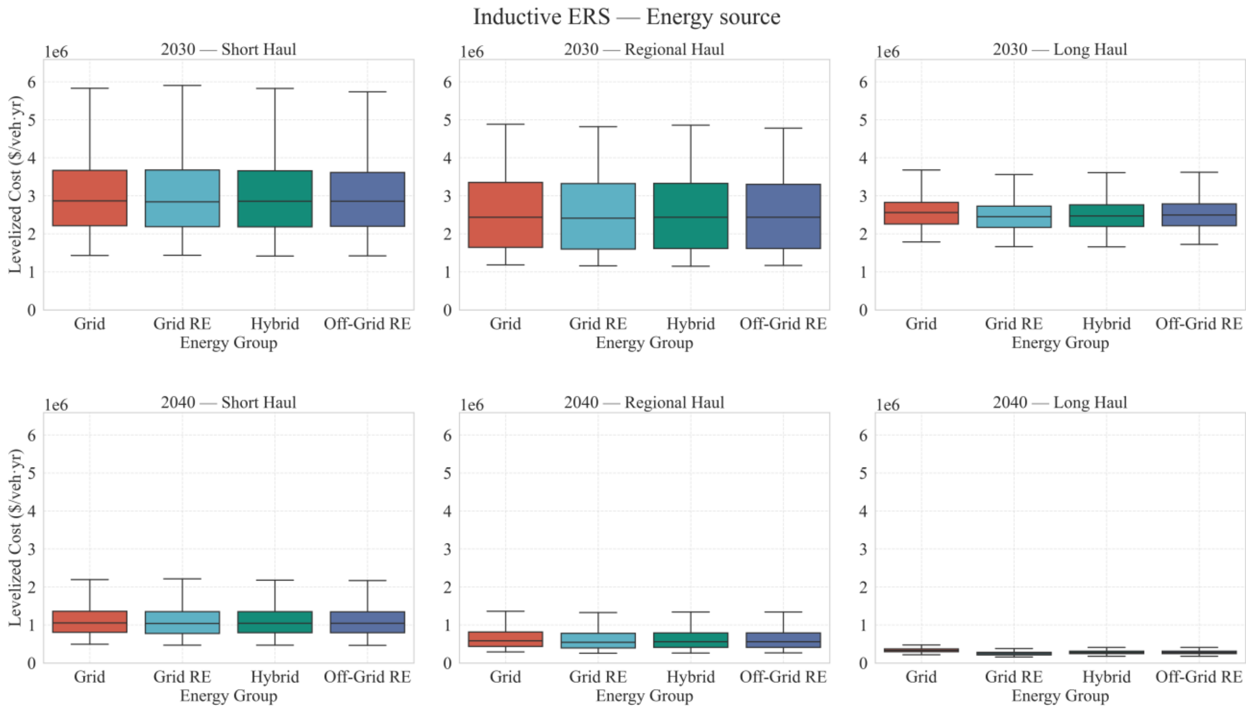
9(a) Fleet-size sensitivity

Wireless charging power influences system costs through a trade off between energy transfer capability and infrastructure requirements (Figure 9b). Higher power levels allow greater energy transfer during in-motion charging and can reduce the minimum electrified roadway length needed to satisfy vehicle energy balance constraints. However, higher-power inductive systems also require more complex and costly embedded infrastructure, which offsets some of these operational advantages. As a result, cost outcomes vary across power levels, reflecting the combined effects of infrastructure scale, utilization conditions, and technology-specific infrastructure complexity.



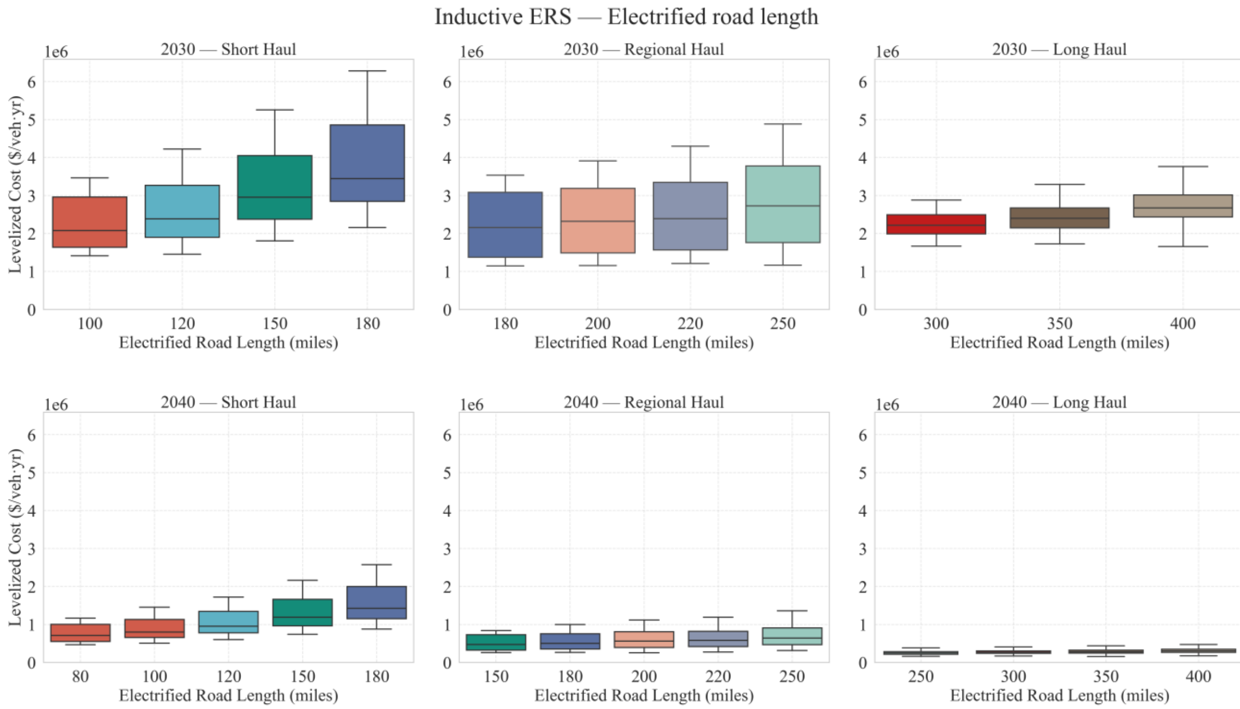
9(b) Charger-power sensitivity

Electricity supply conditions exert relatively limited influence on total system cost in earlier deployment stages (Figure 9c). In 2030, the difference between grid electricity and renewable electricity pathways produces only modest variation in levelized system cost because infrastructure capital recovery dominates total cost. By 2040, as infrastructure costs decline and operational efficiency improves, electricity pricing begins to play a somewhat larger role, although its impact remains smaller than that of infrastructure related parameters.



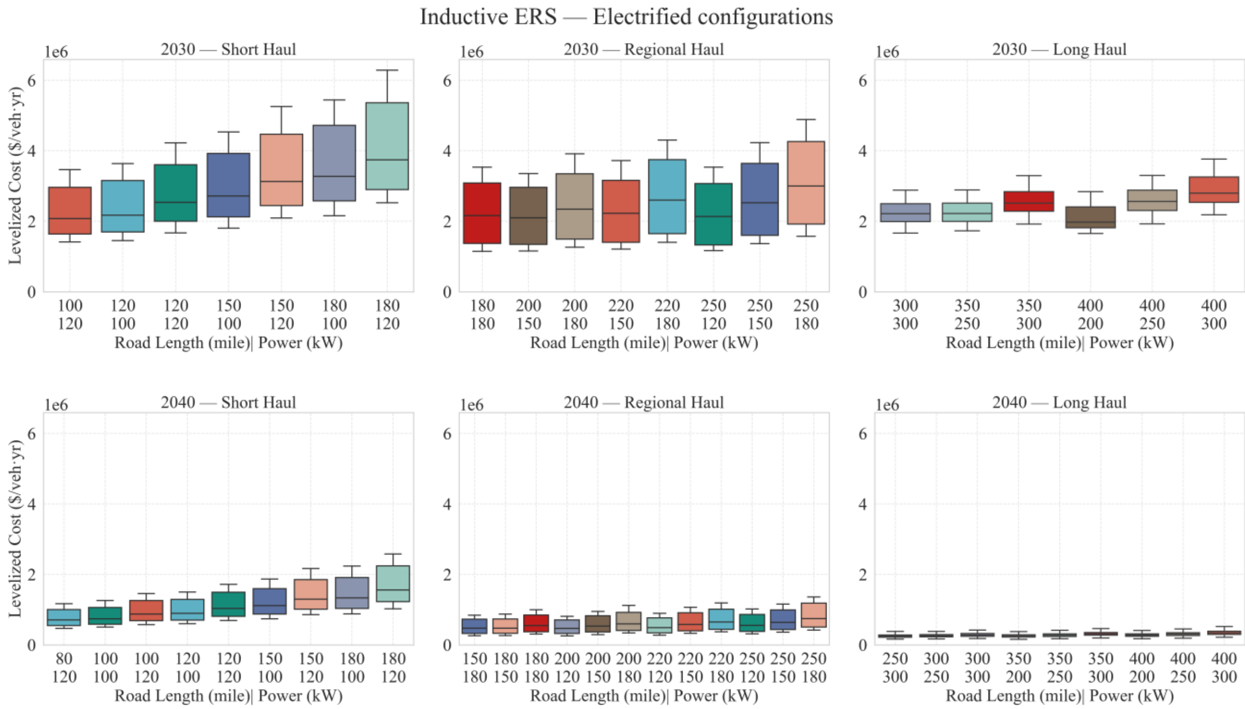
9(c) Energy-supply sensitivity

Electrified roadway length emerges as a dominant cost driver across all duty cycles (Figure 9d). Extending the embedded inductive infrastructure over longer road segments leads to steep increases in levelized system cost because of the high unit capital cost per mile of inductive roadway. This sensitivity is especially pronounced for long haul operations, where longer travel distances require extensive electrified corridors to maintain energy balance during operation.



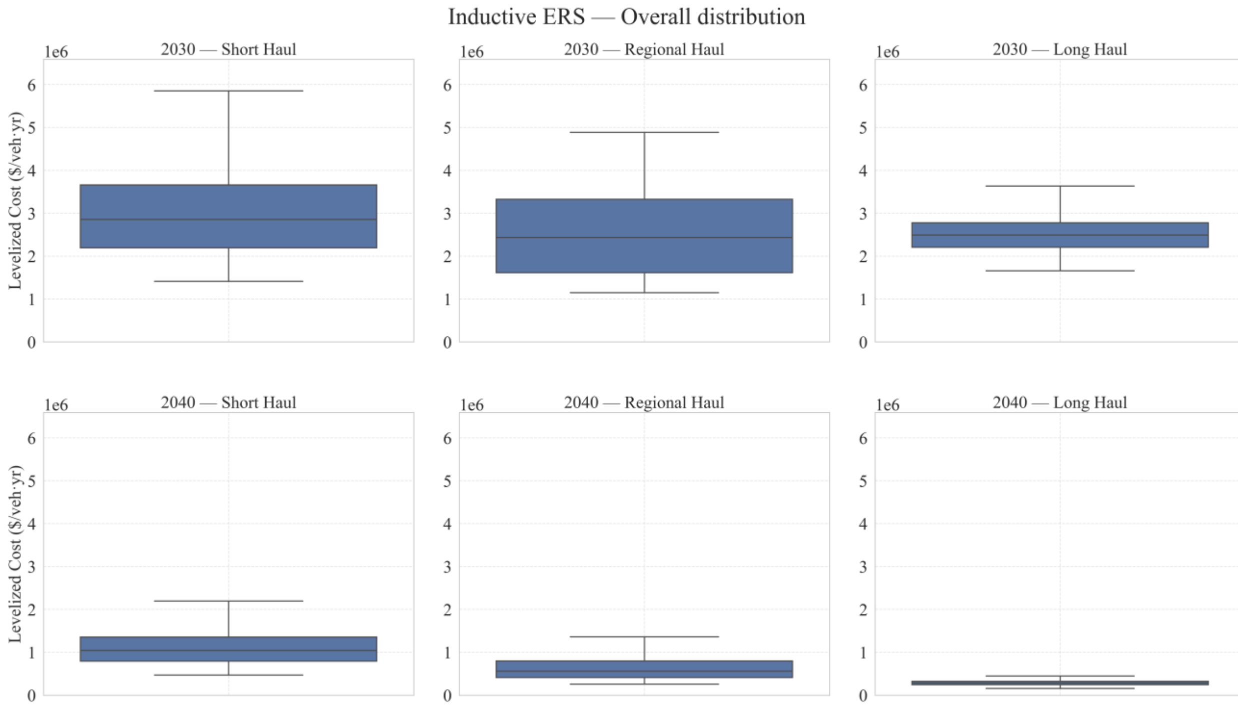
9(d) Electrified road length

Joint configuration outcomes highlight the interaction between wireless charging power and electrified roadway length (Figure 9e). Configurations that combine relatively higher charging power with shorter embedded roadway segments generally achieve lower levelized system costs, because sufficient energy transfer can be achieved without extensive infrastructure deployment. In contrast, configurations with lower power often require longer electrified segments to maintain feasibility, which increases total infrastructure costs.



9(e) Electrified configurations

These sensitivities are reflected in the overall system cost distributions (Figure 9f). In 2030, the levelized system cost distribution is broad across all duty cycles, indicating substantial uncertainty associated with early stage deployment conditions and infrastructure design choices. By 2040, the cost distribution narrows considerably, reflecting improvements in infrastructure efficiency, declining capital costs, and higher utilization levels. Although inductive charging systems remain capital intensive relative to conductive alternatives, the results indicate that large scale corridor deployment with high vehicle throughput can substantially improve the economic performance of inductive electric road systems over time.



9(f) Overall cost distribution

Figure 9. Levelized System Cost of Inductive Electric Road for Short-Haul, Regional-Haul, and Long-Haul Applications in 2030 and 2040

5.3.5 FCEVs

Hydrogen refueling infrastructure is a cornerstone for the deployment of FCEVs in heavy-duty freight applications, offering fast energy replenishment and extended driving range. Compared to battery-based systems, hydrogen refueling requires a distinct infrastructure architecture, one that balances station throughput, dispenser capacity, and fuel production economics. The analysis follows a four-stage framework analogous to that of battery swapping:

5.3.5.1 Stage 1: Feasibility and Dispenser Sufficiency

The fleet's daily hydrogen demand is

$$Q_{\text{fleet}} = F \cdot V_{\text{daily}} \cdot r_{\text{fuel}} \tag{52}$$

where F is fleet size (vehicles); V_{daily} is per-vehicle daily mileage (miles/veh·day); r_{fuel} is per-mile hydrogen use (kgH_2/mile).

The minimum number of dispensers required is

$$D_{\min} = \max\left(D_{\text{floor}}, \left\lceil \frac{Q_{\text{fleet}}}{q_{\text{disp}} H_y} \right\rceil \right) \tag{53}$$

where D_{floor} = 2 is a redundancy floor (dispensers); q_{disp}=80 is dispenser throughput (kgH_2/h); H_y denotes the station operating hours per day (24 h).

5.3.5.2 Stage 2: Infrastructure Cost Annualization

Capital expenditure for hydrogen stations includes a base cost for essential infrastructure and a nonlinear term that scales with dispenser count to reflect compressor, storage, and fueling system complexity:

$$C_{\text{station}} = k \cdot Q^{\beta} \tag{54}$$

where Q is the station hydrogen dispensing capacity (t/day), k is a scaling coefficient, and β is the scaling exponent representing economies of scale in station construction. The parameters k and β are calibrated using NREL cost estimates for 700-bar hydrogen refueling stations, \$11.0 million for a station with a capacity of 2 metric tons per day [52]. A power-law fit to these data yields parameter values of k=7.75 (million USD) and β=0.633, which are used in this study to estimate station capital costs as a function of daily hydrogen throughput.

The annualized infrastructure cost is calculated using the capital recovery factor and maintenance rate r_{maint}:

$$C_{\text{infra, annual}} = CRF \cdot C_{\text{station}} + r_{\text{maint}} \cdot C_{\text{station}} \tag{55}$$

where CRF is the capital recovery factor reflecting financing assumptions for infrastructure investments, and r_{maint} is the annual operation and maintenance rate applied to station capital cost. This is normalized on a per-vehicle basis as:

$$C_{\text{infra, veh}} = \frac{C_{\text{infra, annual}}}{N} \tag{56}$$

N represents the fleet size served by the station.

5.3.5.3 Stage 3: Hydrogen Production and Delivery Cost Estimation

Hydrogen production costs are derived from electricity pricing and electrolysis conversion efficiency. We assume an energy-to-hydrogen conversion factor of:

$$p_{\text{H2, prod}} = p_{\text{elec}} \cdot E_{\text{elec}} \tag{57}$$

where $p_{\text{H2, prod}}$ is the hydrogen production cost (\$/kg), p_{elec} is the electricity price (\$/kWh) based on the source-specific electricity cost scenarios, and E_{elec} is the effective electricity requirement for hydrogen production (kWh/kg), which decreases from 50 kWh/kg [53] in 2025 to 42.5 kWh/kg in 2040 in the model to reflect expected improvements in electrolyzer efficiency and auxiliary system performance.

Electricity cost ranges are drawn from source-specific distributions, with lower-cost options for grid-connected renewables. Hydrogen production costs in this study reflect stylized assumptions about electricity prices and electrolyzer efficiency improvements over time. These estimates are sensitive to the durability of policy support mechanisms such as the U.S. Inflation Reduction Act (IRA) hydrogen production tax credit and to the scale of hydrogen transport infrastructure deployment. In particular, large-scale pipeline development can materially reduce delivery costs relative to truck-based distribution, whereas slower infrastructure rollout or reduced policy support could lead to higher delivered hydrogen prices.

In addition to production costs, hydrogen delivery costs are included to account for transportation and distribution from production facilities to refueling stations. These delivery pathways include pipeline transport and truck-based distribution, depending on the infrastructure configuration assumed in each scenario. The delivered hydrogen price used in the vehicle fuel cost calculation is therefore expressed as:

$$p_{\mathrm{H2}} = p_{\mathrm{H2,\,prod}} + C_{\mathrm{delivery}}$$

where p_{H2} represents the delivered hydrogen price ($/kg) and C_{delivery} represents hydrogen transportation and distribution costs ($/kg).

The total annual fuel cost per vehicle is calculated as:

$$C_{\mathrm{fuel,\,veh}} = p_{\mathrm{H2}} \cdot D_{\mathrm{H2}} \tag{58}$$

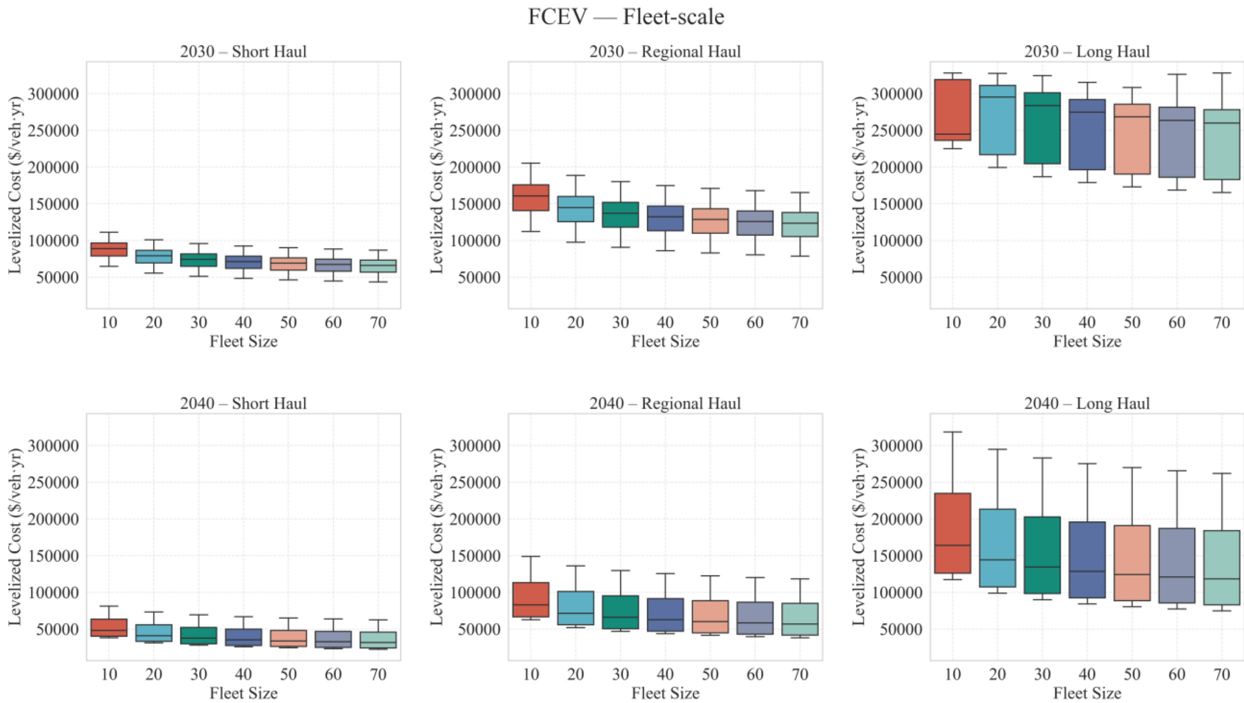
where $C_{\mathrm{fuel,\,veh}}$ is the annual hydrogen fuel cost per vehicle and D_{H2} is the annual hydrogen demand per vehicle (kg/year), determined by vehicle efficiency and annual mileage.

5.3.5.4 Stage 4: Levelized System Cost

The final levelized system cost per vehicle per year combines infrastructure and fuel expenditures:

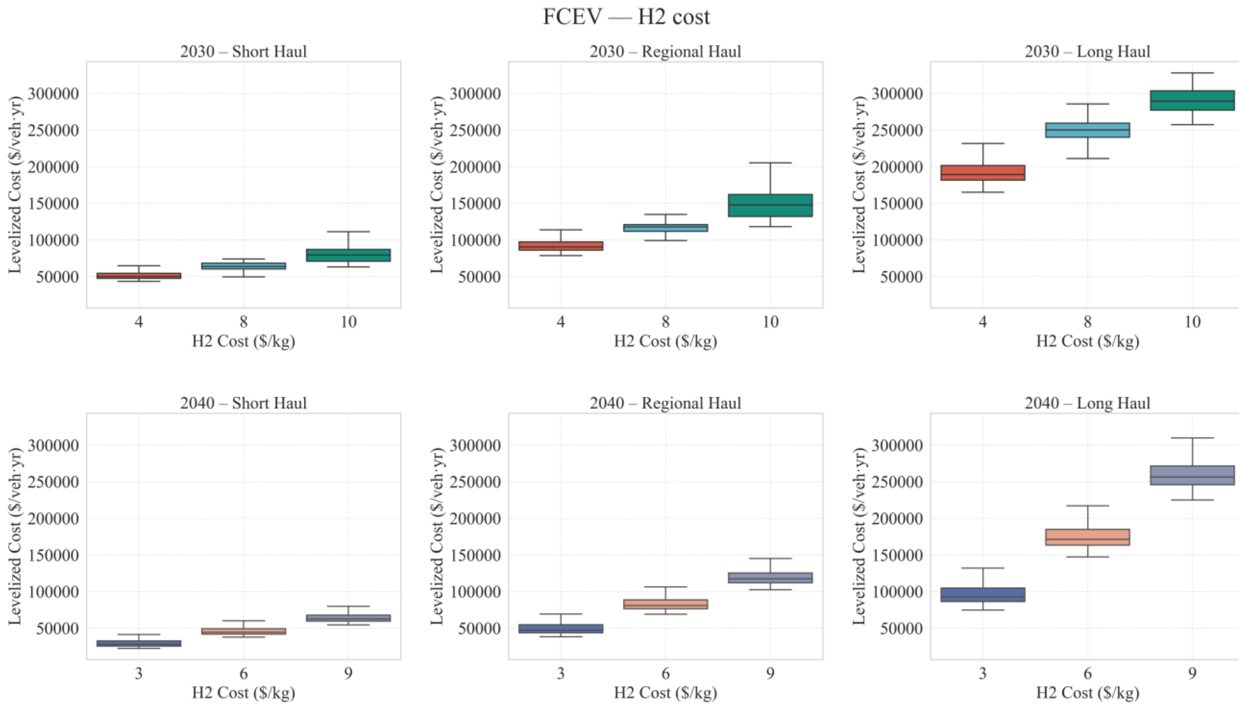
$$C_{\mathrm{LSC,\,FCEV}} = C_{\mathrm{infra,\,veh}} + C_{\mathrm{fuel,\,veh}} \tag{59}$$

Figure 10a shows a pronounced fleet-scale effect on FCEV levelized system cost. As fleet size increases, per-vehicle infrastructure costs decline because station CAPEX is allocated across more vehicles and utilization penalties relax as expected dispenser sufficiency improves under higher throughput. The reduction is steepest from small to medium fleets, after which marginal benefits diminish, consistent with approaching saturation of effective infrastructure utilization. This pattern is strongest in long-haul operation where annual hydrogen throughput per station is highest, enabling more rapid amortization of capital cost and more stable utilization behavior.



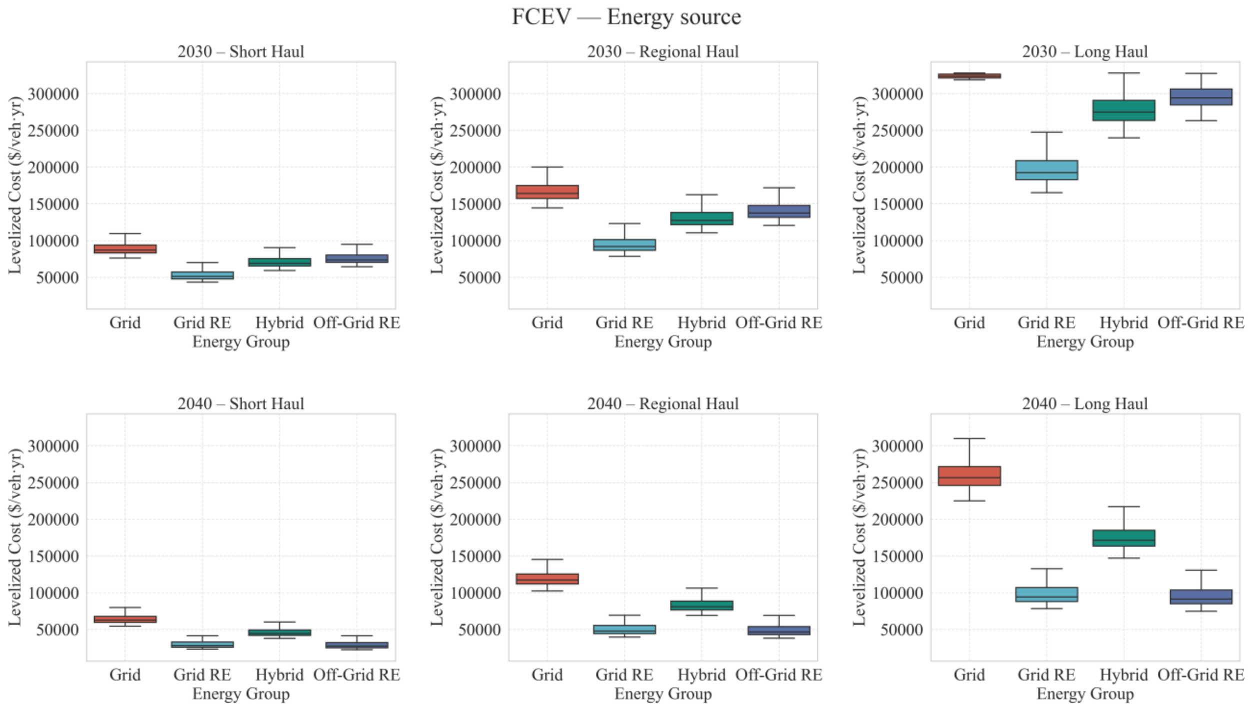
10(a) Fleet-size sensitivity

Figure 10b shows that hydrogen price is the primary factor shaping the stratification of system costs, with clear separation of levelized system cost distributions across hydrogen price ranges. Changes in hydrogen price translate almost directly into shifts in total system cost because fuel expenditure scales with annual hydrogen consumption per vehicle. Infrastructure costs and utilization conditions mainly influence the spread of outcomes, particularly under low throughput conditions, but the overall cost structure remains largely governed by the delivered hydrogen price. This sensitivity reflects the integrated nature of hydrogen supply costs, which combine electricity input, conversion processes, delivery infrastructure, and scale effects within the hydrogen provisioning pathway.



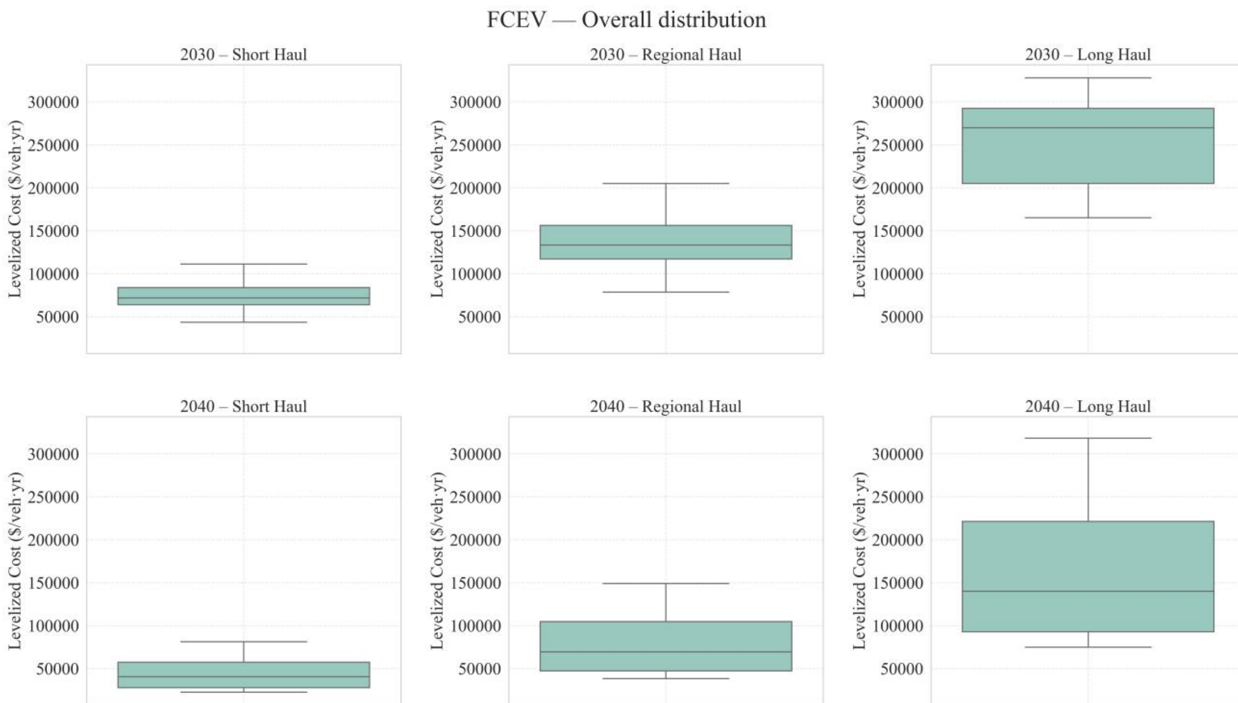
10(b) Hydrogen cost sensitivity

Figure 10c highlights the structural role of energy supply architecture in shaping FCEV economics, particularly by 2040. In 2030, differences among energy-source categories translate into moderate shifts in levelized system cost because infrastructure costs and utilization penalties remain material contributors. By 2040, as capital recovery burdens and maintenance rates decline while hydrogen conversion efficiency improves, energy-source differences become more decisive. Grid-connected renewable and hybrid pathways generally yield lower and tighter levelized system cost distributions than grid-only pathways due to lower electricity baselines used for electrolysis. The lowest median outcomes occur in the off-grid renewable plus pipeline configuration despite the explicit pipeline surcharge, indicating that sufficiently low-cost renewable electricity can dominate the total hydrogen price even after adding delivery-related penalties.



10(c) Energy-supply sensitivity

Figure 10d summarizes the combined influence of these factors and shows a clear temporal compression from 2030 to 2040 across duty cycles. In 2030, the distributions remain relatively broad, reflecting sensitivity to utilization conditions and variability in energy costs. By 2040, the distributions shift downward and become more compact, consistent with improvements in hydrogen production efficiency, declining supply costs, and more favorable infrastructure utilization. Across duty cycles, long-haul applications retain higher absolute cost levels because annual hydrogen demand per vehicle is larger. Overall, long-haul cases also exhibit stronger scale effects, reflecting greater sensitivity to hydrogen price, infrastructure utilization, and per-vehicle cost penalties.



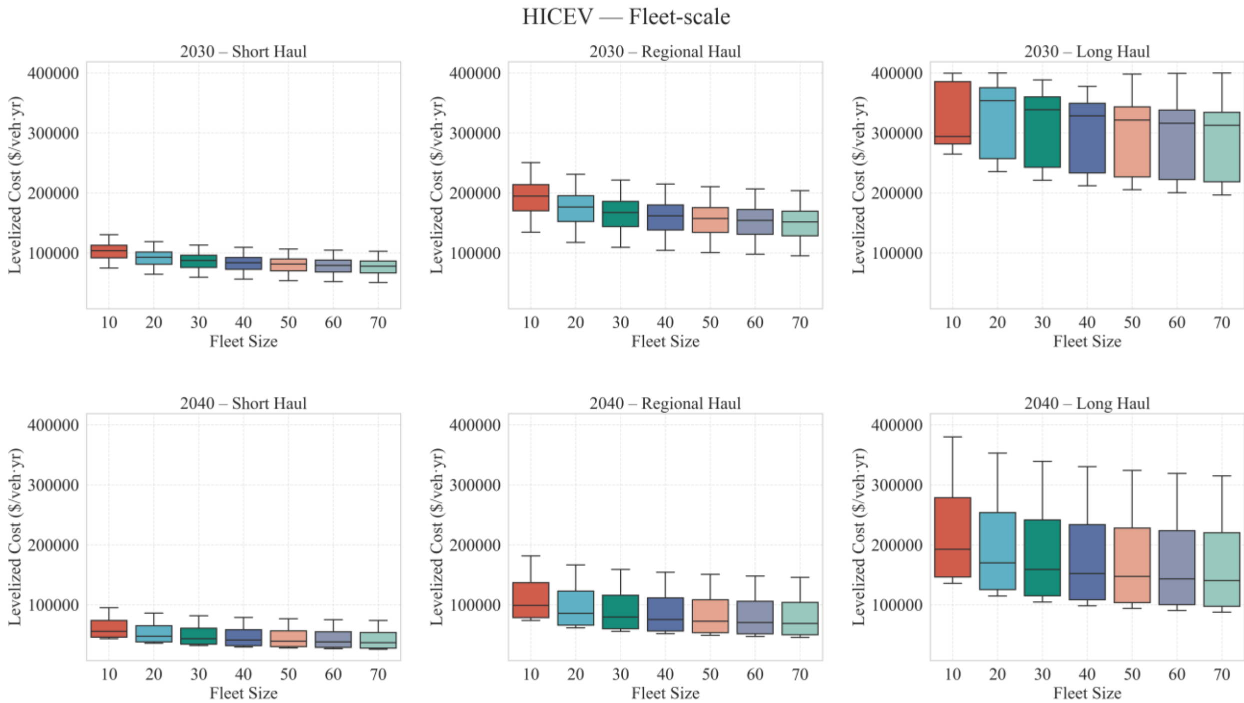
10(d) Overall cost distribution

Figure 10. Levelized System Cost of Hydrogen Refueling for Short-Haul, Regional-Haul, and Long-Haul FCEVs in 2030 and 2040

5.3.6 H_2ICEVs

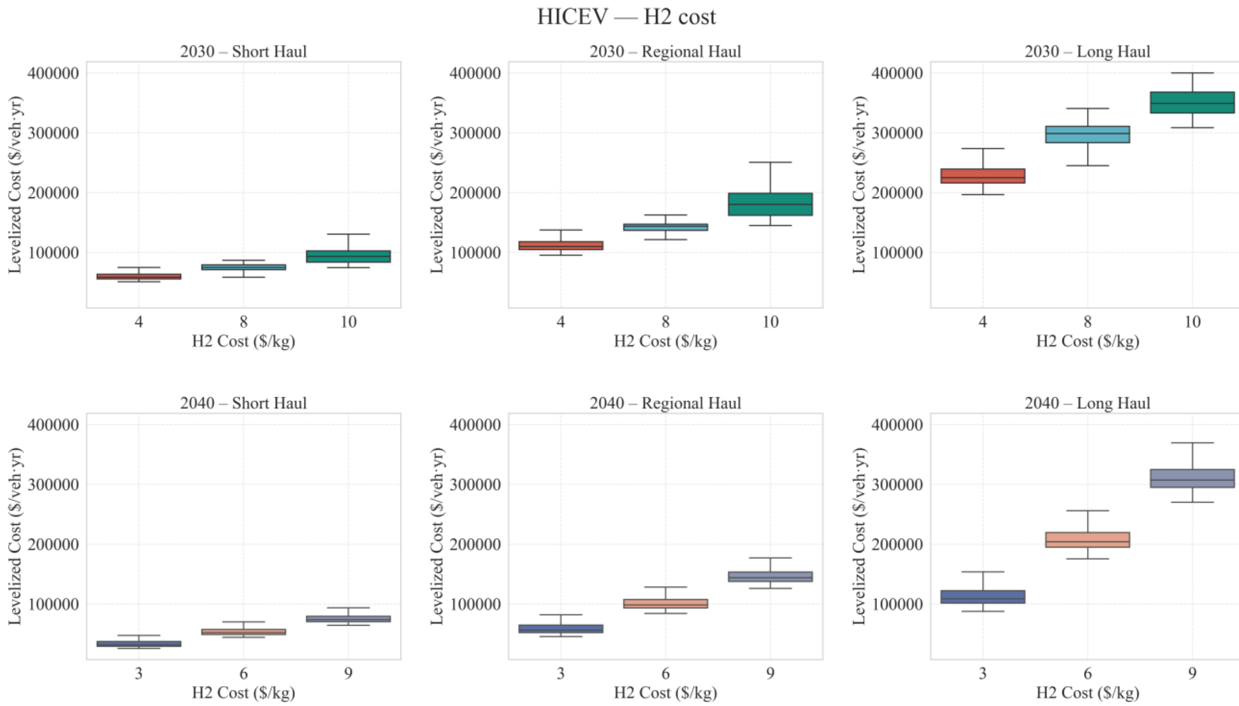
H_2ICEVs are modeled using the same hydrogen refueling infrastructure formulation as FCEVs in this study. Accordingly, the station feasibility conditions, infrastructure cost formulation, and hydrogen cost modeling follow the same framework and equations presented previously. The distinction between H_2ICEV and FCEV pathways in the infrastructure model arises from the vehicle-specific hydrogen consumption intensity, r_{fuel} (kg H_2/mile), which determines fleet hydrogen demand and the resulting station throughput and utilization levels. All other infrastructure and energy supply assumptions remain consistent with those applied to FCEVs.

The results (Figure 11) indicate that H_2ICEV (electrolysis) exhibit a pronounced and systematic dependence of levelized system cost on haul type, deployment scale, and time horizon. Figure 11a examines the influence of fleet deployment scale on system cost. Increasing fleet size produces a clear reduction in median levelized system cost across all duty cycles, particularly when scaling from small fleets to moderate deployment levels. This pattern reflects economies of scale in shared hydrogen refueling infrastructure. As station capital costs are distributed across a larger number of vehicles, the infrastructure cost contribution per vehicle declines rapidly with increasing fleet size. The marginal benefit of scale diminishes at larger fleet sizes, suggesting that many infrastructure cost advantages are realized once stations approach efficient utilization levels. These results indicate that deployment scale is an important determinant of hydrogen trucking economics, particularly during early stages of market development.



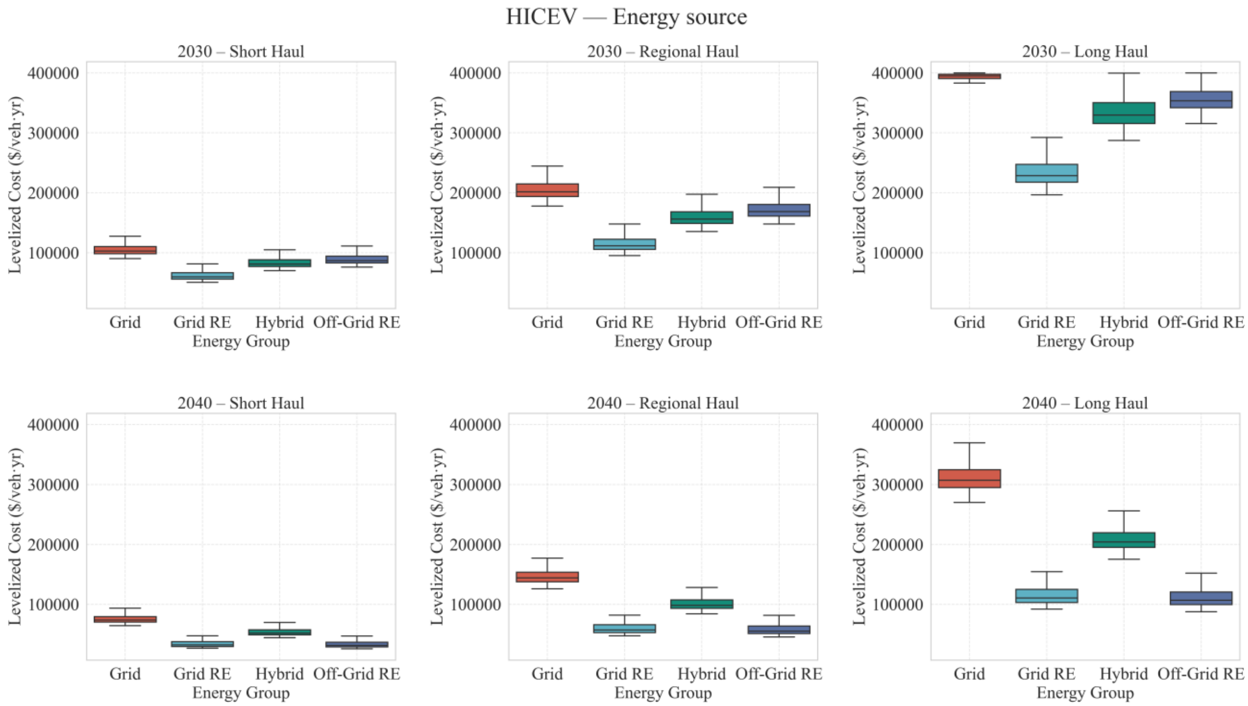
11(a) Fleet-size sensitivity

Figure 11b explores the sensitivity of system cost to hydrogen price. Across all duty cycles, levelized system cost increases significantly with hydrogen price, indicating that fuel cost represents a major component of total system cost for hydrogen combustion trucks. However, the magnitude of this sensitivity varies across operational duty cycles. Long-haul applications exhibit the strongest response to hydrogen price changes because annual hydrogen consumption per vehicle is substantially higher. Conversely, short-haul operations show more moderate cost sensitivity. The results therefore indicate that the economic competitiveness of H_2ICEV systems is tightly coupled to the availability of low-cost hydrogen, particularly for high-utilization freight operations.



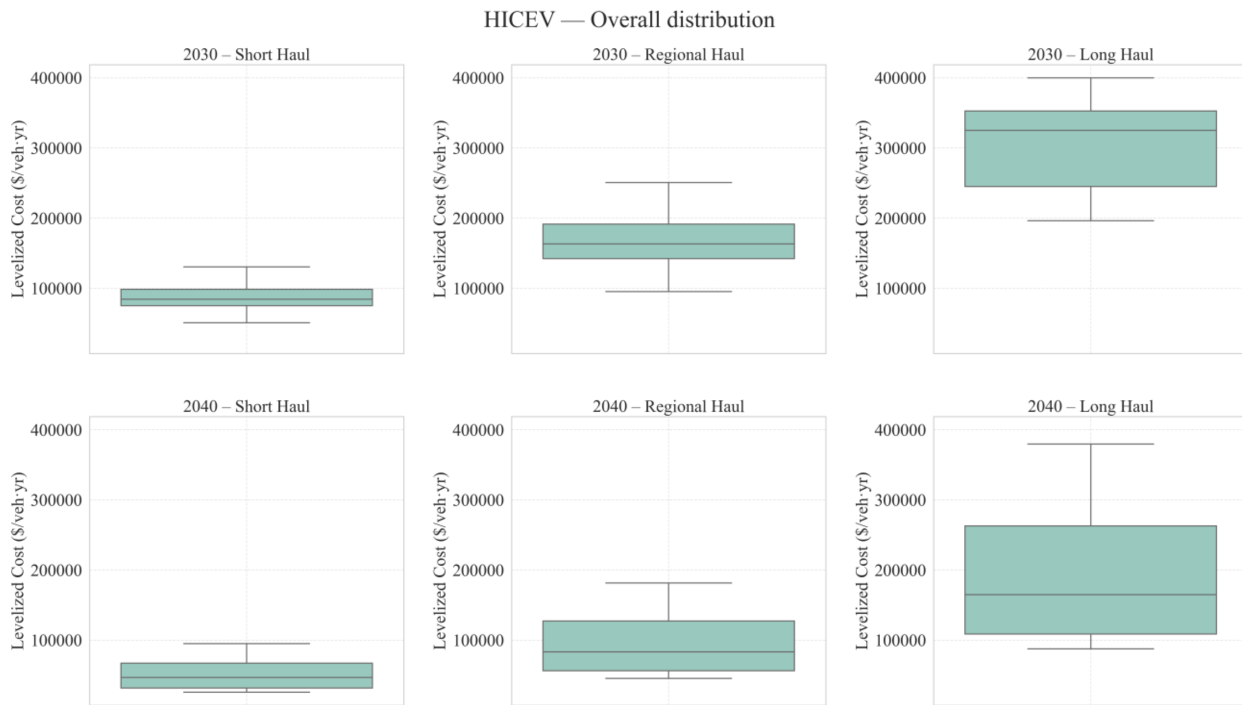
11(b) Hydrogen cost sensitivity

Figure 11c compares outcomes across alternative electricity supply architectures for hydrogen production. Grid-connected renewable pathways yield lower levelized system costs than grid-based configurations, reflecting lower electricity generation costs and reduced storage requirements. Hybrid systems occupy an intermediate position, whereas off-grid renewable configurations exhibit higher costs due to the additional storage and infrastructure needed to balance intermittent generation. However, by 2040, off-grid renewable pathways become comparatively more competitive as improvements in electrolyzer efficiency, declining renewable electricity costs, and reductions in battery-based energy storage costs reduce the overall cost of hydrogen production. This shift highlights the critical role of electricity supply conditions in determining hydrogen system economics.



11(c) Energy-supply sensitivity

Collectively, these results (Figure 11d) indicate that the economic viability of hydrogen internal combustion trucking improves substantially over time but remains highly dependent on deployment scale and hydrogen production cost. Cost reductions emerge primarily from two mechanisms: declining electricity costs that reduce hydrogen production prices, and infrastructure economies of scale associated with larger fleet deployments. Nevertheless, long-haul applications remain structurally more sensitive to hydrogen price volatility due to their high fuel demand. These findings suggest that large-scale fleet deployment combined with access to low-cost electricity will be critical conditions for achieving competitive hydrogen combustion trucking systems.



11(d) Overall cost distribution

Figure 11. Levelized System Cost of Hydrogen Refueling Short-Haul, Regional-Haul, and Long-Haul H_2ICEVs in 2030 and 2040

5.3.7 ICEVs with CCS

Internal-combustion engine vehicles equipped with on-board carbon capture and storage can substantially reduce tailpipe CO_2 emissions while leveraging familiar fueling logistics. To assess techno-economic viability at fleet scale, we structure the analysis in four stages:

5.3.7.1 Stage 1: Feasibility and Station Sufficiency

The required number of dispensers is determined by the total fleet fuel demand relative to dispenser throughput and station operating hours:

$$n_{\text{dem}} = \left\lceil \frac{N_{\text{fleet}} V_{\text{daily}} g_{\text{pm}}}{q_{\text{disp}} H_{\text{op}}} \right\rceil \tag{60}$$

where n_{dem} is the required dispenser count; N_{fleet} is fleet size; V_{daily} is effective per-vehicle daily mileage (miles/veh·day); g_{pm} is diesel consumption (gal/mile); q_{disp} is dispenser throughput (gal/h); and H_{op} is station operating hours per day (h/day).

$$n_{\text{real}} = \max\left(n_{\text{min}}, \lceil \kappa n_{\text{dem}} \rceil\right) \tag{61}$$

where n_{real} is the installed dispenser count after reliability and queuing margins; $n_{min} = 2$ is the minimum allowable dispenser count for redundancy; and κ is an over-provisioning factor capturing congestion and procurement granularity.

5.3.7.2 Stage 2: Infrastructure Cost Annualization

Capital costs scale with the number of dispensers under economies of scale and are converted to annual streams using recovery and maintenance rates.

$$C_{\text{cap}} = C_{\text{base}} + C_{\text{marg}} n_{\text{real}}^{\alpha} \quad (62)$$

where C_{cap} is total station capital cost; C_{base} is fixed base cost; C_{marg} is the marginal cost parameter (\$/disp$^{\alpha}$); n_{real} is installed dispensers; and α is the scale exponent reflecting economies of scale.

Annualized infrastructure cost can be expressed by:

$$C_{\text{infra}} = \text{CRF} C_{\text{cap}} + m C_{\text{cap}} \quad (63)$$

where CRF is the capital recovery factor; and m is the annual O&M rate.

5.3.7.3 Stage 3: Annual Fuel Cost

First, the total annual fuel consumption per vehicle is determined as:

$$G_{\text{yr}} = 365 V_{\text{daily}} g_{\text{pm}} \quad (64)$$

where G_{yr} is the annual diesel consumption per vehicle (gal/veh·yr); V_{daily} is the effective daily mileage per vehicle (mile/veh·day); and g_{pm} is the diesel fuel consumption rate (gal/mile).

The corresponding annual fuel cost per vehicle is given by:

$$C_{\text{fuel, veh}} = p_{\text{diesel}} G_{\text{yr}} \quad (65)$$

where $C_{fuel, veh}$ is the annual fuel cost per vehicle (\$/veh·yr); and p_{diesel} is the diesel cost (\$/gal).

Next, the annual amount of CO_2 captured per vehicle is computed as:

$$M_{\text{CO}_2} = \frac{G_{\text{yr}} e_{\text{CO}_2} \eta_{\text{cap}} a_{\text{v}}}{1000} \quad (66)$$

where M_{CO2} is the captured mass of carbon dioxide per vehicle per year (t/veh·yr); e_{CO2} is the emission factor of diesel combustion (kg/gal); η_{cap} is the capture efficiency of the on-board CCS unit; and a_v is the annual system availability factor accounting for downtime.

The electricity-related CCS cost is then proportional to the captured CO_2 mass and the specific electricity demand of all capture-related processes:

$$C_{\text{CCS, elec}} = p_{\text{elec}} E_{\text{CCS}} M_{\text{CO}_2} \quad (67)$$

where $C_{\text{CCS, elec}}$ is the electricity cost for CCS per vehicle per year (\$/veh·yr); p_{elec} is the electricity cost applicable to CCS operation (\$/kWh); and ECCS is the specific electricity requirement per ton of captured CO_2 encompassing capture, compression, transport, and injection (kWh/tCO_2).

Finally, the non-electric CCS cost is modeled as a per-ton base charge plus a stochastic transport/injection tariff, is given by:

$$C_{\text{CCS,non}} = c_{\text{non}} M_{\text{CO}_2} \quad (68)$$

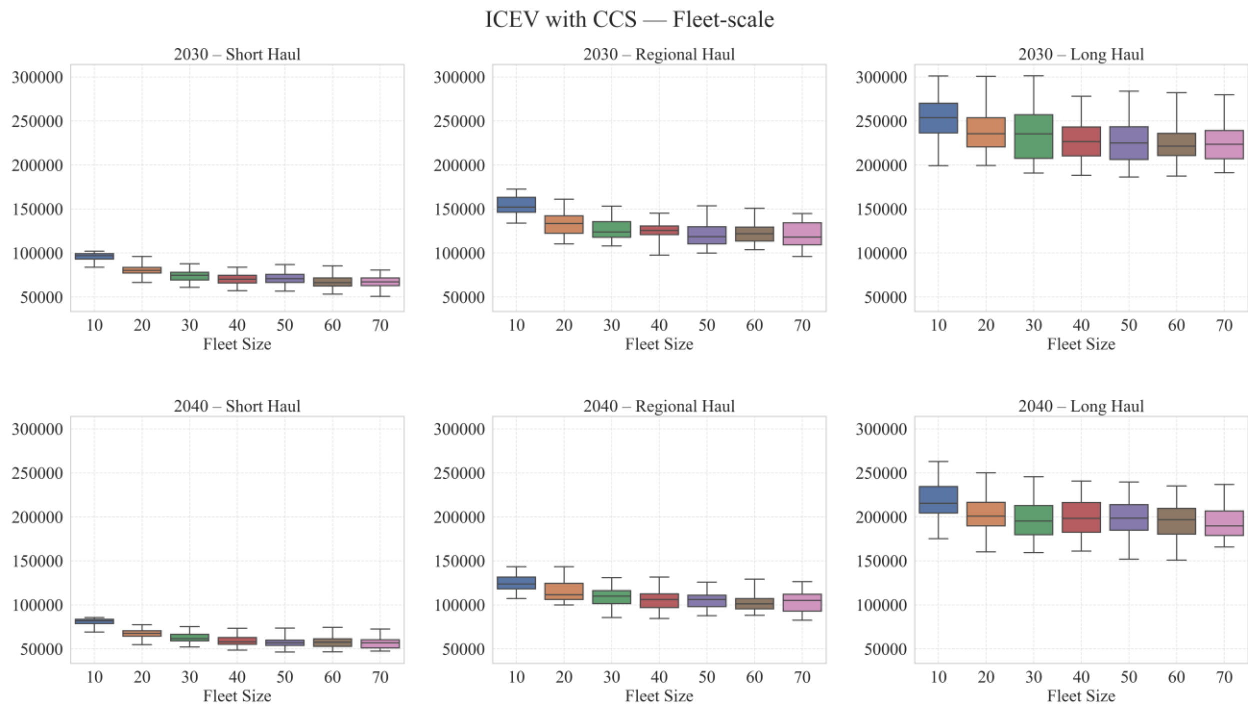
where $C_{\text{CCS,non}}$ is the non-electric operating cost for CCS per vehicle per year ((\$/veh·yr); and c_{non} is the non-electric CCS cost coefficient (\$/tCO_2).

5.3.7.4 Stage 4: Levelized System Cost

The levelized system cost, which reflects the total economic burden of operating an ICEV with CCS over one year of service on a per-vehicle basis, is calculated as:

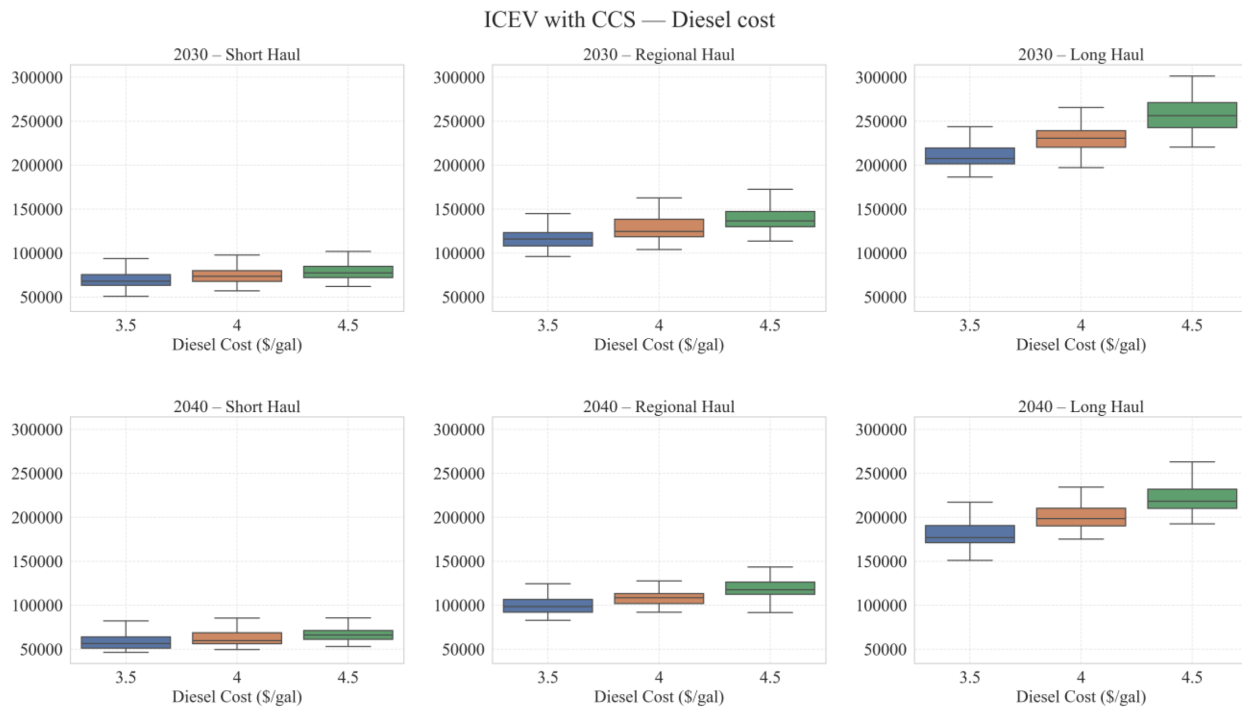
$$C_{\text{LSC, ICEV}} = C_{\text{infra}} + C_{\text{fuel, veh}} + C_{\text{CCS, elec}} + C_{\text{CCS, non}} \quad (69)$$

The ICEV with CCS simulations (Figure 12) produce levelized system cost distributions that remain stratified by duty cycle and fleet scale. Figure 12a presents the overall distributions for the 2030 and 2040 scenarios across different fleet sizes. In both years, a clear hierarchy emerges: long-haul applications exhibit the highest system costs, followed by regional and short-haul operations. This ordering reflects differences in vehicle utilization. Higher daily mileage increases diesel consumption and, consequently, the volume of CO_2 requiring capture, compression, transport, and storage. Comparing the 2030 and 2040 scenarios reveals a downward shift in the cost distributions across all duty cycles, reflecting improvements in baseline fuel intensity and reductions in CCS system costs. Importantly, while these temporal improvements lower overall cost levels, they do not alter the structural ordering imposed by duty cycle and fuel throughput.



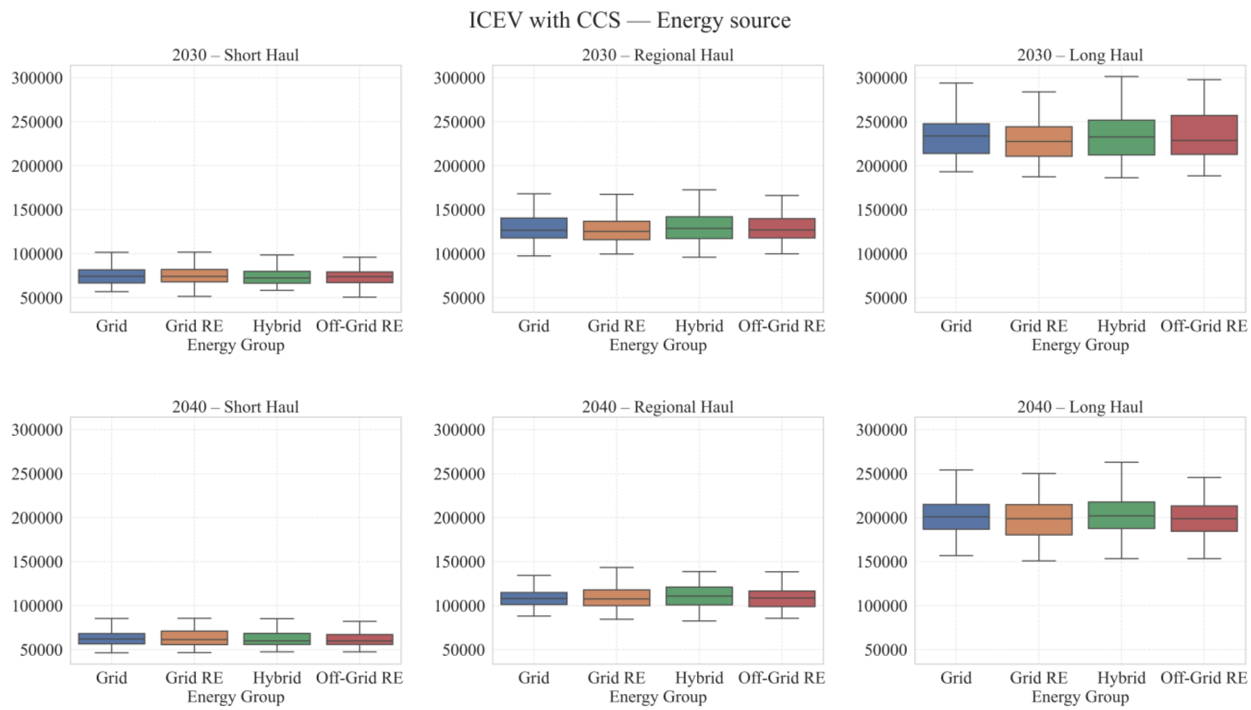
12(a) Fleet-size sensitivity

Figure 12b shows that diesel price remains the dominant determinant of levelized system cost even when CCS is incorporated. Across all duty cycles, higher diesel prices shift the cost distributions upward, with the largest absolute effect observed in long-haul applications where fuel consumption is greatest. The addition of CCS does not eliminate this sensitivity, as higher capture rates and fuel penalties modestly increase fuel consumption. Consequently, the cost competitiveness of ICEV with CCS remains largely governed by the underlying diesel price regime.



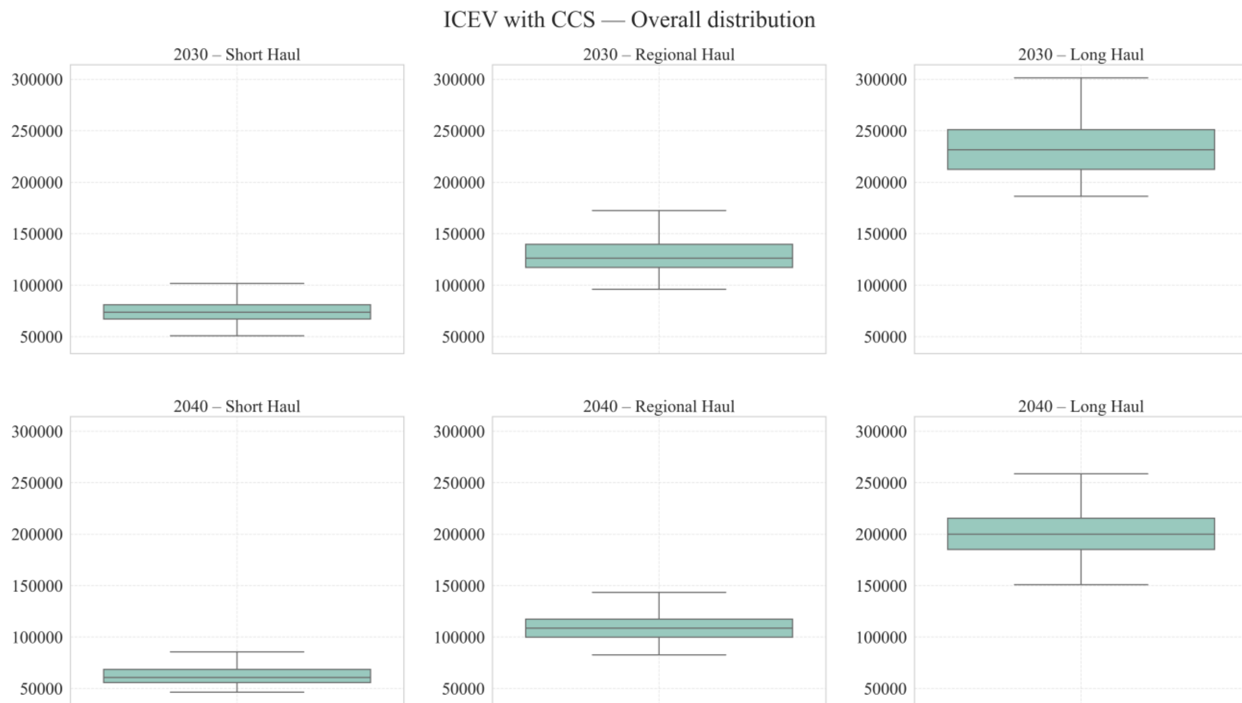
12(b) Diesel cost sensitivity

Figure 12c examines the influence of electricity supply conditions through the electricity demand associated with CCS operations, including both CO_2-chain processes and station-side loads. Across duty cycles and years, differences in electricity supply architecture produce only modest shifts in the levelized system cost distributions. Although electricity is required for CO_2 compression, transport, storage, and station operations, these energy inputs represent a relatively small share of total system cost compared with diesel fuel expenditure and the direct costs of the CO_2 handling chain. As a result, lower-cost or decarbonized electricity can modestly reduce CCS-related energy penalties, but it does not fundamentally alter the overall cost structure of combustion-based freight systems when diesel consumption remains the dominant cost component.



12(c) Energy-supply sensitivity

Collectively, Figure 12 shows that ICEV with CCS maintains a clear cost ordering by duty cycle and strong sensitivity to diesel price, whereas fleet aggregation and electricity supply conditions primarily influence costs at the margin. While incremental system optimization and favorable fuel price conditions can improve competitiveness, long-haul applications remain structurally constrained by high annual fuel consumption and the corresponding scale of CO_2 capture, transport, and storage required for compliance.



12(d) Overall cost distribution

Figure 12. Levelized System Cost of Hydrogen Refueling for Short-Haul, Regional-Haul, and Long-Haul Applications in 2030 and 2040

5.3.8 Comparative Levelized System Cost

The temporal evolution of levelized system cost reveals fundamentally distinct scaling behaviors across zero-emission freight pathways, reflecting the structural characteristics of their underlying infrastructure systems. As shown in Figure 13, early-stage deployment conditions in 2030 are characterized by low fleet penetration and limited vehicle throughput, under which capital-intensive systems exhibit pronounced cost disadvantages. Electric road systems, including both catenary and inductive configurations, incur high per-vehicle costs due to the fixed and corridor-bound nature of their infrastructure, which cannot be effectively amortized under low utilization. In contrast, modular infrastructure systems such as fast charging and battery swapping maintain comparatively lower and more stable levelized system cost values, owing to their ability to scale incrementally with fleet size and to align infrastructure capacity with localized demand.

The transition from 2030 to 2040 is marked by a systematic reduction in levelized system cost across all pathways, emerging from a combination of four underlying drivers: (i) improved infrastructure utilization as fleet deployment expands, (ii) bounded reductions in energy cost ranges embedded in the scenario assumptions, (iii) capital cost improvements associated with technology learning, and (iv) incremental gains in system efficiency. As summarized in

Table 7, the relative importance of these drivers varies across technology classes, leading to differentiated cost trajectories despite a general trend toward convergence.

The most pronounced cost reduction is observed for ERS pathways, driven by their strong dependence on utilization. As vehicle throughput increases, fixed infrastructure costs are distributed over a larger service base, resulting in a nonlinear decline in levelized system cost. Model results indicate the presence of a threshold regime: at intermediate throughput levels of approximately 320 to 440 vehicles per day, representative of early deployment corridors, levelized system cost declines rapidly as utilization improves. At higher throughput levels, on the order of 2,800 to 4,600 vehicles per day, corresponding to mature corridor-scale deployment, ERS pathways can achieve cost levels comparable to or lower than those of modular alternatives. This scaling behavior reflects the high capital intensity and low marginal operating cost of ERS infrastructure, and highlights the critical role of spatially concentrated deployment in achieving cost competitiveness.

Battery-electric pathways, including fast charging and battery swapping, exhibit more gradual and stable cost reductions over time. Their modular architecture allows infrastructure expansion to track fleet growth, avoiding the sharp utilization thresholds observed in ERS systems. As a result, levelized system cost remains relatively insensitive to fleet scale compared to corridor-based systems. Cost reductions in these pathways are primarily driven by narrower electricity cost ranges and incremental improvements in capital efficiency. Battery swapping introduces additional operational flexibility by decoupling charging from vehicle operation, enabling load shifting and reducing exposure to peak electricity pricing, which contributes to more stable system cost outcomes.

Hydrogen-based pathways occupy an intermediate position in the levelized system cost landscape, with cost competitiveness strongly governed by effective hydrogen cost ranges. Under modeled conditions where hydrogen prices fall within approximately $4 to $7 per kilogram, FCEVs can achieve levelized system cost levels comparable to battery-electric systems. In this case, the cost structure is dominated by hydrogen production and refueling infrastructure. The observed cost reductions between 2030 and 2040 arise from improved utilization of hydrogen production and delivery systems, reduced parameter bounds in energy cost assumptions, and scaling effects captured through stochastic sampling. However, hydrogen pathways remain sensitive to upstream energy costs and external policy conditions, including incentives for low-carbon hydrogen, carbon intensity regulations, and zero-emission freight mandates, which influence long-term economic viability.

Across all pathways, the relationship between fleet scale and levelized system cost is strongly technology-dependent. Modular systems such as fast charging, battery swapping, and hydrogen refueling maintain relatively stable cost structures across a wide range of deployment conditions, reflecting their ability to adjust capacity in response to localized demand. In contrast, ERS pathways exhibit a distinct threshold behavior, transitioning from economically unviable under low utilization to highly competitive under high-throughput conditions. This divergence underscores the importance of aligning infrastructure deployment strategies with both traffic density and spatial operating patterns, rather than evaluating technologies under uniform scaling assumptions.

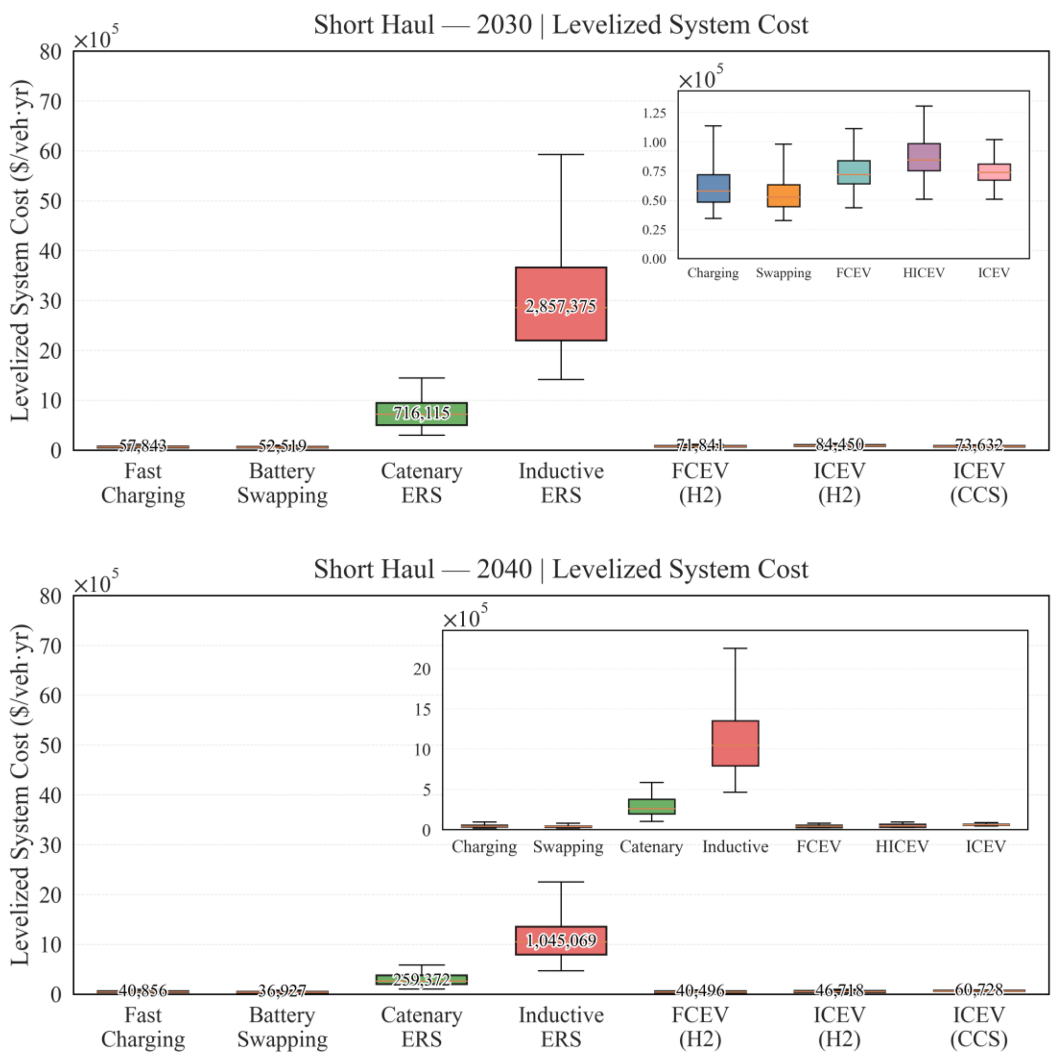
Further analysis of cost decomposition, as summarized in

Table 7, reinforces these distinctions. For ERS pathways, infrastructure utilization and capital amortization dominate cost reduction dynamics. For battery-electric systems, delivered electricity cost and incremental capital efficiency play a more prominent role. For hydrogen pathways, reductions in effective hydrogen cost, driven by improvements in production efficiency and infrastructure scaling, constitute the primary driver. Changes in financial parameters, such as discount rates and capital recovery factors, contribute to cost reductions across all pathways but remain secondary relative to these structural factors.

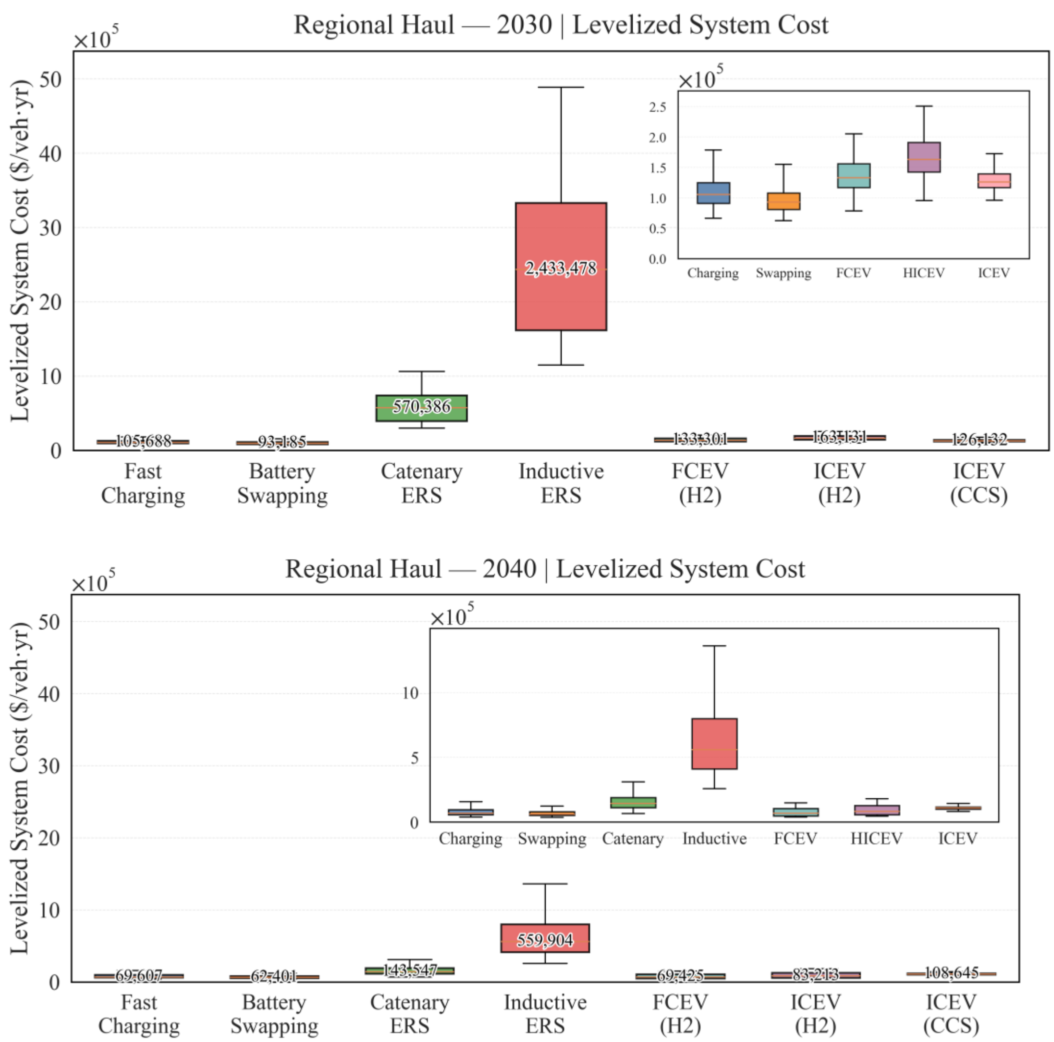
Overall, the results indicate that no single technology pathway is universally optimal. Instead, cost competitiveness is intrinsically context-dependent and closely linked to deployment conditions. ERS pathways are best suited to dense, high-utilization freight corridors where infrastructure can be effectively amortized. Inductive systems provide an alternative where overhead infrastructure is impractical, but face additional efficiency and cost constraints at high power levels. Battery-electric pathways are more suitable for dispersed or moderate-scale fleets, where modular deployment enables flexibility and cost control. Hydrogen pathways remain advantageous for long-range applications and operational contexts requiring rapid refueling or reduced reliance on grid infrastructure, with FCEVs generally outperforming hydrogen internal combustion engine vehicles due to higher drivetrain efficiency. Achieving cost-effective decarbonization of heavy-duty freight systems therefore requires deployment strategies that explicitly account for the interaction between infrastructure scaling behavior, technology characteristics, and operational demand patterns, rather than relying on a single dominant pathway.

Table 7. Key Drivers of Cost Reduction from 2030 to 2040 Across Zero-Emission Freight Technologies.

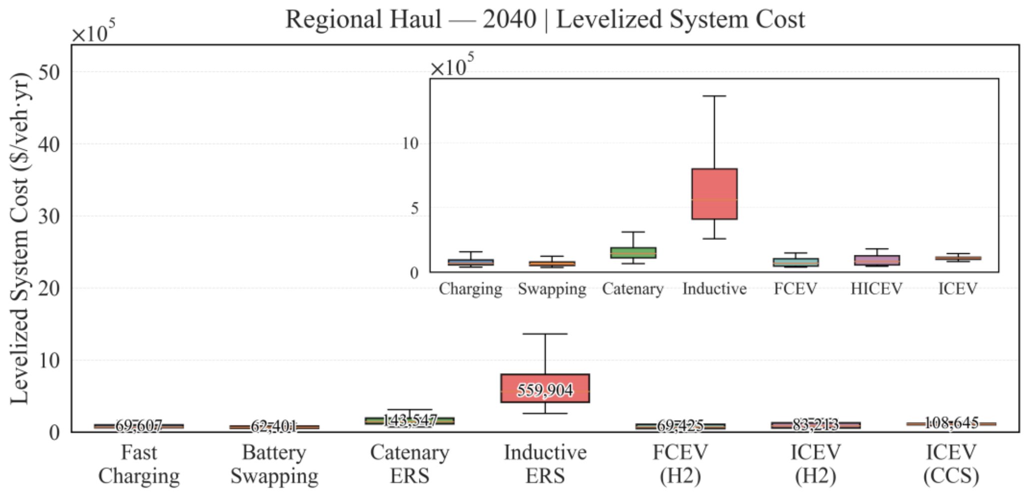
Driver Category	System Evolution (2030–2040)	Mechanism	Technologies Most Affected	Impact on Cost
Infrastructure utilization	Transition from low to high utilization levels, driven by fleet aggregation and corridor-scale deployment	Infrastructure costs are distributed over higher throughput, substantially reducing per-vehicle annualized cost	Electric road systems (catenary, inductive)	Primary
Energy supply cost	Decline in the cost ranges of electricity across supply configurations	Lower levelized cost of electricity and reduced effective markups decrease delivered energy cost	All technologies, particularly battery-electric and hydrogen pathways	Primary
Energy logistics optimization	Transition from distributed, small-scale delivery to centralized production and optimized distribution (e.g., hydrogen pipeline delivery)	Reduced delivery losses, improved capacity factors, and lower infrastructure markups significantly reduce effective fuel cost	Hydrogen pathways (FCEV, H_2ICEV)	Primary (Hydrogen-specific)
Technology learning and CAPEX reduction	Progression from early-stage deployment to mature, scaled manufacturing and infrastructure rollout	Capital cost reductions in key components (chargers, electrolyzers, infrastructure systems) lower annualized system cost	All technologies	Secondary
System efficiency improvements	Incremental improvements in drivetrain efficiency, charging efficiency, and energy conversion processes	Reduced energy consumption per mile contributes to lower operational cost, though impact is smaller relative to structural drivers	All technologies	Secondary
Capital recovery conditions	Reduction in assumed discount rates and improved capital recovery factors over time	Lower annualized infrastructure cost burden through reduced financing costs (CRF)	All technologies	Marginal

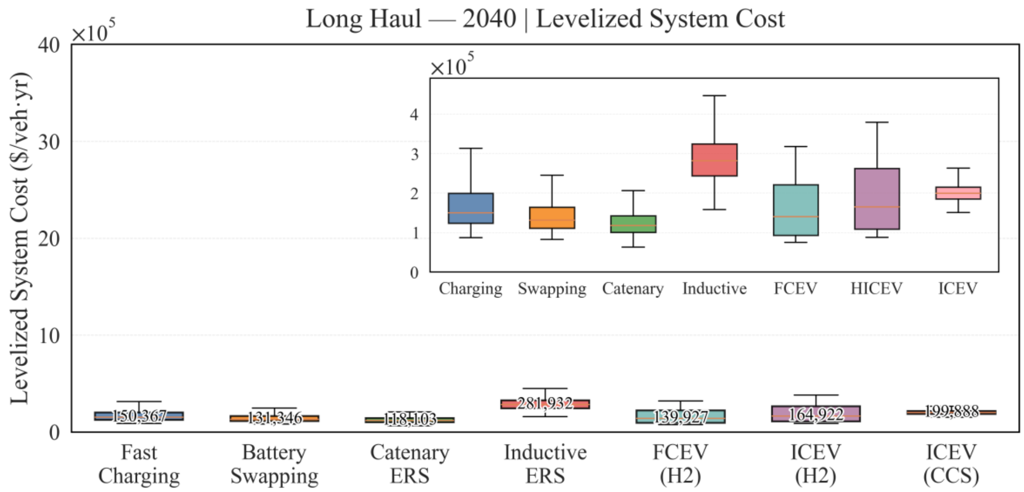


13a. Levelized System Cost ($/Vehicle·Year) for Short-haul ZEV Technologies



13b. Levelized System Cost ($/Vehicle·Year) for Regional-haul ZEV Technologies





13c. Levelized System Cost ($/Vehicle·Year) for Long-haul ZEV Technologies

Figure 13. Comparison of Levelized System Cost ($/vehicle·year) for 2030 and 2040

5.3.9 Sensitivity Analysis

(1) Energy Consumption

Sensitivity analysis of energy consumption shows that it strongly affects the levelized system cost of long haul freight electrification technologies (Figure 14). Across all technologies in the 2040 long haul scenario, a 15% change in energy consumption causes a clear shift in the cost distribution. The magnitude of this shift is broadly similar across pathways, indicating that energy consumption acts as a common cost driver regardless of differences in infrastructure configuration or fuel pathway. This occurs because energy use directly determines the amount of electricity or fuel required to provide freight service, thereby influencing operating cost in a systematic way across all technologies. These results show that improvements in vehicle energy efficiency can yield meaningful cost reductions across the full range of freight decarbonization pathways.

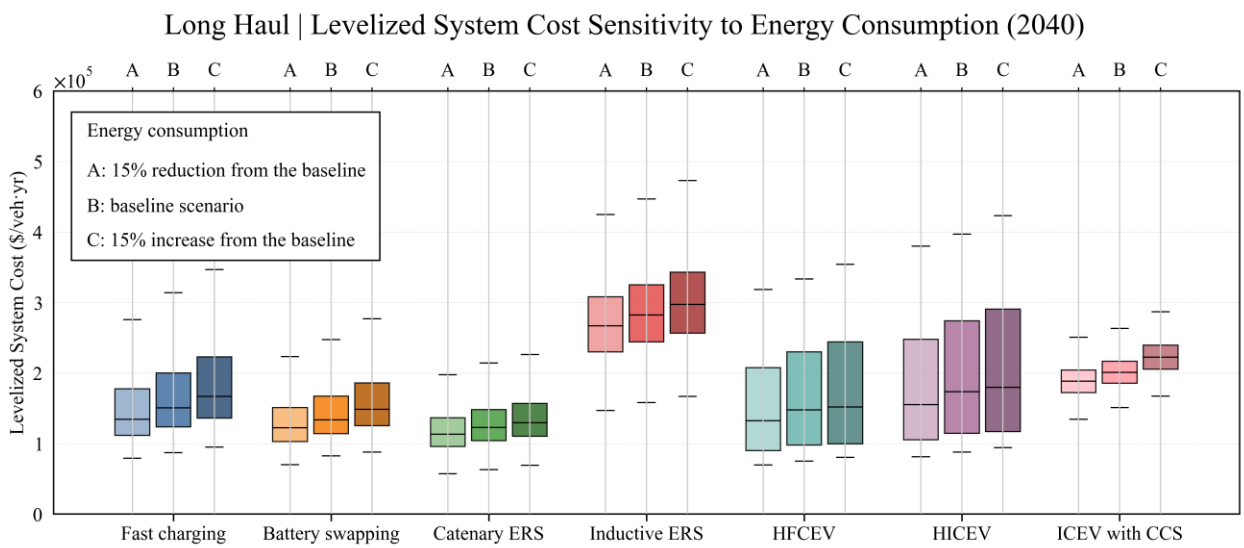


Figure 14. Sensitivity of Levelized System Cost to Energy Consumption for Long-Haul Freight Technologies In 2040

(2) Infrasture Discount Rate

Sensitivity analysis of the discount rate (Figure 15) shows a heterogeneous impact on the levelized system cost of long haul freight decarbonization technologies in 2040. The strongest response is observed for corridor based solutions, catenary electric road systems and inductive electric road systems, where a higher discount rate shifts the entire cost distribution upward. This pattern reflects the large upfront infrastructure investment required for corridor electrification, which makes total system cost highly sensitive to financing conditions. Hydrogen based pathways also exhibit noticeable increases in levelized system cost under the higher discount rate. Both FCEV and H_2ICEV experience moderate upward shifts in their cost distributions, indicating that capital requirements associated with hydrogen production and refueling infrastructure contribute to this sensitivity. In contrast, battery based charging systems show only limited responses to changes in the discount rate. Fast charging and battery swapping pathways exhibit relatively small differences between the baseline and higher discount rate scenarios, suggesting that their cost structures rely less on large centralized infrastructure investments. Overall, these results indicate that technologies requiring extensive corridor infrastructure deployment are substantially more sensitive to financing conditions than battery based charging systems.

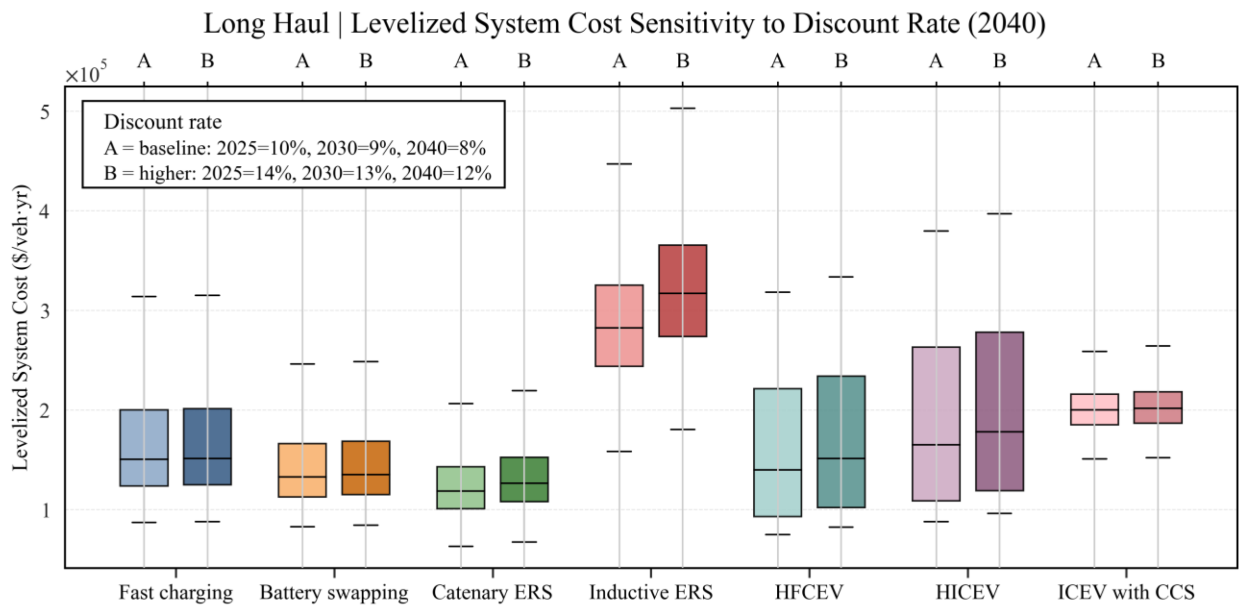


Figure 15. Sensitivity of Levelized System Cost to Discount Rate for Long-Haul Freight Technologies In 2040

5.4 Levelized Cost of Transport ($/vehicle·year)

Building on the levelized system cost framework, this section extends the analysis to derive the levelized cost of transport (LCOT), expressed on a per-vehicle, per-year basis. Beyond infrastructure-, energy-, and maintenance-related system costs, LCOT explicitly incorporates vehicle-level costs, yielding an integrated economic metric for cross-technology comparison. All cost components in the LCOT formulation are expressed on an annualized basis, such that LCOT represents the total cost incurred per vehicle per year. Accordingly, LCOT can be expressed as:

$$\mathrm{LCOT} = C_{\mathrm{infrastructure}} + C_{\mathrm{energy}} + C_{\mathrm{maintenance}} + C_{\mathrm{vehicle}} \tag{70}$$

where, C_{vehicle} is calculated based on the vehicle cost model [12] and economic parameter assumptions, as shown in Table 8.

Table 8. Vehicle Capital Costs, Service Lifetimes, and Discount Rates for LCOT Calculation.

(a) Short-Haul Truck

Year	Technology*	Vehicle Cost ($)	Key Components and modificaitons ($)
2030	BEV (Fast charging/Swapping)	200k	Battery system: 180 $/kwh [50]
	BEV (Catenary)	215k	BEV + pantograph system (15k) [54]
	BEV (Inductive)	207.5k	BEV + Wireless charging receiver (7.5k) [55]
	FCEV	238k	Fuel cell system: 200 $/kW [50]
	H_2ICEV	178k	+8% vs. conventional diesel [56]
	ICEV	165k	Conventional diesel powertrain
2040	BEV (Fast charging/Swapping)	160k	Battery system cost: 120$/kwh [50]
	BEV (Catenary)	175k	BEV + pantograph (15k) [54]
	BEV (Inductive)	167.5k	BEV + Wireless charging receiver (7.5k) [55]
	FCEV	180k	Fuel cell system: 140 $/kW [50]
	H_2ICEV	181k	+8% vs. conventional diesel [56]
	ICEV	168k	Conventional diesel powertrain

*Assumes ZEVs with a 300-mile driving range; lifetime: 8 years; discount rate: 10%.

(b) Regional-Haul Truck

Year	Technology*	Vehicle Cost ($)	Key Components and modificaitons ($)
2030	BEV (Fast charging/Swapping)	255k	Battery system: 180 $/kwh [50]
	BEV (Catenary)	270k	BEV + pantograph system (15k) [54]
	BEV (Inductive)	262.5k	BEV + wireless charging receiver (7.5k) [55]
	FCEV	268k	Fuel cell system: 200 $/kW [50]
	H_2ICEV	199k	+8% vs. conventional diesel [56]
	ICEV	184k	Conventional diesel powertrain
2040	BEV (Fast charging/Swapping)	200k	Battery system cost: 120$/kwh [50]
	BEV (Catenary)	215k	BEV + pantograph (15k) [54]
	BEV (Inductive)	207.5k	BEV + Wireless charging receiver (7.5k) [55]
	FCEV	202k	Fuel cell system: 140 $/kW [50]
	H_2ICEV	189k	+8% vs. conventional diesel [56]
	ICEV	175k	Conventional diesel powertrain

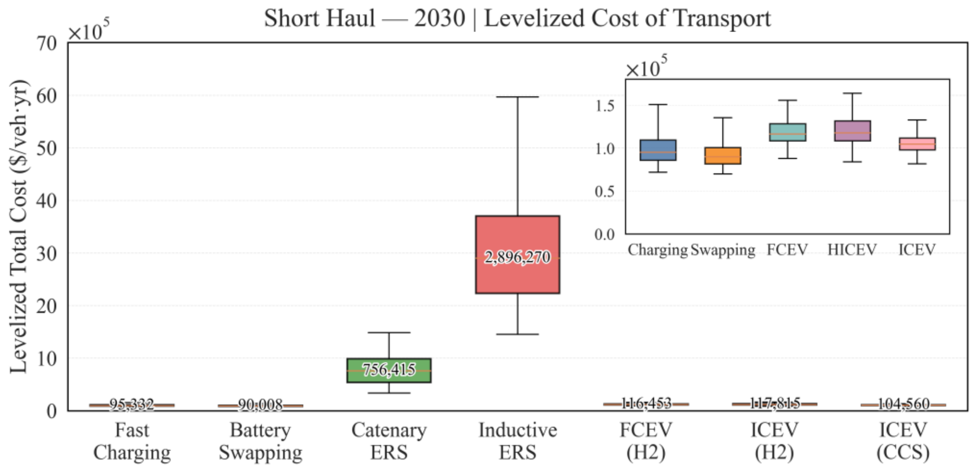
*Assumes ZEVs with a 300-mile driving range; lifetime: 8 years; discount rate: 10%.

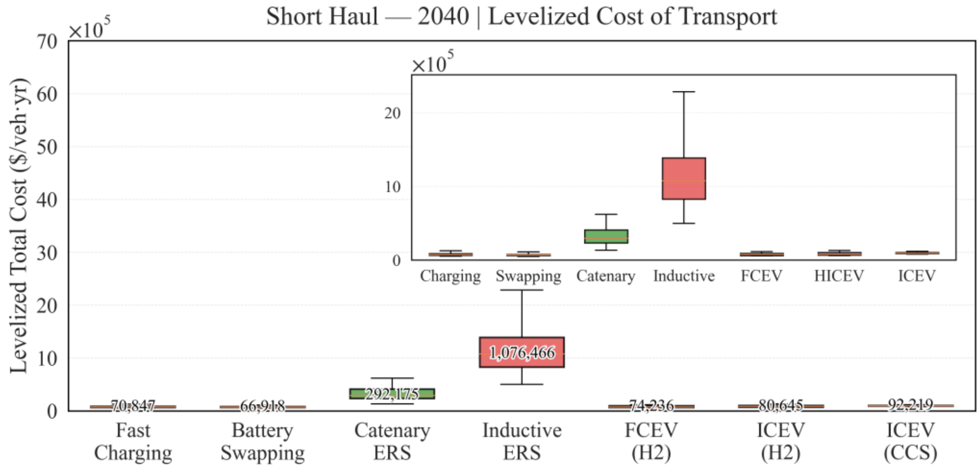
(c) Long-Haul Truck

Year	Technology*	Vehicle Cost ($)	Key Components and modificaitons ($)
2030	BEV (Fast charging/Swapping)	350k	Battery system: 180 $/kwh [50]
	BEV (Catenary)	365k	BEV + pantograph system (15k) [54]
	BEV (Inductive)	357.5k	BEV + Wireless charging receiver (7.5k) [55]
	FCEV	287k	Fuel cell system: 200 $/kW [50]
	H_2ICEV	203k	+8% vs. conventional diesel [56]
	ICEV	188k	Conventional diesel powertrain
2040	BEV (Fast charging/Swapping)	255k	Battery system cost: 120$/kwh [50]
	BEV (Catenary)	270k	BEV + pantograph (15k) [54]
	BEV (Inductive)	262.5k	BEV + Wireless charging receiver (7.5k) [55]
	FCEV	220k	Fuel cell system: 140 $/kW [50]
	H_2ICEV	205k	+8% vs. conventional diesel [56]
	ICEV	190k	Conventional diesel powertrain

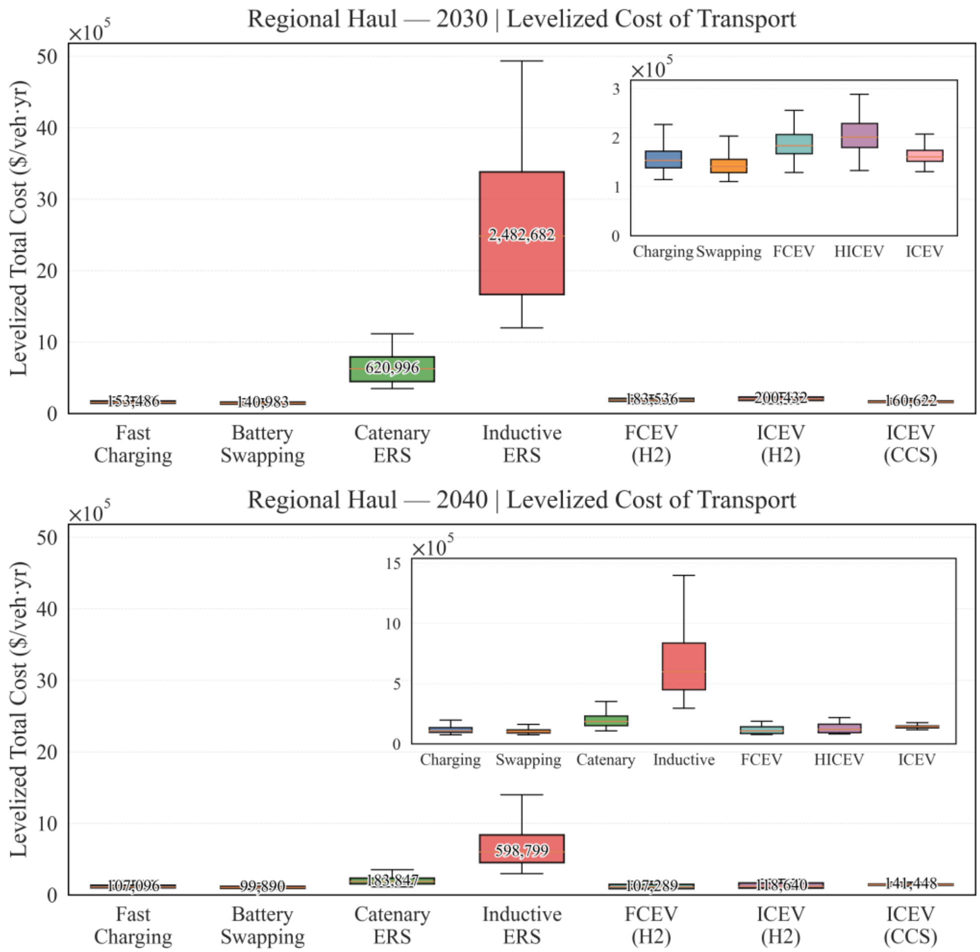
*Assumes ZEVs with a 500-mile driving range under harsh real-world operating conditions (e.g., high payload, roadway gradients, temperature extremes and auxiliary loads).

Figure 16 presents a comparative assessment of the levelized cost of transport for trucking across the seven decarbonization pathways examined in this study. The results indicate that levelized cost of transport trends closely track those observed for levelized system cost across all pathways, reflecting the dominant contribution of infrastructure and energy costs to long-haul freight economics. Differences among technologies are relatively modest and are driven primarily by variations in upfront vehicle capital costs, which play a secondary role relative to infrastructure utilization and fuel or electricity supply conditions in shaping long-term transport costs.

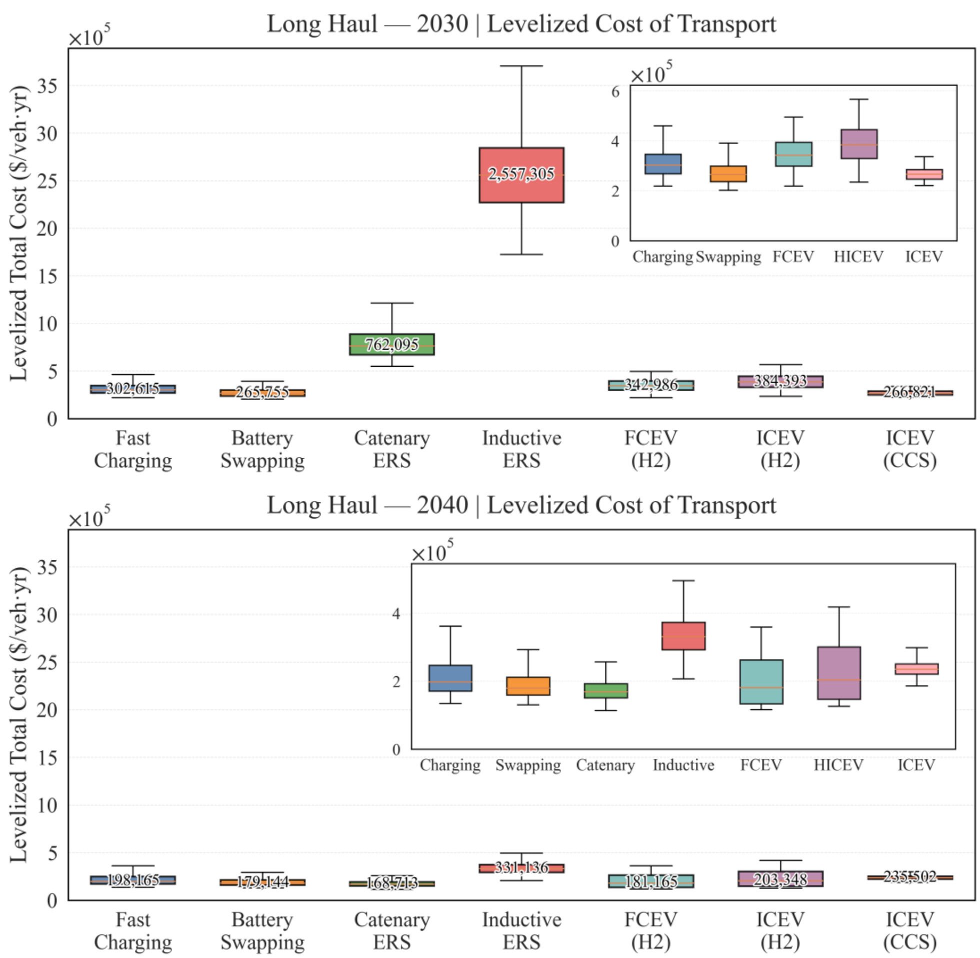




16a. LCOT ($/Vehicle·Year) for Short-haul ZEV Technologies



16b. LCOT ($/Vehicle·Year) for Regional-haul ZEV Technologies



16c. LCOT ($/Vehicle·Year) for Long-haul ZEV Technologies

Figure 16. Comparison of Levelized Cost of Transport ($/vehicle·year) for 2030 and 2040

6 Policy Implications

6.1 Decision Context: Agency and Stakeholder Roles

At the federal level, including agencies such as the USDOT and the DOE, the primary policy function is to establish a coordinated strategic framework that reflects the structural diversity of zero-emission freight infrastructure, rather than prescribing uniform deployment approaches across technologies. These findings indicate that different infrastructure archetypes impose fundamentally different planning requirements, particularly in terms of capital intensity, spatial coordination, and utilization dependence. Accordingly, federal action is well positioned to support large-scale coordination mechanisms, including corridor designation, multi-state planning alignment, and long-term funding certainty.

At the state level, including air resources boards, energy commissions, public utilities, and public utility commissions, policy influence is exerted primarily through electricity market design, infrastructure permitting, and interconnection governance. The results indicate that delivered electricity cost is strongly shaped by tariff structures, demand charges, and interconnection timelines, which in turn influence the operational economics of electrification pathways. State-level institutions therefore play a central role in translating high-level decarbonization targets into implementable infrastructure conditions.

For ports, metropolitan planning organizations, corridor authorities, and local governments, the key role lies in spatial planning and project facilitation. The results reinforce the importance of depot-centric and node-based deployment strategies for short-haul and drayage applications, where infrastructure utilization can be maximized. Local authorities can support deployment by coordinating land use, streamlining permitting, and enabling freight–energy hub development.

From an industry perspective, including fleets, vehicle manufacturers, charging service providers, and hydrogen suppliers, near-term constraints are more closely associated with infrastructure utilization and revenue certainty than with technology performance. The results indicate that underutilized infrastructure and tariff exposure represent key economic risks. As a result, private-sector strategies are more likely to align with predictable demand aggregation, contracted offtake, and infrastructure co-development models.

6.2 System Strategy: Infrastructure Investment Priorities

The results indicate that infrastructure investment strategies should be differentiated based on the structural relationship between infrastructure scale, utilization, and deployment flexibility. Modular infrastructure systems, including fast charging, battery swapping, and hydrogen refueling stations, exhibit relatively high scalability under incremental deployment. These systems can be deployed in a distributed manner as fleet adoption grows, thereby limiting exposure to early-stage underutilization. Their economic performance is primarily driven by local utilization conditions, electricity pricing structures, and operational flexibility. For battery swapping in particular, deployment effectiveness depends on fleets operating as depot- or terminal-based clusters with predictable duty cycles. Under these conditions, centralized charging and load shifting enable reduced exposure to demand charges and improved infrastructure utilization. By contrast, corridor-dependent infrastructure systems, such as catenary and inductive electric road systems, exhibit a fundamentally different investment profile. The analysis reveals a pronounced threshold effect: at low traffic volumes, high fixed costs lead to elevated levelized system costs, whereas at high utilization levels, infrastructure costs can be amortized rapidly, resulting in substantial cost reductions.

These findings indicate that corridor-based systems are particularly well suited to applications characterized by dense and stable freight flows, limited dwell-based charging opportunities, and sufficient institutional capacity to coordinate large-scale deployment. Phased deployment strategies that prioritize high-utilization segments are therefore critical to reducing early-stage investment risk. In the near term, hydrogen refueling infrastructure exhibits relatively high costs among the node-based pathways, reflecting its capital intensity and scale dependence. While refueling stations are modular at the site level, their economic performance is strongly dependent on system-wide utilization of production and delivery assets. The results indicate that hydrogen pathways become increasingly competitive under conditions of high throughput, low-cost upstream electricity, and integrated delivery systems, particularly pipelines. As a result, effective hydrogen deployment is best structured around hub-and-corridor networks rather than isolated stations.

Across all pathways, a central system-level insight is that cost outcomes are governed by the alignment between upstream energy supply and infrastructure deployment configuration. Delivered electricity cost emerges as a key driver of both fuel cost and levelized system cost, indicating that energy supply and infrastructure planning should be treated as a coupled system. While off-grid and hybrid energy architectures can enhance resilience or enable deployment in grid-constrained environments, the results indicate that these configurations shift cost from operating expenditure to capital investment due to buffering and redundancy requirements. Such approaches are therefore particularly well suited to contexts where resilience or grid independence justifies the additional capital burden.

6.3 Policy Instruments: Standards, Market Design, and Enabling Regulation

The results suggest that, given the strong dependence of system performance on utilization, energy supply conditions, and infrastructure configuration, policy design can be more effective when it is structured to enable system-level performance through targeted regulatory instruments, rather than prescribing specific technology pathways. For battery-based systems, particularly battery swapping, interoperability emerges as a critical enabler of system efficiency and scalability. Policy frameworks can support standardization of mechanical, electrical, thermal, and communication interfaces while preserving flexibility for internal design innovation. However, full cross-platform standardization can be constrained by proprietary vehicle architectures and system integration strategies, requiring careful balancing between standardization and innovation. In parallel, high-throughput battery circulation introduces additional requirements for lifecycle accountability and safety governance. Effective policy frameworks should incorporate pack-level traceability, standardized diagnostics, minimum safety thresholds, and clearly defined end-of-life responsibilities. Data governance and cybersecurity standards are also essential to ensure reliable system operation and enable secondary market development.

For corridor-based systems, policy effectiveness depends on aligning infrastructure deployment with measurable utilization and performance metrics. Corridor designation strategies based on freight flow intensity, dwell patterns, and logistics demand enable more efficient allocation of public investment. Phased deployment approaches, in which expansion is triggered by observed utilization and adoption, can reduce the risk of stranded assets.

Utility regulation and electricity market design represent critical enabling mechanisms across all electrification pathways. The results indicate that tariff structures and demand charges can outweigh hardware cost reductions, particularly for high-power charging systems. Policy instruments such as demand charge reform, subscription-based pricing, and incentives for managed charging can significantly improve system economics. In addition, streamlined interconnection processes, transparent queue management, and standardized cost-sharing frameworks for grid upgrades reduce deployment uncertainty and delays.

For hydrogen pathways, supportive policy is particularly effective when focused on utilization, supply-chain integration, and carbon intensity alignment. The results indicate that hydrogen competitiveness improves under high utilization of production and delivery assets, supported by low-cost renewable electricity. Policy mechanisms such as hub-scale procurement, contracts for difference, and infrastructure cost-sharing frameworks can stabilize utilization and reduce cost variability.

Across all zero-emission pathways, performance-based public funding structures emerge as a key policy principle. Capital support can be more effective when tied to infrastructure utilization, availability, and verified emissions outcomes, rather than static deployment targets. Such approaches reduce stranded-asset risk while enabling adaptive policy adjustment as technologies mature. Finally, standardized reporting of system performance metrics, including delivered energy cost, utilization, downtime, and throughput, is essential for consistent cross-technology benchmarking and evidence-based policy refinement.

7 Conclusion

This study presents an integrated techno-economic assessment of seven leading zero-emission and near-zero-emission freight technologies, including (a) battery fast charging, (b) battery swapping, (c) catenary electric road systems, (d) inductive in-motion electric road systems, (e) fuel cell electric vehicles, (f) hydrogen internal combustion engine vehicles, and (g) diesel internal combustion engine vehicles equipped with carbon capture and storage. These pathways are evaluated across short-haul, regional-haul, and long-haul freight applications, with deployment horizons extending to 2040. A bounded techno-economic possibility space is explored using Monte Carlo–based sampling with common random numbers. This approach preserves cross-technology comparability of key system parameters, including fleet size, energy and fuel costs, and infrastructure configurations. This unified simulation framework allows for consistent cross-technology comparisons and systematic sensitivity analysis across realistic deployment scenarios.

Fuel cost analysis indicates meaningful differences among technologies. In the near term (2030), catenary electric road systems exhibit relatively low and stable per-mile fuel costs, owing to their high energy efficiency and access to centralized and predictable electricity supply. These are followed by fast-charging and inductive-charging solutions, which are influenced by demand charges and power-transfer inefficiencies. Hydrogen fuel cell electric vehicles exhibit the highest fuel costs at this stage, reflecting the limited maturity of hydrogen production and delivery infrastructure. In the longer term (2040), however, these cost differentials narrow substantially. This convergence is associated with modeled improvements in infrastructure utilization, hydrogen logistics, and evolving energy supply configurations, which together reduce fuel-cost variability across pathways. These results reflect system-level cost dynamics under coordinated infrastructure deployment and energy provisioning strategies and do not imply uniform cost convergence across real-world deployment contexts.

Analysis of levelized system costs indicates that the cost competitiveness of zero-emission vehicle technologies evolves over time. Battery-based solutions, particularly fast charging and battery swapping, are among the more cost-effective options in early-stage deployments, such as in 2030, owing to their modular architectures and compatibility with depot-based fleet operations. However, this early cost advantage becomes less pronounced as alternative systems mature under assumptions for later years. By 2040, hydrogen fuel cell technologies have the potential to achieve comparable system-level costs under conditions of high infrastructure utilization and optimized energy supply, relative to battery-based pathways such as fast charging. These outcomes depend critically on sufficient infrastructure utilization, low-cost energy supply, and coordination across production, delivery, and end-use systems. For long-haul applications, catenary electric road systems can achieve low levelized system costs under large-scale fleet deployment, particularly where corridor-scale demand and operational alignment between fleet activity and energy delivery systems are present. Collectively, the results indicate that no single technology dominates across all freight applications; techno-economic performance is instead strongly determined by route characteristics, fleet scale, energy supply structure, and local infrastructure constraints.

Similar patterns emerge when evaluating the levelized cost of transport, which represents the average annual cost of delivering freight service per vehicle over its economic lifetime and integrates vehicle acquisition costs, infrastructure investments, energy or fuel expenditures, and operation and maintenance costs into a unified metric. Across all pathways, levelized cost of transport trends closely mirror those of levelized system cost, reflecting the dominant influence of system utilization and energy provisioning strategies on long-haul freight economics. Differences among technologies are driven primarily by variations in upfront vehicle capital costs, which play a secondary role relative to infrastructure and energy costs in shaping long-term transport performance.

The analysis presented in this study evaluates the techno-economic cost performance of alternative freight energy delivery pathways under stylized deployment conditions. The modeling framework focuses on system-level infrastructure and energy costs and therefore does not explicitly incorporate several commercial adoption factors that influence fleet decision-making, including residual value uncertainty, financing constraints, dealer readiness, workforce training requirements, and insurance considerations. In addition, the analysis assumes coordinated infrastructure deployment along freight corridors and does not explicitly account for siting constraints, right-of-way limitations, or permitting complexities that affect real-world deployment timelines. Consequently, the modeled cost competitiveness across technologies should be interpreted as indicative of potential economic performance under coordinated deployment conditions, rather than as a direct prediction of near-term technology adoption.

Future deployment strategies can be strengthened by addressing energy cost volatility and technology-specific operational constraints through adaptive planning and coordinated infrastructure development. Research priorities include exploring supply-chain co-optimization strategies, such as integrated planning of hydrogen pipeline infrastructure and renewable electricity siting, and assessing how electricity and hydrogen market structures influence technology adoption pathways. In addition, pilot programs, transparent data-sharing platforms, and coordinated regulatory planning play a critical role in de-risking investment and enabling scalable and equitable deployment of zero-emission vehicle technologies in support of long-term freight decarbonization.

8 Acknowledgements

We acknowledge funding provided by Sustainable Transportation Energy Pathways Program (STEPS+) within the Institute of Transportation Studies at the University of California, Davis.

9 References

[1] Bushnell, J. B., & Hughes, J. E. (2024). The role of modal substitution in rebound effects within US freight transportation. Nature Energy, 9(9), 1153-1160.

[2] Zhao, P., Zhang, S., Santi, P., Cui, D., Wang, F., Liu, P., ... & Wu, Y. (2024). Challenges and opportunities in truck electrification revealed by big operational data. Nature Energy, 1-11.

[3] Lai, X., Chen, Q., Tang, X., Zhou, Y., Gao, F., Guo, Y., ... & Zheng, Y. (2022). Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective. Etransportation, 12, 100169.

[4] Pramuanjaroenkij, A., & Kakaç, S. (2023). The fuel cell electric vehicles: The highlight review. International Journal of Hydrogen Energy, 48(25), 9401-9425.

[5] Bibiloni-Ipata, S., Vielmo-Cogo, V., Frizzo-Prante, G., & Martinez-Boggio, S. (2025). Design and study of the effects of retrofitting diesel engines in hydrogen trucks through simulation. International Journal of Hydrogen Energy, 163, 150806.

[6] Aronietis, R., & Vanelslander, T. (2024). Economic impacts of the catenary electric road system implementation in Flanders. International Journal of Sustainable Transportation, 18(1), 46-61.

[7] Wu, H. H., Gilchrist, A., Sealy, K., Israelsen, P., & Muhs, J. (2011). A review on inductive charging for electric vehicles. In 2011 IEEE international electric machines & drives conference (IEMDC) (pp. 143-147). IEEE.

[8] Speth, D., Plötz, P., Funke, S., & Vallarella, E. (2022). Public fast charging infrastructure for battery electric trucks—a model-based network for Germany. Environmental Research: Infrastructure and Sustainability, 2(2), 025004.

[9] Zhao, J., Burke, A. F., Miller, M. R., & Fulton, L. M. (2024). Integrating market penetration and cost technologies (IMPACT): Procurement incentives on fuel cell electric truck adoption in California. International Journal of Hydrogen Energy, 94, 1266-1287.

[10] Zhao, J., Burke, A., Miller, M., & Fulton, L. (2024). Market Prospects of Fuel Cell vs. Battery-Electric Trucks in Medium-and Heavy-Duty Segments from 2025 to 2040.

[11] Zhao, J., Burke, A. F., Miller, M. R., & Fulton, L. M. (2024). Vehicle choice modeling for emerging zero-emission medium-and heavy-duty vehicle markets in California. Transportation Research Interdisciplinary Perspectives, 26, 101169.

[12] Burke, A., Zhao, J., Miller, M., & Fulton, L. (2023). Vehicle Choice Modeling for Light-, Medium-, and Heavy-Duty Zero-Emission Vehicles in California. https://escholarship.org/content/qt7437p058/qt7437p058.pdf

[13] Burke, A. F., Zhao, J., Miller, M. R., Sinha, A., & Fulton, L. M. (2023). Projections of the costs of medium-and heavy-duty battery-electric and fuel cell vehicles (2020-2040) and related economic issues. Energy for Sustainable Development, 77, 101343.

[14] Speth, D., Plötz, P., & Wietschel, M. (2025). An optimal capacity-constrained fast charging network for battery electric trucks in Germany. Transportation Research Part A: Policy and Practice, 193, 104383.

[15] Alonso-Villar, A., Davíðsdóttir, B., Stefánsson, H., Ásgeirsson, E. I., & Kristjánsson, R. (2025). Optimising fast-charging infrastructure for long-haul electric trucks in remote regions under adverse climate conditions. eTransportation, 24, 100414.

[16] Deshpande, P., de Saxe, C., Ainalis, D., Miles, J., & Cebon, D. (2023). Analysis of Fast Charging Arrangements for Electric Heavy Goods Vehicles. In 2023 IEEE 26th International Conference on Intelligent Transportation Systems (ITSC) (pp. 6138-6143). IEEE.

[17] Ahmad, F., Saad Alam, M., Saad Alsaidan, I., & Shariff, S. M. (2020). Battery swapping station for electric vehicles: opportunities and challenges. IET Smart Grid, 3(3), 280-286.

[18] Li, Y., Zhu, F., Li, L., & Ouyang, M. (2024). Electrifying heavy-duty truck through battery swapping. Joule, 8(6), 1556-1561.

[19] de Saxe, C., Ainalis, D., Miles, J., Greening, P., Gripton, A., Thorne, C., & Cebon, D. (2023). Vehicle and charging requirements for an electrified road freight system demonstrator in the UK. Transportation Research Procedia, 72, 4033-4040.

[20] Ainalis, D., Thorne, C., & Cebon, D. (2023). Technoeconomic comparison of an electric road system and hydrogen for decarbonising the UK's long-haul road freight. Research in Transportation Business & Management, 48, 100914.

[21] de Saxe, C., Ainalis, D., Miles, J., Greening, P., Gripton, A., Thorne, C., & Cebon, D. (2023). An electric road system or big batteries: Implications for UK road freight. Transportation Engineering, 14, 100210.

[22] Deshpande, P., de Saxe, C., Ainalis, D., Miles, J., & Cebon, D. (2023). A breakeven cost analysis framework for electric road systems. Transportation Research Part D: Transport and Environment, 122, 103870.

[23] Shehabeldeen, A., & Mohamed, M. (2024). Optimal Deployment of Overhead Catenary Charging for Electric Bus Transit Systems. IEEE Transactions on Transportation Electrification.

[24] Feng, D., Yu, Q., Sun, X., Zhu, H., Lin, S., & Liang, J. (2021). Risk assessment for electrified railway catenary system under comprehensive influence of geographical and meteorological factors. IEEE Transactions on Transportation Electrification, 7(4), 3137-3148.

[25] Nicolaides, D., Cebon, D., & Miles, J. (2017). Prospects for electrification of road freight. IEEE Systems Journal, 12(2), 1838-1849.

[26] Mude, K. N. (2018). Battery charging method for electric vehicles: From wired to on-road wireless charging. Chinese Journal of Electrical Engineering, 4(4), 1-15.

[27] Islam, A., Islam, T., Mahmud, H., Raihan, O., Islam, M. S., Marwani, H. M., ... & Awual, M. R. (2024). Accelerating the green hydrogen revolution: A comprehensive analysis of technological advancements and policy interventions. International Journal of Hydrogen Energy, 67, 458-486.

[28] Bade, S. O., & Tomomewo, O. S. (2024). A review of governance strategies, policy measures, and regulatory framework for hydrogen energy in the United States. International Journal of Hydrogen Energy, 78, 1363-1381.

[29] CARB. LCFS Electricity and Hydrogen Provisions. https://ww2.arb.ca.gov/resources/documents/lcfs-electricity-and-hydrogen-provisions

[30] IRS. Clean hydrogen production credit. https://www.irs.gov/credits-deductions/clean-hydrogen-production-credit

[31] USDOE. Regional Clean Hydrogen Hubs. https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0

[32] Volvo Trucks. (2024). Volvo to launch hydrogen-powered trucks. https://www.volvotrucks.com/en-en/news-stories/press-releases/2024/may/Volvo-to-launch-hydrogen-powered-trucks.html

[33] Remora. (2025). Carbon capture for vehicles: Monetize train and truck emissions. https://www.remoracarbon.com

[34] ITF (2022), "Decarbonising Europe's Trucks: How to Minimise Cost Uncertainty", International Transport Forum Policy Papers, No. 107, OECD Publishing, Paris.

[35] CARB. Heavy-Duty Vehicle Research. https://ww2.arb.ca.gov/resources/documents/heavy-duty-vehicle-research

[36] Caltrans. CA Truck Network. https://dot.ca.gov/programs/traffic-operations/legal-truck-access/truck-network-map

[37] Southern California Edison. Electricity Rates For EVs. https://www.sce.com/clean-energy-efficiency/electric-vehicles/rebates-rates

[38] CEC. Zero Emission Vehicle and Infrastructure Statistics Collection. https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics-collection

[39] CARB. Advanced Clean Trucks. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks

[40] CARB. Advanced Clean Fleets. https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets

[41] Terawatt Infrastructure. (2025). Fleet charging solutions for medium- and heavy-duty vehicles. https://www.terawattinfrastructure.com/

[42] Prologis, Inc. The Prologis mobility charging network. https://www.prologis.com/essentials-solutions/mobility/hubs?utm_source=google&utm_medium=cpc&utm_content=charging-hubs&utm_campaign=dg-en_us-mob-ps-202506-nb-google

[43] WattEV. (2025). Zero-emission freight charging and electric trucking solutions. https://www.wattev.com

[44] CATL brings battery swapping to electric trucks. https://electricdrives.com/news/catl-brings-battery-swapping-to-electric-trucks

[45] Siemens Mobility. eHighway: Electrification of road freight transport. https://www.siemens.com/mobility/electrification/road/ehighway

[46] Electreon. Wireless charging for electric vehicles. https://www.electreon.com

[47] Hydrogen Fuel Cell Partnership. NorCAL ZERO project: Fuel cell-electric truck demonstration project at the Port of Oakland. https://h2fcp.org/hydrogen-trucks/port-of-oakland

[48] U.S. Energy Information Administration. (2025). Levelized costs of new generation resources in the Annual Energy Outlook 2025. https://www.eia.gov/outlooks/aeo/electricity_generation/pdf/AEO2025_LCOE_report.pdf

[49] Lazard. (2025). Levelized cost of energy+ (Version 18.0). https://www.lazard.com/media/uounhon4/lazards-lcoeplus-june-2025.pdf

[50] Link, S., Stephan, A., Speth, D., & Plötz, P. (2024). Rapidly declining costs of truck batteries and fuel cells enable large-scale road freight electrification. Nature Energy, 9(8), 1032-1039.

[51] Konstantinou, T., Haddad, D., Prasad, A., Wright, E., Gkritza, K., Aliprantis, D., ... & Haddock, J. E. (2021). Feasibility study and design of in-road electric vehicle charging technologies.

[52] Bracci, J., Koleva, M., & Chung, M. (2024). Levelized cost of dispensed hydrogen for heavy-duty vehicles (No. NREL/TP--5400-88818). National Renewable Energy Laboratory (NREL), Golden, CO (United States).

[53] World Nuclear Association. (2024). Hydrogen production and uses. https://world-nuclear.org/information-library/energy-and-the-environment/hydrogen-production-and-uses

[54] Andersson, M., & Plötz, P. (2024). Digital ERS forum 1: Introduction and presentations. https://electric-road-systems.eu/e-r-systems-wAssets/docs/Digital-ERS-Forum-1-Intro-and-presentations.pdf

[55] Qiu, K., Ribberink, H., & Entchev, E. (2022). Economic feasibility of electrified highways for heavy-duty electric trucks. Applied Energy, 326, 119935.

[56] Vijayagopal, R. (2023). Hydrogen internal combustion engines and their use in trucks. Argonne National Laboratory. https://ww2.arb.ca.gov/sites/default/files/2023-12/231128argonnepres.pdf